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DESIGN OF RESILIENT AFFORDABLE HOUSING PROTOTYPES FOR LATIN AMERICAN CITIES

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Abstract. Population growth in Latin America implies a high demand for housing for the next few years. This research focused this demand on the production of affordable housing for low-income families in the region. Producing affordable housing requires resilience-based design strategies that respond to climate change. Resilient design is an alternative for the construction of sustainable buildings. Clean technology is crucial to the resilient design of affordable housing. Since this technology type includes the Life Cycle Analysis throughout the production process, what are the basic guidelines to drive resilient strategies for affordable housing design? The article aims to suggest basic guidelines for housing prototypes and drive clean technologies like resilient strategies. This research developed the research method in two key steps. First, the theoretical step was a literary review using the PRISMA method. Second, the empirical phase shows guidelines for affordable housing prototype design. The result was an Affordable Housing Prototypes applied in the Latin American context. The affordable housing prototypes were developed in Guadalajara, Mexico and Bogotá Colombia.

Keywords: *Affordable housing, resilience, prototype design, Latin America, cities.*

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1. Introduction

Latin America is one of the most urbanized regions in the world. Population growth implies a high demand for social housing in the coming years (de Desarrollo, 2016). This growth involves an increase in the effects of climate change in the region. A report by Economic Commission for Latin America and the Caribbean (ECLAC) affirms that dependence on non-renewable energy in cities causes climate change (Jordán *et al*., 2017). Therefore, the concept of resilience becomes crucial to respond to these challenges.

Figure 1 shows that Brazil is the country that sells the most affordable housing market in Latin America and Colombia has second place (TINSA-RESEARCH, 2018). However, the construction sector in Colombia is one of the lowest productivities

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internationally (McKinsey_Global_Institute, 2017). Currently there is a decrease in the general sale of housing in Colombia.

So affordable housing is emerging as an area of opportunity for the construction sector and the future development of Latin American cities (Guzmán *et al*., 2018). On the other hand, Mexico and Chile finished their highest production and now they are decreasing their affordable housing production. It means that Latin American low-income families need affordable housing to suit their individual needs. Some studies look at implementing clean technologies and government programs that have the potential to develop affordable housing in the region.

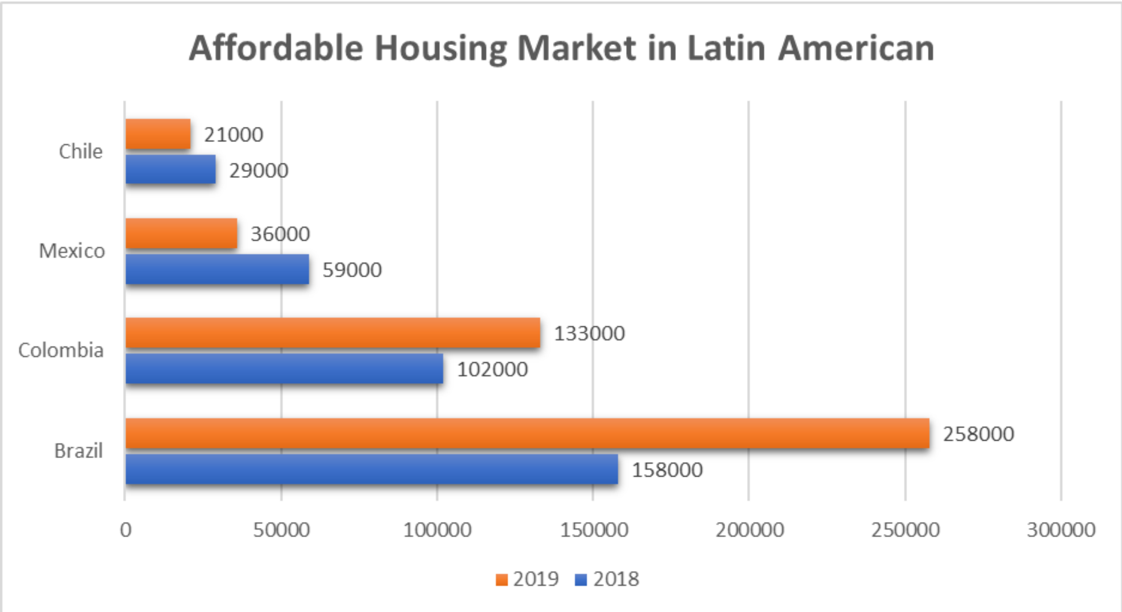


Figure 1. Affordable housing Market in Latin America
Source: Brazil-CEF; Colombia-Camacol, Dane; Chile-MINVU; Mexico-Centro Urbano; 2018-2019

The literature review identified that it is necessary to respond to the effects of climate change. An answer of this type would allow the identification of resilience factors, adaptation to energy consumption and the dynamics of the territory. This research presented resilient design as an alternative to the construction of resilient affordable housing. Also, this kind of design drives clean technologies.

Clean technology plays a crucial role in the development of the concepts of resilience. This concept is defined as “the facility or part of a facility that has been adapted to generate less or no pollution. Clean technology is opposed to the so-called end-of-pipe technology since the reduction of environmental impact is integrated into the production process” (Fu *et al*., 2018; ODEC, 2007; UNITED-NATIONS, 1997).

These technologies applied in the affordable housing field have two areas of application. The first area is Energy Efficiency in housing (DCTI, EuPD Research, 2013; Fu *et al*., 2018). Second, the housing life cycle (Hoppe, 2012; McKenzie *et al*., 2009; Ortiz-Rodríguez *et al*., 2010). Affordable housing resilient design strengthens sustainability in Latin American cities. Applying resilient design and clean technologies in affordable housing reduces the environmental effects caused by climate change.

So, develop affordable housing prototypes that promotion of clean technologies. Also, explore the affordable housing prototype design that adjusts to the resilient inhabitant's needs of Latin American cities. What are the basic guidelines to drive resilient strategies for affordable housing design? The article aims to suggest basic guidelines for housing prototypes and drive clean technologies like resilient strategies.

2. Method

2.1. Research process

This research organized the study in three phases: 1) Literature Review; 2) Research Construct Synthesis; 3) Basic Guidelines for Resilient Affordable Housing Prototype Design (BGRAHPD, Figure 2). Then, this research developed from BGRAHPD some resilient affordable housing in different Latin American countries. This exercise detected distinct relationships between the prototype design and the contexts. Besides, this research recognized the crucial role of technology to design resilient affordable housing.

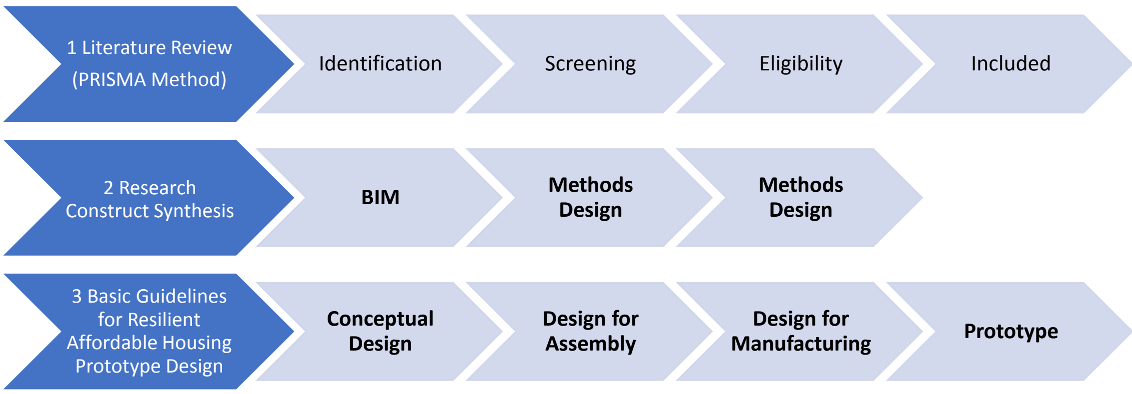


Figure 2. Research process

2.2. Literature review

This research used a PRISMA Method to do a literature review. This step had four research phases: 1) Identification. This research considered records identified through the Scopus database. We identified 360 keywords, 41 organizations and 20 countries from 2007 to 2021. 2) Screening. This phase excluded all the duplicated records. 3) Eligibility. This phase showed the records that had eligibility to be considered for the literature review. 4) Included. This phase showed the articles that were selected to be the final literature review (Table 1).

Table 1. Prisma Method – Literature Review

Item	Identification	Screening	Eligibility	Included
Articles reviewed	234	150	84	38

Table 2 shows the occurrence and link strength of keywords that were found in the literature review. It is the ten main words of 36 keywords. On other hand, figure 3 shows the network analysis of the keywords. The figure presents the link strength of architectural design, prototype design and Housing also, the figure exhibits a resilient design concept knowledge gap. Finally, sustainable development is another concept that needs to study about resilient design and affordable housing. This concept did not appear in the graphic too.

Table 2. Keywords Occurrences – Literature Review

keyword	occurrences	total link strength
Residential sectors	1	5
Buildings	2	3
Heat storage	2	4
Structural design	2	4
Prototype design	2	5
Sustainable development	2	6
Energy efficiency	2	8
Residential building	2	8
Architectural design	4	10
Prototype designs	7	12
Housing	10	19

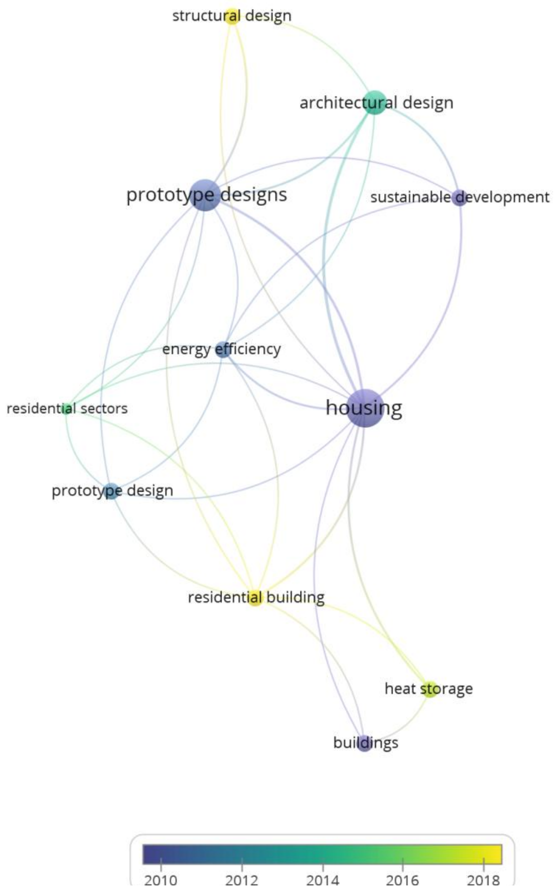


Figure 3. Keywords Network Analysis

2.3. Research Construct Synthesis

A synthesis of the research construct it was conducted once the literary review was completed. We identified three areas of study: BIM, design methods and energy efficiency. BIM keyword is the emergent concept less studied and Energy Efficiency is the keyword more studied. Figure 4 shows the research construct synthesis by the author.

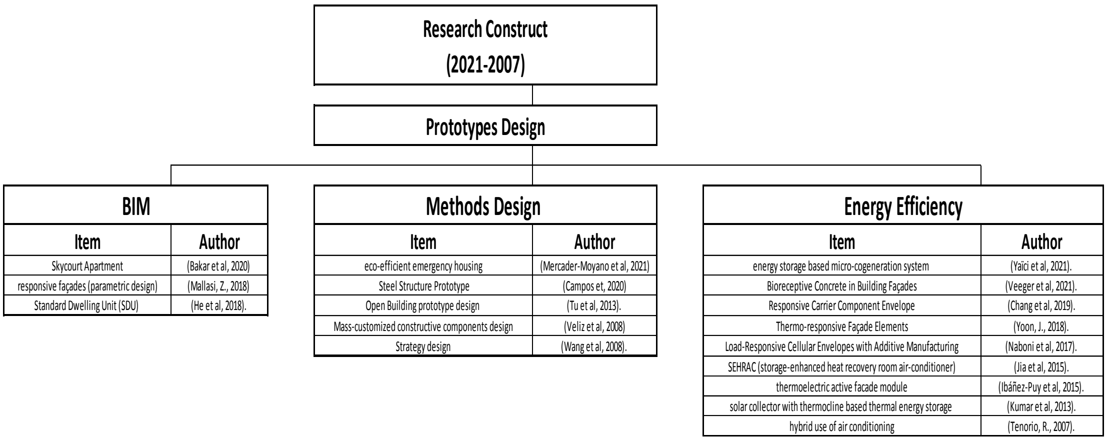


Figure 4. Research Construct Synthesis

2.3.1. BIM

This research identify that authors such as Bakar et al. (2020) explain that BIM can be a helpful tool in designing affordable housing prototypes. This tool makes it possible to compare different affordable housing, determining an adequate life cycle cost analysis. Likewise, this research identified that the life cycle cost analysis allows the inclusion of resilient design strategies. Also, the economic impact evaluation complements the life cycle analyses of environmental impact.

This research found the use of BIM to apply for building envelope design (Mallasi, 2018). This tool is positive for reactions analysis that the envelope may have to the different effects of climate change on buildings. Parametric design is appropriate for developing BIM models that apply climate-responsive strategies. Likewise, the use of these two tools allows one to relate to the principles of resilient design.

Finally, the BIM model using allows the design of standard housing units through multi-aspect similarity evaluation (He *et al*., 2018).This technique allows the evaluation of different home designs according to the analysis of their attributes, typology and shape. This tool can be functional in affordable housing design since it can add resilience attributes. It allows for identifying the optimal configuration for affordable housing and the responses to climate changes that affect the comfort of the housing inhabitants.

2.3.2. Methods Design

The open building design is a method developed by Habraken (1987) that has strengthened over the years. This method is adequate for the habitability users' needs for affordable housing in Latin America (Habraken, 1988; Salingaros & Brain, 2006). habitability related to the shape and use of space. The components that characterize habitability are the quality of buildings, quality of life, flexibility and social patterns (Cubillos-González, 2015).

For example, the government of Taiwan is implementing prototypes of open buildings for social housing. These prototypes provide planning flexibility for local institutions and design flexibility for affordable housing dwellers (Tu & Chu, 2013). Another example is to use concepts of a circular economy and regenerative sustainability. Here, there are emergency housing prototypes that use these two concepts. It could be appropriate for the design of affordable housing (Mercader-Moyano *et al*., 2021).

Also, technology plays a crucial role in making design decisions. Using efficient construction systems allows the design of affordable homes to be easy to assemble and low in cost. Modular systems are a sustainable resource for the systematization of affordable housing design, particularly modular systems in steel (Campos & Bernardo, 2020). Finally, affordable housing design is a great prototyping opportunity from the open building concept. For example, it would be an opportunity to analyze characterization studies of the design of housing prototypes (Wang *et al*., 2008).

The resilient design seeks adaptation to guarantee comfort in a constantly changing climate (Nieto-Barbosa & Cubillos-González, 2020; Resilient Design Institute, 2019). So, it implies actions in buildings to reduce climate change scenarios. Then, Resilient Design in affordable housing allows an adequate response to the need for flexibility and resilience of users. It improves their quality of life and reduces the vulnerability of the building. Finally, responsive architecture is a tool that gives resilient design better media to design affordable housing in Latin America.

2.3.3. Energy Efficiency

The energy efficiency strategy seeks to regulate energy consumption to generate rates below zero. Some studies show that the use of technologies aimed at energy efficiency is helpful for the design of affordable housing (Yaïci *et al*., 2021). The study of the envelope of social housing in response to the effects of climate change. It allows for identifying the energetic behavior of the materials to the climatic changes.

Some studies explore the application of bio-receptive to concrete to improve the characteristics of building envelopes (Veeger *et al*., 2021). This type of work would allow the application of green envelopes in affordable housing prototypes for better energy efficiency. Responsive Architecture allows building components designed with climate-adaptive properties. The envelope plays a crucial role in developing correct responses (Chang *et al*., 2019).

Introducing digital technologies makes it possible to design buildings with greater energy efficiency and low emissions. It is the case with technologies, such as additive manufacturing through 3D printing (Yoon, 2019). Therefore, design processes are changing from a linear to a dynamic approach. Additive manufacturing plays a crucial role in efficient construction systems use (Naboni *et al*., 2017). Digital production is a helpful tool for affordable housing design that is energy efficient in its production. The analysis of the internal efficiency of buildings is a point to consider for the design of affordable housing (Jia & Lee, 2015). Therefore, the combination of passive and active strategies in housing design is critical.

So efficiency analysis can determine the buildings' envelope (Ibáñez-Puy *et al*., 2015). The use of solar collector prototypes is closer to the affordable housing design process (Kumar *et al*., 2013). For example, this research have identified studies of hybrid systems that use passive and active strategies applied to affordable housing with optimal results for this type of housing (Tenorio, 2007). Finally, Figure 5 shows a synthesis of the research framework by the literary review. This figure presents the components for affordable housing design applicable to the Latin American context.

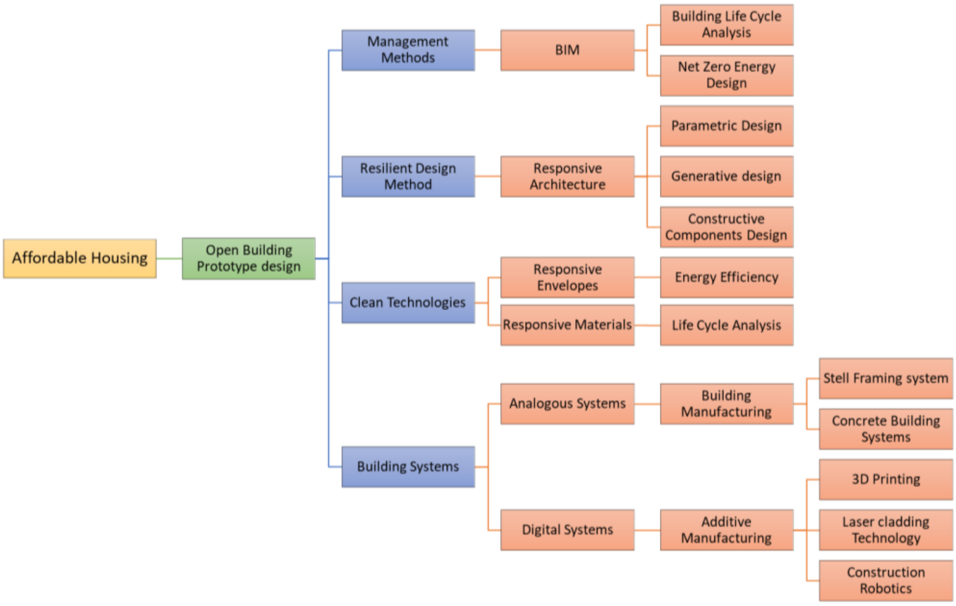


Figure 5. Framework synthesis

2.4. Basic Guidelines for Resilient Affordable Housing Prototype Design

2.4.1. Conceptual design

Affordable housing design requires life cycle analysis to improve housing quality. This is one factor in meeting the need for flexibility in low-income families. The affordable housing design must clearly define the circulations to improve the spatial relationships of the building. An ideal design must include storage spaces to improve the quality of living. Since, in Latin America, there is a tendency to eliminate storage spaces because of costs.

The open building principle (Cubillos-González, 2006) is a strategy that allows for meeting the flexibility needs of home users. What it permits in the social dimension is consistent with the life cycles of the inhabitants. On the other hand, this allows changes in time and the recycling process of the building spaces by having the opportunity for changes of use.

2.4.2. Design for assembly

Another tactic is to develop a design process for assembly in the home layout. The design of different systems facilitates their manufacture. Also, this allows high efficiency in the building's production and a significant reduction in waste production. These factors reduce time and costs in the construction of houses. Within the resilient design strategy, this tactic plays a key role. It permits the introduction of concepts such as reducing, reusing and recycling. So, the resilient strategy makes up a circular design cycle.

2.4.3. Design for manufacturing

Design for manufacturability is a tactic that allows building construction to be efficient. It is complementary to the design for assembly. It can apply to analogue or digital construction systems. With analogous systems, they relate their use to the manufacturing standards of affordable housing. While with digital systems, they relate to the additive manufacturing processes of homes.

2.4.4. Prototype

Two design teams developed affordable housing prototypes. The first team developed their work in the city of Guadalajara, Mexico. The second team developed their proposal in the city of Bogotá, Colombia. These two teams applied resilient strategies in the design of the prototypes.

3. Results

3.1.1. Affordable Housing Prototypes Design in Latin America.

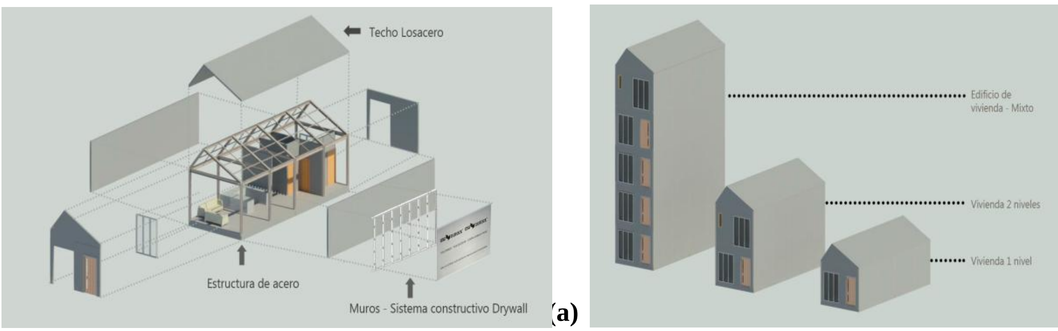
To apply the Basic Guidelines for Resilient Affordable Housing Prototype Design (BGRAHPD) were designed two prototypes that analyze the Latin America context. It was selected Guadalajara and Bogotá cities. The reason was the population growth in those cities in the region. This situation creates a high demand for affordable housing. So, two research teams were created to develop the affordable housing prototypes.

The first design team analyzed the "Laboratory for Research and Practical Experimentation of Housing", belonging to the Research Centre for Sustainable Development (CIDS) of Mexico. This laboratory proposes 32 social housing prototypes. They selected five prototypes as a case study. They constructed a set of social housing data for the case of Mexican cities.

Here, the city of Guadalajara was a reference. Then, they designed two basic prototypes. The first proposal was a housing prototype by the explosion method and urban housing pattern in series, with an isolated building. For this proposal, they designed a house that would respond to the spaces of a low-income family.

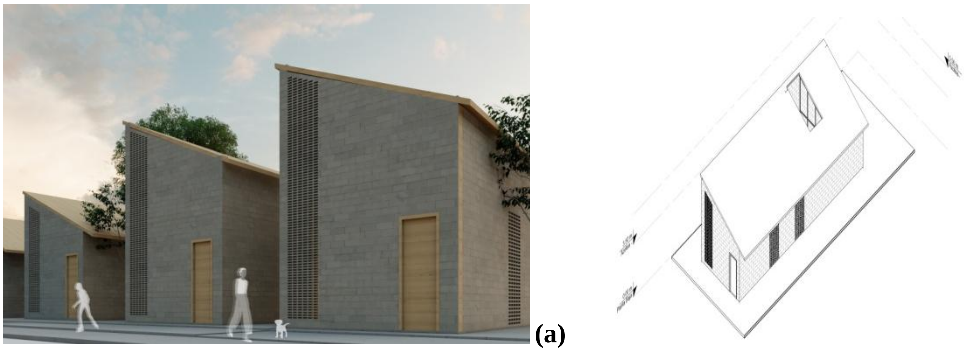
Next, it designed two more prototypes. The first is a two-story house and the second is an apartment building (Figure 6). This housing can contain the prototype of one or two levels in the same structure. It selected a steel structural system. The housing finishes have a drywall system and floors and ceilings in Steel Deck Framing. With this prototype, they seek to be low-cost and easy to assemble.

The second housing prototype uses a similar structure in masonry and concrete blocks (Figure 7). They distributed the ground floor with the services at the entrance. There is a central patio that allows natural lighting and ventilation. Finally, the housing prototype has the possibility of expanding to the second level.



(a) (b)

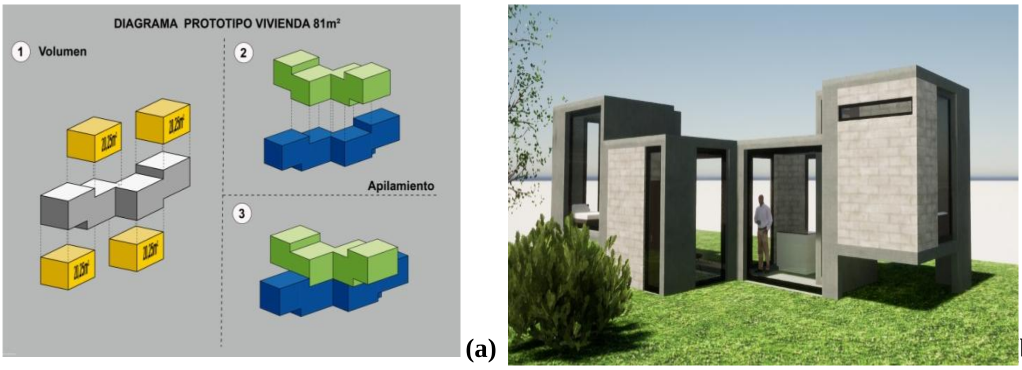
Figure 6. Affordable housing prototype, Guadalajara, Mexico:
(a) Steel Framing system; (b) Density analysis
Source: Arch. Ana Montenegro. Designer, research auxiliary (2021)



(a) **(b)**

Figure 7. Affordable housing prototype, Guadalajara, Mexico:
(a) Steel Framing and CMU systems; (b) Density analysis
Source: Arch. Adriana Haro. Designer, research auxiliary (2021)

The second design team proposed an affordable housing unit. This unit recycles resources generated by the home. The design team incorporated an underground rainwater harvesting system. It reduced approximately 60% of drinking water consumption. Each house has a garden and a space to deposit waste. This space allows a 50% reduction of the total waste generated by housing. The housing unit has a greywater purification system. It reused the treated water in different housing spaces. The design team proposes the use of digital building systems. They proposed additive manufacturing to develop the housing unit. For example, 3D printing for divisors' walls and laser cladding technology to the structure.



(a) **b)**

Figure 8. Affordable housing prototype, Bogotá, Colombia:
(a) Modular unit analysis; (b) 3D Printing, Laser Cladding technology and Construction Robotics
Source: Diana-Mayerly Franco-Zamora (Designer, research auxiliary); Mateo Patiño-Nieto (Designer, research auxiliary); María-Alejandra Muñoz-Morales (Designer, research auxiliary); Natalia Restrepo-Zamora (Designer, research auxiliary); Johao-Nicolás Obando-Vargas (Designer, research auxiliary; Rolando-Arturo Cubillos-González (Designer, researcher) (2021)

4. Conclusions

What are the basic guidelines to drive resilient strategies for affordable housing design? Latin America is one of the most urbanized regions in the world. Therefore, the concept of resilience becomes crucial to respond to these challenges. The literature review identified resilient design as an alternative to the construction of affordable housing. Clean technology plays a role in the development of the concepts of resilience.

So, develop affordable housing prototypes that lead to resilience through the promotion of clean technologies. This research identified three areas of study: BIM, design methods and energy efficiency to build a basic guideline. BIM can be a helpful tool in designing affordable housing prototypes. BIM models are appropriate for applying climate-responsive strategies. Also, BIM models are ideal for developing housing units through multi-aspect.

The open building design is adequate for the habitability users' needs for affordable housing in Latin America. Circular economy and regenerative sustainability could be appropriate for affordable housing design. So, the resilient design seeks adaptation to guarantee comfort in a constantly changing climate.

The energy efficiency strategy seeks to regulate energy consumption to generate rates below zero. Introducing digital technologies makes it possible to design buildings with greater energy efficiency and low emissions. A digital production is a helpful tool for affordable housing design. In conclusion, the Basic Guidelines to Resilient Affordable Housing Prototype Design considered three components: conceptual design, design for assembly and design for manufacturing.

Finally, to apply the Basic Guidelines for Resilient Affordable Housing Prototype Design (BGRAHPD) were designed two prototypes that analyze the Latin America context. So, two research teams were created to develop the affordable housing prototypes.

The first design team builder a set of social housing data for the case of Mexican cities. They selected the city of Guadalajara was a reference. For this proposal, they designed a house that would respond to the spaces of a low-income family. Next, it designed two more prototypes. The first is a two-story house and the second is an apartment building.

The second design team proposed an affordable housing unit. This unit recycles resources generated by the home. The design team proposes the use of digital building systems. They proposed additive manufacturing to develop the housing unit. For example, 3D printing for divisors' walls and laser cladding technology to the structure.

In conclusion conceptual design requires life cycle analysis to improve housing quality. The open building principles are a strategy to give answers to the flexibility needs of home users. Design assembly offers high efficiency in building's production and a significant reduction in waste production. Design for manufacturing can apply to analogue or digital construction systems. The research result shows that affordable housing prototypes could be flexible and resilient applied to these three areas of design.

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