Another way of living: The Prefabrication and modularity toward circularity in the architecture

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Abstract. The world requires housing capable of addressing the ecological challenge and social changes. Various architecture projects have used alternatives to solve these problems, like housing complexes to increase density, fast and low-cost constructions with prefabricated and modular methods and materials. The concrete will always be rooted in the culture of architecture, even the industry of construction can work with other materials and whose manufacture produces a considerable amount of CO₂. Taking into account the different construction cycles and the evolution of uses and users, a change in architectural culture is required. This paper aims to shows that it is possible to achieve the concept of circularity in the built environment through the architectural design process. The research by design methodology was used to develop the recyclable typology named Slab focused on residential prefabrication methods, which will facilitate their disassembly and recycling. As a result, the design process and the models' evolution of the Slab prototypes are presented in this paper. Prioritizing prefabrication and the modularity within the architectural design process has advantages, such highly effective reduce footprint areas, large-scale infrastructure for flexible use, and individual housing units with communal activities, besides, assure the building conditions for future disassembly and recycle.

1. Introduction

The awareness of the increasing restrictions on the availability of resources further the demand for more affordable housing around the world make clear the need for new architectural typologies able to optimize the efficiency of resource use. The uncertainty about the collapse of the natural resource started in the 1970s when the USA oil production has reached its peak initiating the oil crisis affecting the world supply network. The cost of energy, goods, and services rise dramatically, and consequently, the ecological movement began [1].

Buildings and construction sectors account for almost 40% of the world’s energy consumption and process-related to emissions [2][3]. The European Union generated a total of 2533 million tonnes of waste from domestic and economic activities in 2016. The construction sector contributed to 36.4% of this waste [4]. Although there were concerns about the depletion of natural resources, the cities continued to grow. Buildings now cover 30% more land than in 1990 [5]. Urban centers host 54% of the world's population. Cities are susceptible to many environmental risks due to their high people concentration, infrastructure, and economic activity; and will increase further with climate change. The cities activities represent 70-75% of the consumption of natural resources, impacting their availability and ecosystems beyond the urban perimeter. The efficiency and resilience of cities' resources will become more substantial as population and economic growth are pursued [6]. The earth’s population has reached almost 7.6 billion in 2017 and will keep growing until 2050. The projections indicate that
the global population in 2030 will be around 8.7 billion, in 2050, 10.2 billion, and 13.2 billion in 2100 [7]. As the population increases, the need for housing becomes bigger, and the housing shortage more critical. More buildings need to be built to accommodate future generations. As a result, new architectural solutions began to be explored to reduce resource consumption and recycle the used ones.

Circular economy is a reaction to the linear economy ready to break. It aims to disassociate the finite resource consumption growth through restorative and regenerative design. The circular economy includes the built environment, i.e., the cities that are designed to enhance the residents' life quality and reduce virgin material consumption thanks to shared, flexible, and modular spaces [8]. The shift to a circular approach (reuse/recycling) achieves net environmental benefits that contribute to reducing the building lifecycle impacts as a whole, in particular construction and demolition waste [9]. Prefabrication and modularity are a plausible alternative to the primary waste source occurring in the design and construction phases [10]. Prefabrication and modularity through architecture history are essential to understand the building evolution concepts and methods focused on recyclability and circularity.

The problem of the material resources and the population growth brings us to the questions of how the buildings should be designed where the concrete is still rooted in the architecture culture. Therefore this paper presents the architectural design process and physical models that were used to develop the Slab building typology, a shelf structure which prefabricated and modular timber housing units can be plug-in and out, showing that it is possible to achieve the concept of circularity in construction [11]. The Slab prototype was developed at the core of the research project Eco-Construction for Sustainable Development (ECON4SD), co-funded by the European Union in association with the University of Luxembourg. The multidisciplinary team is divided into seven lines to developing alternative recyclable housing models that work as materials bank to other buildings to address these ecological-social issues. First, the architecture field, which I am responsible for the design and architectural solution. Second, engineers responsible for bringing solutions in slab structure in steel-concrete, slab structure in timber-concrete, concrete aging, energy consumption, monitoring systems, and material bank inventory.

The architectural design process described in this paper brings to the first stage the building concepts of adaptability, disassembly, and recyclability, differing from the usual way of architecture design, where architects do not take into account the design process after the first life cycle. Although different ideologies, the concept of circular construction and recyclability is fundamental to the development of architectural expertise. This article contributes to current knowledge by improving the architectural design approach to achieve a circular architecture, encourage prefabrication and modular methods in residential construction, and provide solutions that can be adapted in other construction, helping architects, designers, and the construction industry in decision-making. These research raises questions related to three Sustainable Development Goals (12-Responsible Consumption and production, 9-Industry, Innovation and Infrastructure, and 11-Sustainable Cities and Communities) where there is a concern about the use of natural resources and their reuse in future constructions, through an innovative architectural typology that brings solutions to achieve the concept of circularity in sustainable cities.

2. Methodology
The research by design methodology was used to develop the recyclable architectural typology in an attempt to find a point of departure for the contribution of influential figures on the field [12]. Research can inform the design process in many ways and at many times, and the design process and prototype can engender an abundance of questions [13]. Section 3 presented prefabricated and modular buildings that influenced the design process of the Slab prototype. Section 4 presents the Slab building typology in detail and the evolution of the proposal models through the design process. It is assumed that the building should be adaptable and flexible during the life span to different users' needs, designed for end-of-life disassembly, and their structure should be traced by material bank inventory to be reused or recycled, closing the loop of construction. Physical models were developed to establish these preliminar buildings concepts in action. After each physical model development, the feasibility of the prototype was discussed in regular workshop meetings at the core of the ECON4SD project, where plans, drawing, and 3D models were presented, tested, and analyzed. History and prototypes are essential to the design
thinking process. Combined, they contain both the problem to be solved and a solution hypothesis, addressing the needs of concepts and ideas [14].

3. Modular and Prefabricated Architecture
The history gives us insight into what was done in architecture and what could improve nowadays. The architectural history offers several approaches regarding the prefabrication and modularity. During the Modern Movement, influenced by Jean Louis Nicolas Durant of symmetry, regularity, and simplicity [15][16], Le Corbusier brought the ideas of the manufacturing industry, mass-production and rationalization, also declared “the house is a machine for living” in 1923. Frank Lloyd Wright, in 1932, pronounced the term "assembled house" would consist of standard units that would become the blocks to establish the different rooms [16]. This tradition also included Richard Buckminster Fuller that perceived architecture as embedded technology translated into rationality, mathematics, and energy and developed the Dymaxion house in 1928 [15][16]. Inspired by Fuller’s ideas, Walter Gropius and Konrad Wachsmann, created the “Prepackage House” (1942) with prefabricated and modular wood panels and structure [16][17]. Similar to Gropius in 1941-42, Jean Prouvé, with Pierre Jeanneret, developed timber prefabricated modular packed and demountable shelters, called Pavilions 8x8 meters. He worked to reduce waste and increase benefits [16][17]. Mies van der Rohe also contributed using prefabricated off-site steel and glass elements in their constructions like the Lake Shore Drive Apartments (1951) in Chicago [16][18], which also presents a modular grid. There is also Moshie Safdie that designed the “Habitat 67” in 1967. A range of 158 modular houses built from 354 prefabricated reinforced concrete blocks, juxtaposed [16]. The weakness of these approaches is the absence of adaptation in terms of uses and reusability.

Another approach is the high-tech architectural movement in the 1960s by Archigram’s manifestos seen in the “plug-in cities” extremely industrialized that integrated the concept of residential units split into modules plugged into a megastructure that could be movable using giant cranes, updated as changed their needs [16][19]. This Movement also includes the Centre Georges Pompidou by Renzo Piano and Richard Rodgers, a superstructure and utility systems completely exposed, providing open and flexible floor [16][18]. The sixties also delivered the capsule architecture from Japanese Metabolism. The central idea is that the building would grow by plugging individually prefabricated and modular capsules into a structural service core, materialized in the Nakagin Capsule Tower by Kurokawa (1970-1972) in Tokyo [15][16][20]. Paradoxically, the building is deteriorating and has never been altered or the modules extracted from the core [16].

A third aspect started with the ecological movement with the potential for material collapse and the integration of nature in the building. The SITE’s Highrise of Homes (1981) in the USA is a theoretical project idealized as a vertical community of detached and personalized houses by garden space in a steel and concrete grid [21]. Inspired by these ideas in 1990, Frei Otto developed the Ökohäuser (Ecological houses) in Berlin, a vertical concrete skeleton, adaptable, flexible, and lightweight to support residential houses organized as a community. For him, architecture must be in harmony with nature to improve man's life with minimum consumption of material and energy [15][22]. Besides, the latest 2000s brought the Tiny House movement. Portable and small houses build on wheels by the owners themselves, using fewer materials, reducing waste, and less energy consumption [23].

Finally, today architects integrate the ecological concepts with prefabrication and modularity. Werner Sobek developed the R128 (1998-2000), a single-family house with an exposed bolted steel frame prefabricated off-site that can be dismantled [18][24]. Another example is the cohousing R50 (2010 – 2013) by Berlin by Heide & Von Beckerath office. A reinforced concrete skeleton supports the open design apartments and shared spaces, besides the suspended steel balcony, and modular timber façade partly exposed [25]. It is evident that there is a complex renegotiation of the constructive relations that involve the structure, space, and performance that are remodeling the role of architecture in construction [26]. Nowadays, there is a growing interest in building approaches that allow greater efficiency and accuracy, and that are environmentally conscious. This interest can be seen in modular and prefabricated housing enterprises and architects such as Joe Tanney at Resolution: 4 Architecture, KieranTimberlake Michelle Kaufmann, SHoP, Shigeru Ban, Werner Sobek, and others. Others are
more focused on natural resources and reuse like Lacaton & Vassal, Arno Brandhuber, Eduardo François, Lendager Group, Sidewalk Labs, Chris Precht, and Rotor Deconstruction. The missing thing is the integration between these concepts.

4. Slab design process and Discussions

A recyclable architecture typology named Slab was developed to have components that can be disassembled and reassembled in another place or entire recyclable at life-end, providing flexibility through time. The Slab prototype aims to increase house availability to enhance local density while providing shared and public living spaces. The model was designed towards people living alone, young workers, couples or families with one child. Consequently, the housing units were designed to change according to this evolution and enable people to choose how they want to live by providing affordable houses. The reinforced concrete shelf-form structure made of recyclable concrete allows the connection of wooden housing units. Additionally, the rooftop is a shared space for the inhabitants, and the building ground floor footprint was reduced to provide more public space [11], compare to the contemporaneous buildings that used the same space for garages or incorporated in the private areas. This Section described the evolution and the differences between the four main physical models that were developed during the design process of Slab typology.

The First Slab model, Figure 1, was designed with two vertical cores with the smallest footprint possible on each side for access, i.e., the smallest area on a project site for the building structure. This configuration supports the slabs with prefabricated wooden residential units and creates open public areas as gathering spaces, shops, offices, and gardens. The building is orientated to West and East for better direct solar insulation on both oriented apartments. A corridor in the middle of the slabs served to connect the two cores. The major modification is from the First model to the Second one. Due to the too-long span length, the Second model, Figure 2, was reduced to the distance of five housing units in each slab. The prefabricated, modular wooden portable house was positioned between the ceiling extending over two floors, to enable more possibilities to arrange and expand the houses according to the needs and numbers of the occupants, making it flexible and adaptable to accommodate any changes in use. The slab thickness increased to bear the weight of two floors now together in one. On the other hand, just one vertical core remained to access the elevator, internal stairs, and shafts, and the second core was replaced with a thick wall to support the slabs. Besides, some facilities were integrated into the core as small laundries and bicycle parking on the ground floor. The top of the building will be a sharing space, a compensation for the reduced size of the house units, to give more spaces for the inhabitants.

![Figure 1](image1.png)  
**Figure 1.** First model - Slab building.

![Figure 2](image2.png)  
**Figure 2.** Second Model - Slab building (A - Frontal Facade; B - Back Facade).

The Third model, Figure 3, preserved the same characteristic of the Second one. The difference is the building becomes unilateral orientation allowing the residences to receive daylight on two facades as long as the other facade is an open corridor and integrated the stairs. This open corridor and skyway reduced the area of the vertical core and created a large terrace with a new sense of space, light, and freedom facing their doors to balance the condensed housing units.

Finally, in the last physical prototype, Figure 4, all the previous concepts were being further explored. A central wall was placed to support the housing units and to reduce the thickness and materials used in the slabs. The balcony and corridors were completely open without walls facilitating the building
extension and the housing units’ connections. It was proposed different activities theme-oriented for the shared space from a swimming pool and recreation to collaborative work. The basement offers an appropriate envelope to be occupied based on the building location by shops, offices, or workspaces, Figure 5. The public and shared spaces can be occupied in such a way at the beginning and then change through time satisfying residents or neighborhood needs and improving users’ life.

The housing units are standardized, prefabricated, and modular and can be added or removed into the building sliding through rails on the slabs using cranes. The housing unit was designed to have optimal space for sleep, live, cook, eat, and hygiene to accommodate either a couple or a single person and can be shipped by any standard truck, Figure 6. The wood walls and structure can be disassembled, Figure 7, and the housing can adapt, expand, and contract as the necessity of contemporary ways of life from 1 to 4 arrangement, Figure 8. The housing can expand as a duplex with two modules offering ample living space with a separate room. The three modules of expansion can have two bedrooms and two bathrooms, one bigger than the other one. The four modules configuration, with more space for the occupants, follow the same scenario of the three modules, including one more room and bathroom. As the slabs can be fulfilled or have free spots for expansions throughout the useful life, the ceiling, floor, and structure of housing units maintained the same thickness of 40cm, and the interior of walls can be adapted to the needs of the moment. The housing modules have individual electrical and hydraulic systems. The modules will be connected to the building infrastructure by floor ducts to be provided building services such as HVAC, domestic water supply, sewer, among others. The whole Slab building is working as a module. The structure can be extended in a horizontal complex and continuous building, as shown in Figure 9. This combination offers more than one type of shared space and different activities as a recreation area, swimming pool with sauna, collaborative workspace, urban garden, sports, and communal kitchen, according to the group necessity, Figure 10. The structure can be implanted in many neighborhoods and cities, working as infrastructure for portable houses that can be plug-in or out according to the relocation of their owners. Strategic arrangement and design, sufficient numbers, and the reduced ground floor can affect the landscape positively, balancing the necessity to the density and population growth with nature and preserving the natural soil.
To summarize, the design methodology focuses on improving the use of existing residential prefabrication and modulation to address the housing shortage and ecological issue. The circularity can
be seen in this building from the first stage of design. The difference between the traditional way of design thinking [14] and the improved design process is shown in Figure 11. The aim to include the disassembly, reuse, and recyclable concepts in the design process is to reduce resource and energy use throughout the building life-cycle. The infrastructure was designed to be as open as possible, exposed, and with raw materials to minimize the use of primary resources offering different uses on the same site. The housing units can be connected and separate from the core, and its structure can be disassembled once it is in timber, a material whose maintenance, replacement, and recyclability are simplified. Besides, the prototype can adapt to the occupants in continuous evolution. More generous space for the public and shared spaces for the occupants could be offered in the same size as an ordinary building. After the first building life cycle, since it is no longer useful can be dismantled instead of being demolished, and the components and materials can be either reused or recycled for future buildings. The dismantle process starts with the housing modules plug-out from the infrastructure using cranes. Once on the ground, their external and internal walls, floors, ceiling, windows, and doors can be separated and then stock to reuse in another building as the same, reshaped, or remanufacture. The furniture, pipes, and plumbing can be separated and then reuse in another construction. The concrete structure can be broken, separated from other elements, and transformed in aggregate to be reused to produce new recycled concrete. Finally, the building can be used as material and component banks for future buildings once the building elements have been designed to be separated and reused, facilitating their tracking and uploading on platforms in order to recondition, recycle or resell directly. Also, materials from other constructions can also be implemented in the module assembly or building interior.

5. Conclusion

In collaboration with the ECON4SD team, the objective is the creation of entirely flexible architectures that would be able to smoothly react to different needs and thus respond to the concept of a circular economy. The architectural design process present in this paper shows that it is possible to implement at the first stage the concepts of disassembly and recyclability building towards a circular architecture. The Slab building typology improves the occupants' life by integrating more public, sharing, and flexible space using modular and prefabricated methods to ensure the disassembled and recyclability of the components at the end of the building first lifecycle. Besides, this typology enables the house extension according to the resident’s needs. The combination of this concept at the beginning of the design process minimizes the use of primary resources proposing recycled materials, forecast building modifications, and increase the reusability of building elements in other construction, reaching the circularity in the construction. Prioritizing prefabrication and the modularity within the architectural design process has advantages, such highly effective reduce footprint areas, large-scale infrastructure for flexible use, and individual housing units with communal activities, besides, assure the building conditions for future disassembly and recycle. The study also addressed resource reuse challenges in architecture design, identified strategies for reused materials, and innovative approaches that can be adapted for other developments. The work was limited by the leak of metrics data of existing recyclable buildings and information about the integration between the architectural design processes with a virtual material bank, which will be studied in the next stages of the research.

Acknowledgments

This research is in the framework of the project Eco-construction for Sustainable Developments (ECON4SD), supported by the program “Investissement pour la croissance et l’emploi” - European Regional Development Fund
The author would like to thank the whole team of the ECON4SD project and the thesis supervisor Prof. Florian Hertweck.

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