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Environmental performance assessment: A comparison and improvement of three existing social housing projects

Jani F. Velázquez Robles [a,*], Eloi Coloma Picó [a], S.M. Amin Hosseini [b]

[a] ETSAB, Escuela Técnica Superior de Arquitectura, Universidad Politécnica de Cataluña, Barcelona, Spain
[b] RESUME TECH, America St., Barcelona, Spain

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ABSTRACT

The energy consumption of buildings accounts for 22% of total global energy use and 13% of global greenhouse gas emissions. In this context, this study aims to evaluate the environmental performance of three social housing designs located in emerging economies by analysing sustainability indicators adopting different technical solutions. The analysis incorporates eleven construction strategies to improve the environmental performance of the buildings. The performance assessment is analysed by using EDGE (Excellence in Design for Greater Efficiencies) Methodology. Therefore, this study aims to help identify the construction strategies, with the aim of improving the operational energy performance (kWh/year/m^{2}floor), operational CO_2 emissions (tCO₂eq/Year/m^{2}floor), embodied energy (MJ/m^{2}floor) and operational water consumption of housing (m3/year/m^{2}floor). The results showed that when the technical measures are implemented, the energy demand decreases by 38.52% in Case A, 19% in Case B, and 41% in Case C. The embodied energy savings in materials in Case A 3%, Case B 0% and Case C 36% Regarding water consumption, the demand decreases by 46%, 4%, and 12% in Case A, B, and C respectively.

1. Introduction

Recent demographic trends are indicators of the potential future challenges to sustainable development. In 2019, the Department of Economic and Social Affairs of the United Nations reported that the global population will reach over 8.5 billion in 2030 (United Nations Human Settlements Programme, 2003). In the housing sector, the new designs should assess all the phases of the life cycle of the building to mitigate negative environmental impact (Palmer et al., 2006). However, discussion on dwelling rehabilitation versus its demolition and new construction has been increasing in intensity since the end of the twentieth century, especially due to the necessity for the regeneration of urban centre's caused by the great migration from rural to urban areas (Denhez, 2007; Laefer and Manke, 2008; Rakhra, 1983). In several studies, it is demonstrated that even with a severely damaged building, the repair and retrofit work incurs a lower economic and environmental impact than new construction (Kohler and Hassler, 2002; Itard and Klunder, 2007; Goldstein et al., 2013; Ferreira Sánchez, 2015; Oti et al., 2016). The building reuse projects eked out carbon impact reductions that seemed small when considering only one building. Still, they showed substantial savings on a medium to large scale (Alba-Rodríguez et al., 2017). Several studies find that building reuse can avoid unnecessary carbon outlays and help communities achieve their near-term carbon reduction goals (Alba-Rodríguez et al., 2017). The construction sector should take an active role in encouraging environmental protection, economic growth, and social advancement is crucial to empower technical solutions at the early design stage to reduce operational expenses and environmental impact and to avoid future renovations and investments (Gan et al., 2017; Liu et al., 2020).

In this regard, a rapid large-scale housing strategy called incremental housing has been applied by some architects to provide temporary and permanent housing to low-income users after different natural phenomena events and the increment of house demand in cities (Askar et al., 2019). Incremental housing is a step-by-step process: it starts with a starter core shelter. The starter core could be a kitchen and a bathroom unit or solely an empty lot with a utility connection potential. This incremental housing method has displayed technical advantages and disadvantages through the years. Some disadvantages are, e.g., the lack of understanding of users' needs (spatial design), the poor environmental performance, the difficulties of making urban services accessible, the poor construction quality causing health problems and the high cost of electricity (Marinovic and Baek, 2016; Azizibabani and Bemanian,

* Corresponding author.
E-mail address: jani.fernanda.velazquez@upc.edu (J.F. Velázquez Robles).

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2019; Martins and Saavedra Farias, 2019). This paper aims to answer two main questions concerning environmental performance related to social housing performance, How to improve the existing social housing design to consequently improve the building's environmental performance? And is it possible to reduce operational expenses of the social housing designs by improving the building's environmental performance?

To answer the aforementioned, this study promotes the comparison and analysis of the design of three case studies to obtain higher environmental sustainability indexes. These improvements are based on constructive strategies to reduce operational energy consumption, operational carbon dioxide (CO_2) emissions, water consumption and operational expenses. From the 1910s to the 1970s, the highest percentage of incremental housing constructions was in Europe and USA, and Latin-American countries from the 1970s to the 2000s Martin López L. (2016). The process of incremental housing involves three actors coming into the stage: The individuals, public sector and private sector (Greene and Rojas, 2008). Another proposed measure is Design for Disassembly (DfD), adopting new construction technologies as well as reusing and recycling construction materials. DfD could reduce CO_2 emissions with the Integration of circular economy principles in the construction. Besides all the benefits mentioned, the design based on building sustainable housing developments could create an opportunity to generate new green jobs (Guidance to Design a Low-Carbon, Sustainable and Resilient Project, 2020). Concerning incremental housing, there are several research questions regarding how to improve the units designs to develop more sustainable social incremental housing: How to design affordable social housing for low-income people? How to design a social housing development while taking climate risk into account? How do the existing social housing designs improve the unit's environmental performance? And How to reduce operational expenses (water and energy) of the current social housing designs? (HasgülE, 2016). On this basis, the proposed model assessed the environmental fe asibility of the improvement of three social housing developments assisted by the analysis of environmental indicators Energy efficiency (kWh/year/m^{2}floor), (MJ/m^{2}floor), Carbon Emissions (tCO₂eq/Year/m^{2}floor) and Water consumption (m^3/year/m^{2}floor). Table 1 in the Supplementary Material section summarises ten different examples of incremental housing projects from 1969 to 2018 in emerging economies.

On one hand, the incremental housing strategy has multiple advantages such as: generally, well located inside the cities, accessibility to basic services: potable water, electricity, drainage and internet, public transport accessibility, social inclusion, possibility of commercial spaces on the ground floor, modular design, resistant to earthquakes (when apply), access to urban infrastructure: schools, hospitals, workplaces, high-density developments and partition walls, floor finishing, roof joints, can be changed with no damage to the structure. On the other hand, has disadvantages such as: the high cost of land in well-located zones in the cities, not all low-income users have access to financing for housing, lack of understanding of users needs, lack of participatory planning and cultural understanding, use of high environmental impact construction materials, lack of waste collection and reuse, poor level of maintenance in public spaces inside the low-income housing developments, lack of green areas and outdoor public lighting, lack of baselines to expand their houses in the future, necessity of the analysis of all life cycles of the building in terms of carbon emissions of the house, energy and water consumption and lack in the design to adapt the infrastructure to climate risk. (Source: Wakeman, 1999; Napier, 2002; United Nations Human Settlements Programme, 2003; Williams, 2004; 2005; Lorenzo Galligo, 2005; Mazor, 2006; Greene and Rojas, 2008; Dayaratne et al., 2008; Ahsan and Quamruzzaman, 2009; Rodriguez Cedillo, 2009; Pandelaki and Shiozaki, 2010; Mozas and Fernandez, 2010; Gattoni et al., 2011; Lizarralde, 2011; Wakely and Riley, 2011; Aravena, 2012; Moye and Horne, 2013; Fiji Incremental Housing Workshop, 2014; Hamid et al., 2014; Cuenca, 2015; Blanco et al., 2016; HasgülE, 2016; Marinovic and Baek, 2016; Schneider and Till, 2017; Baitsch, 2018; Adhikari, 2019; Martins and Saavedra Farias, 2019).

As this paper aims to answer research questions concerning the environmental performance of social housing projects, it was key to consider sustainability-building indicators. Heravi et al. (2015) highlight the importance of the performance indicators assessment during the operational phase of the buildings to maintain a balance between environmental, social, economic, and functional aspects. Further, the adoption of green technologies has reasonable economic savings and environmental advantages from the perspective of building a lifecycle (Ge et al., 2020). Sustainability aspects of housing are highlighted and discussed in various references (Alarcon et al., 2001; Pillai et al., 2002; Wong, 2004; Aguado et al., 2006; Botero et al., 2007; Geraedts, 2008; Rankin et al., 2008; Skibniewskił and Ghosh, 2009; Roberts and Latorre, 2009; CII Construction Industry Institute, 2011; Kunz and Fischer, 2012; Wallbaum et al., 2012; Constructing Excellence, 2013; Heravi et al., 2015; Kylili et al., 2016; Orihuela et al., 2017; Adabre et al., 2020; Hosseini et al., 2020; Liu et al., 2020).

Worldwide, there are voluntary environmental certifications and building standards that the construction sector can adopt toward mitigating the negative effects of climate change. This study includes the analysis of seven international sustainability systems (BREEAM, LEED, BCA, HK-BEAM, GBCA, NAERS and Energy Star (See Table 2 in Supplementary Material section section).

In this study, sustainability performance indicators are based on a comprehensive literature review that includes the final list of project indicators identified by Orihuela et al., in 2017, as well as other writers in the International Sustainability Systems. In grey, it highlighted the assessed indicators in this study. See Table 3.

2. Methods

2.1. Excellence in Design for Greater Efficiencies methodology

To evaluate and improve the three case studies, in addition to the extensive literature review, the environmental building performance assessment included the use of green construction strategies of EDGE Methodology. EDGE has been developed for global use, the software has been customised at the local level through the support of different country-based institutions that provided data collection. EDGE relies on information gleaned from typical building practices as well as local building codes, where they are in existence and being enforced to determine the base case parameters for efficiency in energy, materials and water. Baseline assumptions have been adjusted where necessary to improve the pair to local conditions. To contrast the EDGE energy results, the calculation was compared using dynamic simulation software (eQuest) for buildings in nine locations. Additionally, initial reviews of EDGE for Homes have been conducted by different consultants in the Philippines and Mexico to compare the software for local markets. In the Philippines, WSP Group12, conducted a study to compare results between EDGE and Software Integrated Environmental Solutions. The test concluded a variation of 5%. In Mexico, Lean House Consulting was commissioned to compare results between EDGE and DOE, and Design Builder for four locations: Cancun, Guadalajara, Mexicali and Hermosillo. The test concluded a variation of 7–8%. Finally, EDGE includes LEED v4, DGNB, HQE, E + C sustainability criteria.

2.2. Calculations

For the Energy demand, since a building generally uses more than one fuel from different carriers (e.g. electricity, natural gas, diesel, or district cooling/heating), EDGE converts "delivered" energy values into primary energy to provide a common metric. Renewable energy generated on site is deducted from the building's improved case and is expressed as energy savings (Steadman et al., 2000; Mervin, 2008; Bertoldi and Atanasiu, 2006; Roger, 2007). Regarding energy demand

Table 3
Quantitative sustainability performance indicators. Source: Alarcon et al., 2001; Pillai et al., 2002; Wong, 2004; Aguado et al., 2006; Botero et al., 2007; Geraedts, 2008; Rankin et al., 2008; Skibniewskił and Ghosh, 2009; Roberts and Latorre, 2009; CII Construction Industry Institute, 2011; Kunz and Fischer, 2012; Wallbaum et al., 2012; Constructing Excellence, 2013; Heravi et al., 2015; Kylili et al., 2016; Orihuela et al., 2017; Adabre et al., 2020; Hosseini et al., 2020; Liu et al., 2020.

REQUIREMENTS	CRITERIA	INDICATORS	OVERVIEW	REFERENCES
R1. Economic	C1 Invest capital	I1 Construction system (including the mechanical, electrical, plumbing installations, and finishes level) (euros/m^2)	Includes all direct costs of the superstructure and standard equipment, such as windows, door, interior walls, kitchen and bathroom furniture. The labour cost is included. The price of the land and urban infrastructure is not included in the initial construction cost.	Alarcon et al., 2001; Aguado et al., 2006; Kunz and Fischer, 2012; Wallbaum et al., 2012; Orihuela et al., 2017: Hosseini et al., 2020
R2. Environmental	C2 Energy efficiency	I2 Energy efficiency (kWh/year/m^2floor)	Include the operational energy for heating, cooling, lighting, domestic water heating and appliances.	Alarcon et al., 2001; Aguado et al., 2006; Botero et al., 2007; Rankin et al., 2008; Constructing Excellence, 2013; Heravi et al., 2015; Kylili et al., 2016; Orihuela et al., 2017; Adabre et al., 2020; Liu et al., 2020; BREEAM, LEED.
		I3 Embodied Energy (MJ/m^2floor)	Include the quantification of all the energy needed to bring the raw material from the extraction to their manufacture and lifting; it includes the energy associated with transport.	
	C3 CO_2 Emissions	I5 Carbon Emissions (tCO_2eq/Year/m^2floor)	Emissions from operation include heating, cooling, lighting, domestic water heating and appliances and these can be direct or indirect. For example, a furnace could be direct (gas-powered), or indirect (electricity-powered).	
	C4 Water consumption	I6 Water consumption (m3/year/m^2floor)	Water consumption during the operational phase of the building. Include kitchen use, bathroom use and washing use.	
R3. Social	C5 Customer satisfaction	I7 Delivery time (days/m^2)	This indicator evaluates the importance of prefabrication, supply chains and management.	Pillai et al., 2002; Wong, 2004; Aguado et al., 2006; Rankin et al., 2008; Geraedts, 2008; Skibniewskił and Ghosh, 2009; CII Construction Industry Institute, 2011; Constructing Excellence, 2013; Orihuela et al., 2017
R4. Functional	C6 Modifiability and layout flexibility	I8 Incremental facility (%)	This indicator assesses in m^2 the flexibility of a building for a future expansion to satisfy users units space needs.	Geraedts, 2008; Wallbaum et al., 2012;
		I9 Safety (Flood resilience measures)	The service lifespan of the house plays a vital role in the creation of local value. Indicators to assess the durability of the building include construction techniques and materials resilient to floods according to the construction regulations of each country.	

for hot water requirements, algorithms were based on EN 15316-3. In terms of water demand, the Water Efficiency Calculator for New Dwellings from the United Kingdom was used. EDGE estimated annual water use through the number of water fixtures (taps, toilets, showers, etc.) and water usage loads (occupancy, the water flow rate through the fixtures and usage rates). A monthly quasi-steady-state calculation method based on the European Committee for Standardisation (CEN) and ISO 13790 standards was used to assess annual energy use for the space heating and cooling of residential or non-residential buildings. For energy efficiency building codes COMcheck in the U.S Simplified Building Energy Model (SBEM) and Standard Assessment Procedure (SAP) in the United Kingdom, and Energy Performance Certificates (EPCs in the EU) was implemented to find a quick and cost-effective way to benchmark buildings and to quantify energy savings. For the embodied energy, EDGE incorporates available data of global construction materials (See Eq. (1) and Eq. (1.1)). The GaBi databases represent the largest internally consistent collection of life cycle inventory data with over 7,200 profiles, allowing more representative data to be used specifically to model the EDGE materials.

For example for a wall:

$$\text{Embodied Energy per } m^2 \text{ of wall } (MJ/m^2) = \text{Thickness of the wall (m) x Density } (kg/m^3) \text{ x Embodied Energy (MJ/kg)} \tag{1}$$

For example per m^2 of floor:

$$\text{Embodied Energy per } m^2 \text{ of floor } (MJ/m^2) = \text{Thickness of the wall (m) x Density } (kg/m^3) \text{ x Embodied Energy (MJ/kg) x Density of wall } (m^2\text{wall}/m^2\text{floor}) \tag{1.1}$$

2.3. Case studies

In this paper, three social housing designs were assessed, compared and improved in environmental performance. The assessment included a cost-benefit study that considered annual energy and water operational cost reduction applying different technical solutions from EDGE Method. The selection of the case studies was based on the principles of Comparative Case Studies, Methodological Briefs: Impact Evaluation of UNICEF Office of Research (Goodrick, 2014). The projects were selected based on factors for the comparison and to identify the variation in circumstances of the different cases: building budget (between 8, 000–15,000 Euros), climate conditions (tropical), design area (between 36 and 55 m^2), a high-natural phenomenon risk (floods), located in emerging economies (Mexico, Puerto Rico and Indonesia) and the incremental strategy included in the design.

2.3.1. Case A, México

The first social housing project was Case A designed in 2014–2016 by the Tabasco government in México. A two years construction housing development of 120 houses (5 houses/month). Case A is a social housing development located in Nacajuca Villahermosa, one of the most flood risk areas in México. As shown in Fig. 1, the design includes a 42 m^2 house (50%) distributed in two bedrooms, one bathroom, kitchen and dining room. The concrete palafito structure allows the users to expand the house vertically to one floor with 42 m^2 (50%) above the core house (100%). The main construction system was built by an in-situ reinforced

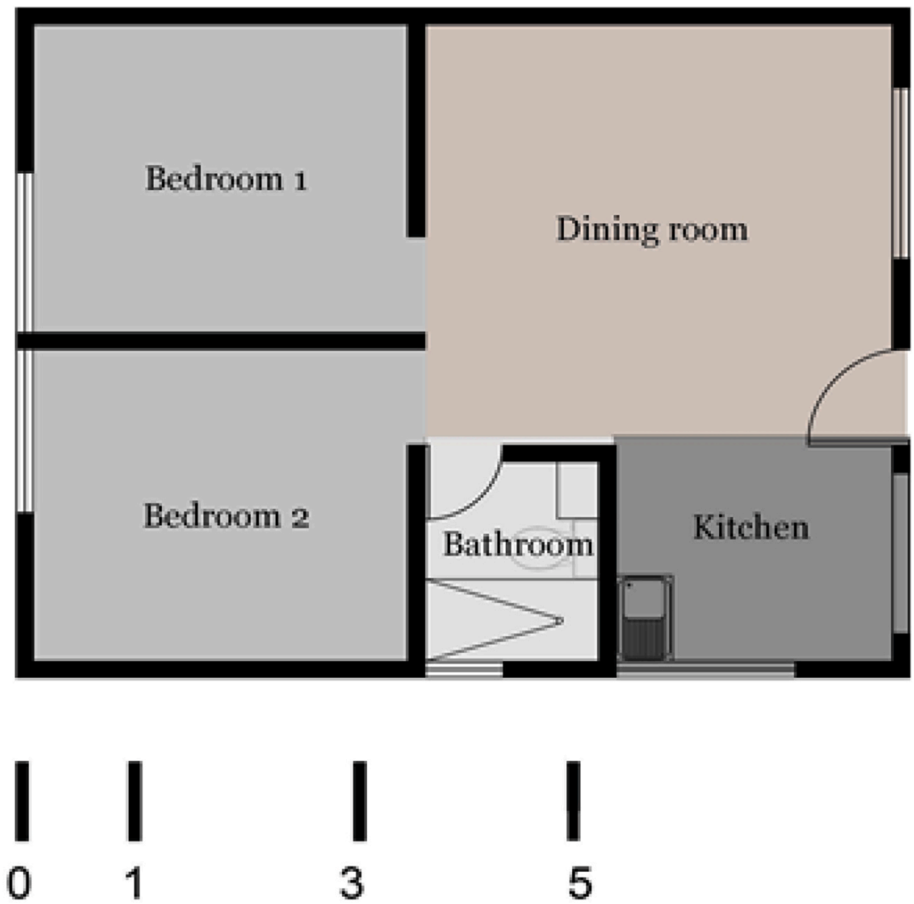

Fig. 1. Floor plan Case A.
Elaboration: Jani Fernanda Velazquez with Gobierno de Tabasco information, 2020

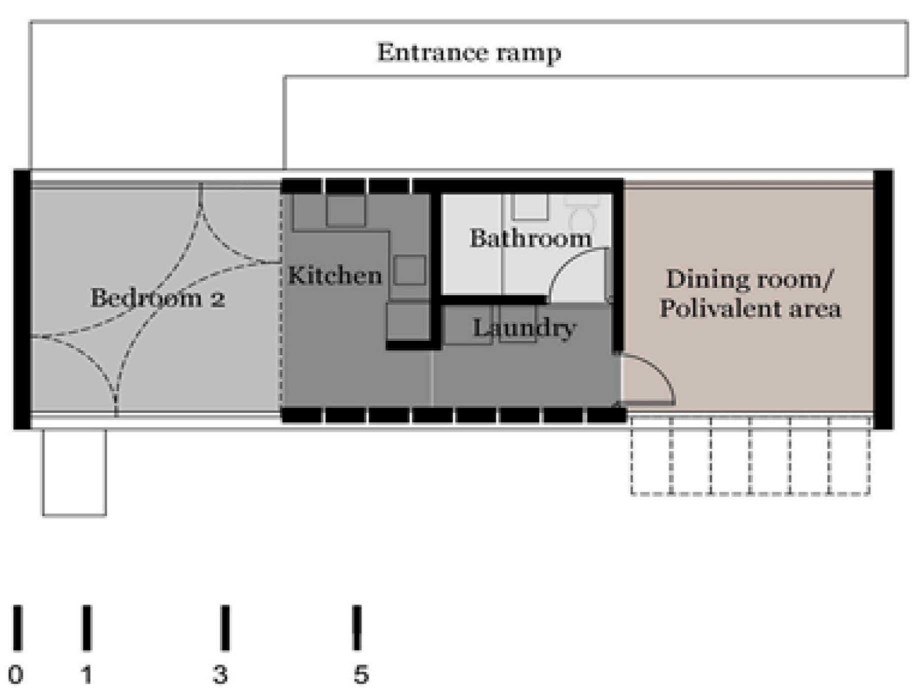

Fig. 2. Floor plan Case B.

concrete pillars system, common brick walls, plaster finishes in the exterior walls and lightweight fibre cement roofing. Resilience measures for floods included elevated structures, green embankments in the development, and reinforced concrete for the foundations. The design had no modular or prefabricated architecture that allowed future adaptability of the spaces because of the features of modular architecture such as the incorporation of changeable elements, the creation of multi-purpose spaces, and the freedom of operation (Kronenburg, 2003; Doran, D. & Giannakis, M. 2011; Quale et al., 2012; Horwitz-Bennett, 2020) are not integrated into the project.

2.3.2. Case B, Puerto Rico

The second social housing project was Case B House designed by Marvel Architects in 2018, a project based on Patillas Puerto Rico. It is a 53 m^2 house and the design includes one bedroom, one polyvalent space, one bathroom, kitchen and laundry space. The 53 m^2 (50%) house could be expanded vertically one floor more to 106 m^2 (100%) in total. The delivery time was one month. The materials chosen were meant to be local and with a prefabricated concrete construction system. The modular design allows the users to expand their houses with an easy kit of materials and tools, minimising waste products and demonstrating resiliency at house-site-community economy. See Fig. 2.

The construction system was designed as a basic module with reinforced concrete prefabricated blocks, prefabricated wooden planks, and galvanised steel connector plates. The project included passive strategies such as modular wood screens assembled out of treated lumber and plywood using simple screw connections, elevated slabs for indoor temperature control, water management, active systems, and low-consumption equipment. Case B was designed to maximise solar energy incorporating photovoltaic cells on the roof and minimise water consumption by incorporating low-consumption furniture in the bathroom and kitchen. All conduit and piping were exposed to facilitate installation and future maintenance. Solid walls could be made of concrete blocks, clay bricks, or compacted earth. Screens and shutters could be bamboo, woven lattices, or corrugated metal. The floor could be stone over an elevated earth pad. The design was adapted to include non-residential uses, such as home businesses or community support facilities. Flood resilience measures included elevated structure, reinforced concrete for foundations, modular window protections for hurricanes and rain gardens in common areas.

2.3.3. Case C, Indonesia

Case C was designed by Urban-Rural Systems in 2017 and built the first phase in 2018, a project based on Riau Islands in Indonesia. It was a 36 m^2 house (33%) and was expanded to its limit to three floors 108 m^2 (100%). Approximately it took 10 months to build the house, but the manpower was very reduced. Included one polyvalent space, one bathroom, kitchen and kitchen garden. The modular design allows the inhabitants to accommodate commercial functions on the ground floor in front of the house. The Indonesian house included water-saving measures, solar collectors, passive cooling principle, a kitchen garden and the integration of bamboo plantations creating productive landscapes and natural shadow in the development. Flood resilience measures included collecting and storing rainwater, rainwater harvesting, sewage systems, and drainage systems in the foundation. See Fig. 3.

Elaboration: Jani Fernanda Velazquez with https://urs.sec.sg information, 2020

2.4. Methodology application

2.4.1. Data input of case A, case B house and case C

To begin the evaluation of each case study, the project details, building data, area details, building systems, and key assumptions were indicated in the EDGE methodology software. See Table 4.

2.4.2. Construction materials in the base cases and improved cases of case A, case B house and case C

In Table 5, the original construction materials according to the system level (structure, floor slabs, roof, external walls, internal walls, windows and finishes) of three case studies were introduced to the EDGE Methodology. To reduce operational CO_2 emissions, the roof materials were changed. Substituting the roof's materials for new ones would have a considerable embodied energy versus keeping the existing ones, but the indoor quality and comfort would be improved. With the substitution of the roof, the use of electricity needed to cool the house will be reduced due to the thermal attributes of the proposed materials. According to the EDGE Method, the roof materials of Case A and Case C were the materials with the highest embodied energy per m^2. It was not

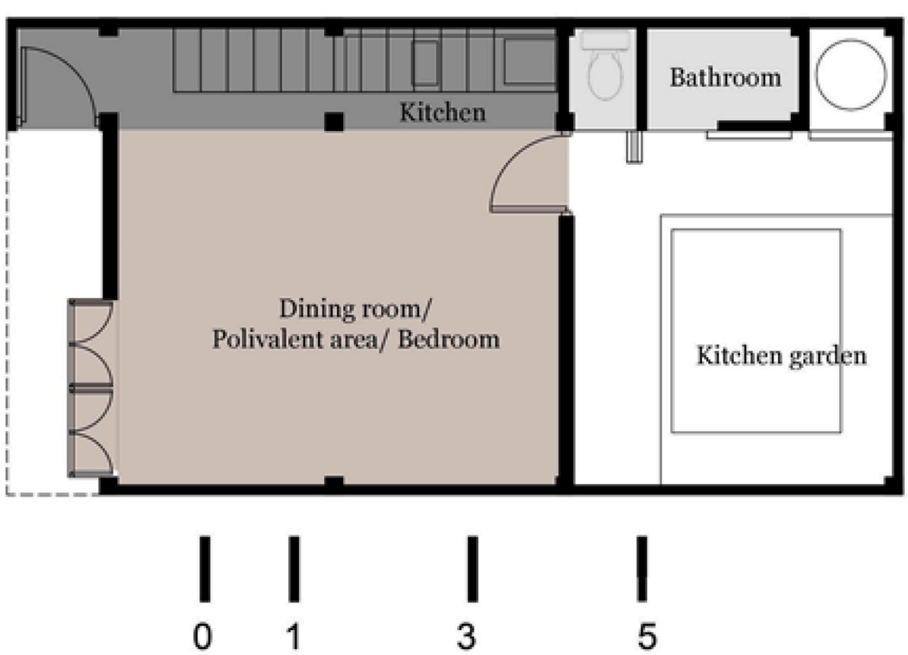

Fig. 3. Floor plan Case C.

Table 4
Building data of Case A, Case B House and Case C. Source: EDGE Methodology, 2021.

			Case A	Case B	Case C
DES0NG	**PROJECT DETAILS**	Country	México	Puerto Rico	Indonesia
		State/Province	Villahermosa	Patillas	Riau Archipelago
		City	Nacajuca	Providencia	Batam
		Income Category	Low	Low	Low
		Climate	Warm wet	Tropical rainforest	Tropical
		Year	2014	2018	2018
	BUILDING DATA/AREA DETAILS	Type Of Unit	House	House	House
		m^2	42	53	36
		Cost (Euro)	8,270.00	15,000.00	14,500.00
		Construction System	In situ	In situ + Prefabricated	In situ + Prefabricated
		Expandable m^2	42	53	72
		Initial Occupancy (People/Unit)	4	4	2
		Number Of Bedrooms	2	1	1
		Number Of Bathrooms	1	1	1
		Flood Resilience Strategy	Elevated structure	Elevated structure	Drainage systems in the foundation
		Type Of Incremental Variations	Vertical	Vertical	Vertical
		Initial Levels	1	1	1
		Incremental Levels	1	2	3
		Total Levels	2	3	3
		Roof Area/Unit (m^2)	42	53	36
	BUILDING SYSTEMS	Air Conditioning System	No	No	No
		Heating System	N/A	N/A	N/A
	KEY ASSUMPTIONS FOR THE BASE CASE	Fuel Used For Hot Water and Cooking	LPG	Natural gas	Natural gas
		Fuel Used For Space Cooling	Electricity (floor fan)	Electricity (floor fan)	Electricity (floor fan)
		Latitude (Deg)	18	18	1
		Average Outdoor Temperature (°C)	26.4	24.5	26.8
		Max. Outdoor Temperature (°C)	33	32	29
		Min. Outdoor Temperature (°C)	20	20	25
		Precipitation/year (mm)	2,550	1,686	2,441

Table 5
Original and proposed construction materials of Case A, Case B House and Case C. Source: EDGE Methodology, 2022.

	Case A original	Case A improved	Case B original	Case B improved	Case C original	Case C improved
Structure	In-Situ Reinforced Concrete	–	In-Situ + prefabricated Reinforced Concrete	–	In-Situ Reinforced Concrete	–
Floor Slabs	In-Situ Reinforced Concrete Slab	–	In-Situ Reinforced Concrete Slab	–	In-Situ Reinforced Concrete Slab	–
Roof	Synthetic lightweight Tiles	Steel clad sandwich panel	In-Situ Reinforced Concrete Slab	–	Aluminium Sheets on Steel Rafters prefabricated	Aluminium clad sandwich panel
External Walls	Medium weight hollow concrete blocks	–	Precast concrete panels and timber panels	–	Medium weight hollow concrete blocks	–
External Walls finishes	Plaster	–	Plaster and concrete	–	No finishes	–
Internal Walls	Medium weight hollow concrete blocks	–	Precast concrete panels	–	Medium weight hollow concrete blocks	–
Internal Walls finishes	Plaster	–	Plaster and concrete	–	No finishes	–
Flooring	Finished Concrete Floor	–	Finished Concrete Floor	–	Finished Concrete Floor	–
Window Frames (Single Glazing)	Aluminium	–	Timber	–	Timber	–

necessary to propose a new roof for Case B house because the material already met EDGE green standards.

2.4.3. Construction solutions applied for energy and water efficiency

Edge Methodology recommended certain measures according to the type of the building and income. In this case, these 12 measures were recommended for low-income users based on project data, the stage in the lifecycle of the building (existing building), year of construction and location conditions to improve actual environmental performance at least 20% of improvement according to EDGE calculations. If the performance of the installed components varies across the project for any reason, then a weighted average of the performance metric must be used. If the measure is not present in the project, then the requirement does not apply. To calculate performance against Key Performance Indicators, EDGE makes assumptions on how the occupants will use the building: Final energy consumption kWh/year/m^2floor, final Water Use m^3/year/m^2 floor, operational CO_2 Savings tCO_2/year/m^2 floor, based on the final energy use multiplied by the CO_2 emission factor for the generation of grid electricity, embodied energy savings MJ/m^2floor, from the building dimensions and the materials selected in the materials section, base case utility monthly cost euros/year or local currency in specific countries, for energy and water use, euros/year or local currency in specific countries. When measures are selected, EDGE makes default assumptions on the typical improved performance over the base case. To summarise, the energy efficiency measures the assessment include (external shading elements with AASF of 0.49, natural cross ventilation, ceiling fans in all habitable rooms, energy saving bulbs and solar hot water collectors 50% of hot water demand collector area (m^2/unit 0.4) and solar reflective paint for external walls solar reflectivity (albedo) of 0.7. Water efficiency measures include low-flow showerheads 8 L/min, low-flow faucets in all bathrooms 6 L/min, rainwater harvesting system 50% of roof area used for rainwater collection, rainwater harvesting system 50% of roof area used for rainwater collection and recycled grey water for flushing. Material efficiency measures include roofs of steel clad sandwich panel and aluminium clad sandwich panel.

The energy measures assumption includes: The solar water heaters will reduce the grid electricity (fossil fuels) used by the building for water heating. The default-improved case assumes 50% of total hot water demand in the improved case being met by the solar thermal installation. Energy saving bulbs can be claimed if the light bulbs used in the project are either compact fluorescent (CFL), LED, or T5, or other types of light fixtures that achieve 90 lm/W or greater. Ceiling fans reduce cooling requirements and improves occupant comfort without actively cooling the air. Therefore, ceiling fans are only beneficial in spaces that have a demonstrable cooling load.

Specifying a reflective finish for the walls can reduce the cooling load in air-conditioned spaces and improve thermal comfort in non-mechanically cooled spaces (Taleb, H.M., 2014). A city's core temperature is often significantly higher than its surrounding area due to the retention of heat from the built environment. Specifying a reflective finish for the walls can reduce the cooling load in mechanically and non-mechanically cooled spaces and improve indoor thermal comfort. Unlike visible solar reflectance, it includes the full solar spectrum, but does not include the effect of emittance which is reflected in a metric such as Solar Reflectance Index (SRI). The impact that the solar reflectivity of the walls has in the energy consumption in a building is dependent on the insulation, as well as the approach used to cool the building. Super-insulated buildings may not benefit significantly from wall finishes with a high solar reflectivity (EDGE methodology, 2020). The installation of mechanical systems such as ceiling fans in each house help to reduce the cooling load and will result in improved performance and the savings are only reflected in the operational CO_2 emissions and cost savings. However, to determine the number and size of the fans required in each space of the 3 case studies, We analysed the volume of each room to get the m3 of air that a fan is rated for. Proposed as key consideration to improve the environmental performance, the measure of natural cross ventilation could reduce cooling load, which lowers initial capital and maintenance costs (Moosavi et al., 2014). In this study, the 3 case studies meet the conditions for a proper natural cross-ventilation without the necessity of compromising the structure according to the floor plans. Cross-ventilation with banked rooms can be achieved by creating openings in the corridor partition. It is only acceptable where a room has ownership of both windward and leeward sides of the building, as the ventilation of the leeward space relies on the occupant of the windward space. The potential solution simulated by EDGE in this study is to provide a channel that bypasses the windward space, allowing the occupant of the leeward space complete control of airflow. These include the 'room depth to ceiling height ratio' and the 'minimum area of the opening to provide access to fresh air as well as reduce the temperature. To evaluate whether the openings on a wall qualify for natural ventilation, take the window-to-wall ratio for that particular wall. The window area must be at least 10% of the wall area to be counted as an opening for natural ventilation. A well-designed natural cross ventilation strategy can improve inhabitant comfort by providing both access to fresh air as well as reducing the indoor temperature. To achieve acceptable natural ventilation flow, EDGE Methodology considered: i) maximum ratio of floor depth to ceiling height, and ii) the heat gains to be dissipated, which determines the total area of the opening. The latter is simplified by only providing the percentage of floor area as the openable area. The depth of space that can be ventilated using a cross-flow ventilation strategy is dependent on the floor to ceiling height and the number and location of the openings.

The designer of the rainwater harvesting system needs to be able to advise on appropriate sizing. However, the two key factors to consider when sizing the tank are the rate of supply (local rainfall data and collection area) and the demand. EDGE automatically calculates the approximate maximum quantity of water collected by a rainwater harvesting system using rainfall data from the project location and the size of the roof area. Although the EDGE assumption is that the roof will serve as the rainwater collection system, a rainwater collection system is located on the grounds of the building. In this regard, the cost and the energy required for the electric water pump were already considered. However, Eq. (2) can be used as a rough guide:

Total annual rain water: Area of Catchment (roof area-m^2) x Amount of Potential or Volume of Rainfall (mm) x Filter Coefficient (assuming 20% losses) x Run-off Coefficient (2)

3. Results and discussion

3.1. Base cases vs. improve cases assessment

Assessment showed that Case A had an initial energy performance of 4.78 kWh/m^2floor/month in the base case vs. 3.75 kWh/m^2floor/month (38.52% in savings) in the improved case applying the energy efficiency measures required for cooling, lighting, hot water and home appliances. In Terms of operational CO_2 emissions savings the improved case showed 0.007 tCO2/m^2floor/year. With an initial water consumption of 162 l/m^2floor/month, the initial water efficiency was 0%, while it was about 46.35% in the improved scenario with 87 l/m^2floor/month. Finally, the utility cost reduction was 9.79 euros/month/unit in case A, that means 0.23 euros/month/m^2floor. Case B required 2.81 kWh/m^2floor/month in the base case for cooling, lighting, hot water, and home appliances, however, in the improved case required 2.21 kWh/m^2floor/month (19% in savings). The operational CO_2 emissions were reduced to 0.009 tCO_2/m^2floor/year. The initial water consumption passed from 51.30 l/m^2floor/month to 46 l/m^2floor/month (4% in savings). Finally, the utility cost reduction was 3.23 euros/month/unit, that means 0.061 euros/month/m2floor. Case C had an improvement of requiring 4.65 kWh/m^2floor/month to 1.85 kWh/m^2floor/month. The operational CO_2 emissions were reduced to 0.028 tCO_2/m^2floor/year. The initial water consumption passed from 229 l/m^2floor/month to 183 l/m^2floor/month (12% in savings). Finally, the utility cost reduction was 6.31 euros/month/unit to 0.17 euros/month/m^2floor.

3.2. Cost-benefit analysis base cases vs. improved cases

To reduce the energy consumption of the three case studies, one measure was to change the roof material in Case A and Case C to improve the indoor thermal quality and to reduce operational CO_2 emissions. The roof changed from Synthetic Lightweight tiles to steel clad sandwich panel in Case A and from aluminium sheets on steel rafters to aluminium clad sandwich panel in Case C. This measure assisted to reduce the energy needed for cooling the house. The total cost of the implementation of the eleven technical measures into the existing houses and the payback of the inversion was calculated in this study. Finally, it is important to mention that in some cases, the government in low-income housing developments subsidises the price of the water and electricity. However, it is important to consider and extrapolate this cost-benefit analysis on a medium-large scale. See Table 6.

3.3. Discussion

The proposed eleven measures in this study were selected according to the availability of the measures in the different locations, the climate

Table 6
Implementation of the construction measures and payback in years of the inversion including the carbon savings. Source: EDGE Methodology, 2022.

	Cost of construction measures (euros/unit)	Cost of construction measures (euros/m^2floor)	Operational cost reduction (euros/month/unit)	Operational cost reduction (euros/month/m^2floor)	Annual savings (euros/unit)	Annual savings (euros/m^2floor)	Carbon savings (TCO_2/year/unit)	Carbon savings (TCO2/year/m^2floor)	Payback (years)
Case a	***3772.80***	***90***	***9.79***	***0.23***	***117.48***	***2.80***	***0.29***	***0.007***	***32-35***
Case b	***5399.10***	***102***	***3.23***	***0.061***	***39***	***0.74***	***0.48***	***0.009***	***43-48***
Case c	***5323.05***	***148***	***6.31***	***0.17***	***75.71***	***2.10***	***1.01***	***0.028***	***70-72***

conditions, the users' income and construction cost to improve the environmental building performance. One measure applied to the case studies was the use of solar hot water collectors. The solar water heaters will reduce the grid electricity (fossil fuels) used by the building for water heating. The gas heaters are planned to be replaced 100% by the solar heaters. In this assessment, the improved cases assume 50% of the total hot water demand with solar heaters. This measure is linked with the number of occupants, the type of boiler, the flow rates of the kitchen, showers, laundry and basin faucets of each case. In terms of CO2 emissions, the electrification of the house by the use of renewable energy is reduced in Case A (LPG) 0,11 kgCO2/kWh and in Case B and C (Natural Gas) 0,84 kgCO2/kWh. Energy-saving bulbs can be claimed if the light bulbs used in the project are either compact fluorescent. Ceiling fans reduce cooling requirements and improve occupant comfort without actively cooling the air. Therefore, ceiling fans are only beneficial in spaces that have a demonstrable cooling load. The assumption is that the ceiling fans have a rated power of 60 W and for 12 h of operation they consume 0.43 kWh.

According to the material analysis of EDGE Methodology, the roofs of Case A and Case C were materials with high-embodied energy and low limits to thermal resistance. Consequently, the roofs' materials were changed in order to save operational energy, annual energy costs, and CO_2 operational emissions. According to the EDGE simulations, the new materials in Case A and Case C have thermal properties and sound insulation qualities that improve indoor comfort quality. See Table 7 in the Supplementary Material section. Another advantage is that the chosen prefabricated roofs can be disassembled for future vertical house expansion, and the same roof could be reused or recycled. In Case C, the original roof material was designed to be disassembled; however, the new proposed material improved the indoor comfort because of the insulating properties maintaining the disassembled property. Furthermore, the use of recycled aluminium in the roof is an efficient measure to reduce the material's embodied energy; it uses just 5% of the energy it takes to create primary aluminium. The potential of reusing the maximum possible amount of components to reduce embodied energy of the construction materials is key to designing resilient and more sustainable housing (Adhikari, 2019). For future social housing designs, it is highly recommended to consider local and low-carbon construction materials to improve the environmental performance of the buildings. Salzer, C., et al. (2017) demonstrate that alternative construction methods used in developing economies (e.g. the Philippines), such as bamboo frames and coconut husk panels, could be durable and resistant material when it is well designed and applied to low-income housing designs.

The construction time of the three case studies varies based on the housing size, level of skills and capabilities of the construction crew, number of workers and the equipment used. In Case A, B, C the manpower number and equipment is considerably different, consequently, the delivery time was not a comparable variable to assess. In this research, the analysis is punctual on a small scale (one unit), but following analysis in a large-scale housing development could assist to demonstrate the potential of life cycling thinking improving the environmental performance of existing and future social housing developments.

4. Conclusions

Results show that the optimization of the environmental building performance in social housing design has not reached a high level in emerging economies so the overall potential for possible improvements is important. Especially, in low-income housing developments where the necessity for energy optimization and water consumption in the operational use have been archived poorly. In contrast to this, the base case of Case B had the highest environmental performance; nonetheless, the improved version of Case C had the highest environmental performance per m^2floor. Table 8 (the Supplementary Material) shows the comparison of the final consumption and savings per m^2 floor of each base case vs improved case in terms of energy use, water consumption, carbon emissions, and embodied energy. It is important to mention that the analysis was focused on emerging economies, although environmental policies are considered and implemented at a national level, calculations of the indicators were based on an extensive literature review and international environmental certifications and building standards criteria. The main conclusions of the study are the following:

External shading elements combined with ceiling fans, energy light bulbs, solar hot water collectors, the openings for natural cross ventilation and the solar reflective paint in external walls reduced the heat gain and, therefore, cooling loads. In Case A the operational saving cost was 2,80 euros/annual/m^2floor, Case B 0,74 euros/annual/m^2floor and Case C 2,10 euros/annual/m^2floor. In Case A and C, the savings in the energy consumption were higher compared with Case B because of the implementation of the steel-clad sandwich panel and the aluminium-clad sandwich panel roofs with an improvement of 27–31% in the energy simulation needed to achieve thermal indoor comfort. In terms of water consumption, low-flow showerheads and faucets, rainwater collection system and recycled grey water for flushing were solutions that saved in Case A 80 l/month/m^2floor, in Case B 5 l/month/m^2floor and in Case C 50 l/month/m^2floor respectively. Taking into account that in the location of Case A and C there are heavy rains in summer, the rainwater collection system involved a major collection of water compared to Case B. CO_2 emissions were considerably reduced in Case C with the roof material change, saving 1,01 tCO_2/year/unit that means 0,028 tCO_2/year/m^2floor. See Table 8 in the Supplementary Material section. Summarising the assessment, after applying the eleven technical measures, Case A had the highest performance regarding final water consumption savings and Case C had the highest performance concerning operational cost savings, carbon emissions and energy use savings per m^2floor.

These findings demonstrated that energy efficiency (kWh/year/m^2floor), embodied energy (MJ), carbon emissions (tCO_2eq/Year/m^2floor) and water consumption (m^3/year/m^2floor) can be used as indicators to improve the environmental performance of different existing and new housing projects. The methodology may guide improvements in the environmental performance of social housing projects by assisting in decision making in the selection of environmental performance indicators to encourage environmentally-friendly practices.

Collaborations among different actors along the supply of local construction materials and green construction measures are key to making better use of the resources in the complete life cycle of the project. These collaborations could help to boost opportunities for new businesses such as increasing the local economy, reducing environmental impacts from logistics, saving time and money with transportation and driving research to design construction materials and products to reduce waste and improve products' second life. Furthermore, there are some incentives that the public administration in emerging economies are implementing to reduce the negative environmental impact of the constructions, e.g., the reduction in taxes when building with low carbon materials and low to zero carbon emission projects. However, these measures are helping to encourage voluntary actions to design more sustainable but further actions are required to ensure results on a medium-large scale.

When a decision-maker is informed about the environmental performance of a project, the manager can define priorities regarding proper environmental performance by taking into account the characteristics of the construction and assessing different design alternatives with the respective indicators. The learning process of the methodology applied in this study enables decision-makers to recognize the environmental actual and future consequences of the existing and new housing developments and could guide them through taking the most sustainable measures. Finally, assessment results can provide an insight to decision-makers and construction professionals for enhancing design alternatives. This study shows the necessity to start using low carbon materials to develop more sustainable projects in emerging economies.

Limitations: Aspects such as time and cost, could make the selection of the best design alternative more difficult, however, it is important to encourage sustainable social housing designs to develop more green and liveable cities. This study did not include health concerns that users face in flood-risk areas such as mosquitoes diseases. Furthermore, even though the construction techniques and sustainability performance are correlated, the limits of this link still need to be discussed.

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Declaration of competing interest

The authors Jani F. Velazquez Robles, Eloi Coloma Pico and S. M. Amin Hosseini declared that they have **no** known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2022.100077.

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