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Recyclable Architecture: Prefabricated and Recyclable Typologies

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Abstract: Buildings are being demolished without taking into the account the waste generated, and the housing shortage problem is getting more critical as cities are growing and the demand for built space and the use of resources are increasing. Architectural projects have been using prefabrication and modular systems to solve these problems. However, there is an absence of structures that can be disassembled and reused when the structure's life ran its course. This paper presents three building prototypes of new recyclable architectural typologies: (i) a Slab prototype designed as a shelf structure where wooden housing modules can be plugged in and out, (ii) a Tower prototype allowing for an easy change of layout and use of different floors and (iii) a Demountable prototype characterized by the entire demountability of the building. These typologies combine modularity, flexibility, and disassembling to address the increasing demands for multi-use, re-usable and resource-efficient constructions. Design, drawings, plans, and 3D models are developed, tested and analyzed as a part of the research. The results show that the implementation of the recyclable architectural concept at the first design stage is feasible and realistic, and ensures the adaptation through time, increases life span, usability and the material reusability, while avoiding demolition, which in turn reduces the construction waste and, consequently, the CO_2 emissions.

Keywords: recyclable architecture; disassembly; adaptation; prefabrication; modularity

1. Introduction

Buildings are places where people spend most of their lives. According to the United Nations [1], 1.7 billion people, which are 23% of the world's population, lived in a city with at least 1 million inhabitants in 2018. It is estimated that the world's population will reach 9.8 billion people in 2050 [2] leading to a growth of high-rise building construction in cities in order to provide work and habitation spaces required by the ever growing population. Undoubtedly, the building construction industry is responsible for a significant amount of global resource consumption and demand for natural resources will increase with the population growth in the future. Apart from that, the building industry accounts for more than 50% of the global energy use and over 35% of CO_2 emissions [3–5]. This implies that the building industry is having an enormous impact on the environment and is responsible for a misuse of a significant amount of natural resources and the generation of waste. Therefore, resource and waste management has become an important issue around the world.

Considering the responsibility and influence the industry has on the environment, new typologies and building concepts should be designed to adapt to the posterity, where they can be upgraded, transformed, disassembled and recycled to reduce the construction material waste and increase the service life of buildings. The materials and methods used to construct a building affect the environment just as much the way they are designed to operate has a significant impact on their whole life cycle and future use [6]. Nowadays, there is an increasing effort to move towards sustainable and circular living spaces. A circular city is based on a built environment that is shared, flexible, based on a modular design, improves the quality of life of its residents and minimizes virgin material use [3]. The new ecological needs require a global and integrated way of thinking and designing in an effort to save material and energy, to care about the environment and to optimize resources in the construction [7]. The overall lifecycle of buildings has to be considered, as there is energy involved in demolition, in new construction and in building operations as well as energy generated in the process of mobility needs [8]. As an alternative to conventional building procedures, prefabrication and modular systems are adopted in the building design. The offsite manufacturing processes can offer greater accuracy, shorter construction times, safer working conditions and better value, as well as promote recycling and reduce waste [9], although it can create a monotonous landscape if not studied and explored enough.

The integration of reusable and recyclable materials and components in the construction can be used for effective waste management, because it reduces the environmental impact of construction, including the depletion of natural resources, cost and energy use incurred by landfilling [10]. The use of recycled materials can save more than 60% of the initial embodied energy of buildings [11]. As well as striving to create the lightest possible structures, the future of lightweight construction must also be guided by the need to develop recycling-friendly building methods and to minimize the production of grey energy from fossil fuels [12]. The growing demand for an expandable built environment can only be met if the amount of materials used is reduced and made available for further reuse [12]. The design for disassembly (DfD) aims to reduce the consumption of materials, cost and waste in the construction, renovation and demolition and eliminate waste that cannot be reintroduced into the cycles by reducing the physical interdependence and increasing the simplification of systems. Moreover, it increases the service life of buildings, all while making them material banks for the future [12,13]. The material recovery is intended to maximize economic value and minimize environmental impacts through subsequent reusing, repairing, remanufacturing and recycling [3,13,14]. The benefits of increasing building material recycling rates from 20% to 70% are considerable, as demolition and renovation waste can account for up to 50% of waste [4].

This paper intends to present new architectural typologies which can offer solutions to reduce waste generated in construction. Applied at the early stage of the design process, disassembly concepts and prefabricated and modular systems address the issue of housing shortage, while opening the discussion about recyclable architectural concepts. Prefabricated architecture is not new, and the aspects of history in which it was most relevant often reflect today's circumstances. Architects, engineers and contractors need to improve their understanding of the history and pragmatics of prefabrication so that they can effectively develop and implement these methods in architectural production [9]. Therefore, a documentary research methodology was applied to create a historical narrative in Section 2 from the literature review on the history of prefabrication of buildings to approach recyclable buildings based on journals, books, newspapers, reposts and websites in the fields of prefabrication, recycling, architecture and construction. The history and the building projects are a reference used to develop prototypes through the research by design methodology. In order to establish a starting point, the view of eminent people in the field on the topic at hand was examined [15]. Section 3 presents three conceptual building typologies and proposal models—"Slab", "Tower" and "Demountable"—as an answer to social problems, which had been developed within the Eco-Construction for Sustainable Development (ECON4SD) research project co-funded by the European Union in partnership with the University of Luxembourg. The overall objective of this project is to strengthen capacities in sustainable construction by developing components and design models for resource and energy-efficient buildings based on construction materials such as concrete, steel and timber. The design of these three prototypes differs from other buildings as they are designed to be dismantled at the end of their service life, are highly effective spaces with a minimal footprint as well as large-scale structures with flexible and adaptable uses which combine individual housing with community activities and a variety of modular and prefabricated construction types.

Despite different ideologies, for many academics and practitioners of architecture, the concept of recyclable architecture has remained essential to the evolution of architectural knowledge. This paper contributes to the current body of knowledge by providing a deep insight into prefabrication and modular typologies leading towards the Recyclable Architecture. The outcomes, i.e., the projects of the architectural typologies developed during this research, are intended to be implemented in cities or regions where there is a need for new construction to provide houses offering shared and public spaces while enabling the adaptation to social needs, while reducing the use of natural resources and waste generated. The projects of the buildings can be adapted to the regulations of each region keeping the same typology. For example, the buildings' height can be changed by adding or reducing floors. In addition the Slab, Tower and Demountable prototypes and concepts are intended to serve as a guideline for other building projects and may help architects and designers, as well as decision-makers, policymakers, clients, developers and the construction industry to have a better understanding of recyclable architecture and adapt appropriate strategies to overcome the identified challenges.

2. The History of Prefabrication Towards Recyclable Buildings

The concepts of modularity, disassembly, reuse, and recycling in construction are presented for a better understanding of the history of prefabrication. Modular methods are closed systems in which elements are prefabricated independently for a specific building. In addition, the modules can be assembled into complete entities by combining them in several different ways [16]. Disassembly is a process in which a product is separated into its components and/or subassemblies by nondestructive or semi destructive operations. Reuse is the use of components and modules obtained from the end-of-life products as replacement parts. Recycling is the recovery of materials from end-of-life waste products [17].

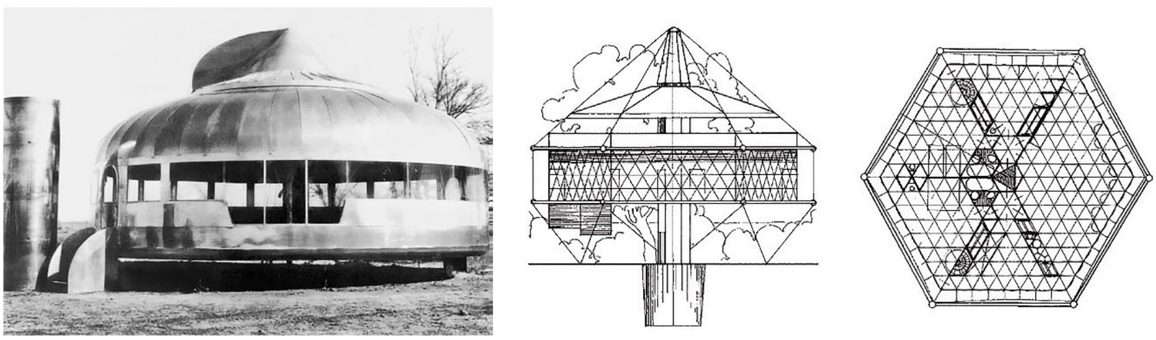
Prefabrication is a method of producing components offsite in a factory and then assembling them onsite [9,18]. It challenges architecture, bringing up the question of the authorship of a concept and singularity, and requires knowledge of production and construction methods. If architecture could suit these requirements and succeed, a difference could be made to the quality of the built environment [9]. It has been found that prefabrication increases the safety and quality of construction while reducing the time, cost, material waste and the impact on the environment [19,20]. The projects presented in this Section inspired the design concepts of the prototypes presented in this paper in Section 3, using critical analysis about what could be brought to the present and work nowadays.

2.1. Prefabricated Buildings

The history of prefabrication begins with Great Britain's colonization, which required a rapid building initiative in the settlements [9]. In 1830, Henry John Manning designed the Portable Colonial Cottage, a timber and panel infill prefabricated system, for emigrants to Australia [9,18]. In the mid-1800s, William Fairbairn built four cruiseships using the techniques of the first iron steamboat. Built from riveted plates to form units, they could be assembled, disassembled, and reassembled. This technology was later transferred to build prefabricated iron plate homes. Manufacturing methods paved the way for new theories and approaches to prefabrication technology in architectural production [9]. The ideas of rationalization in architecture used later on in prefabrication started in the first half of the nineteenth century with Jean Nicolas Louis Durand and his architectural conception of *symétrie, regularité* and *simplicité* (symmetry, regularity and simplicity). The Joseph Paxton Crystal Palace is one of the earliest prefabricated buildings. It was built in London to house the Great Exhibition of 1851. After the exhibition, it was dismantled and relocated elsewhere [9].

At the turn of the twentieth century, the idea that the city and architecture are transitory and temporary has appeared in the pioneer Antonio Sant Elias's Manifesto of Futurist Architecture in 1914. He pronounced that each generation must build its own city: "The houses will not last as long as we do." This experience of the rapid passage of the time now leads for the first time to the renunciation of the old principle of Durability. Besides, futuristic projects were designed to focus on rationalized, mechanical, and industrialized cities and high-rise buildings, integrating different uses such as offices, houses, shops and public spaces in the same building [21]. In the 1920s, Walter Gropius adapted flat roofs and the loss of green ground was reclaimed on rooftops used as accessible gardens in order to incorporate nature into the city [21]. The evolution of the flat roof garden is used as a reference for sustainable building today.

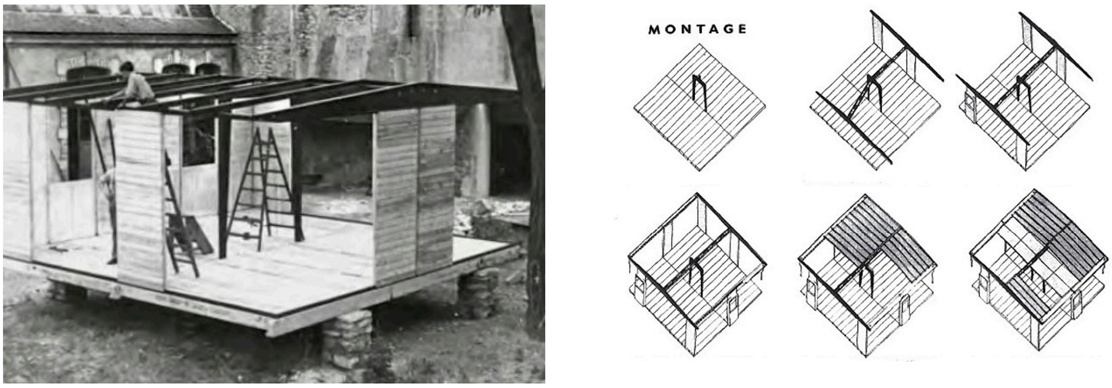
During the Modernist movement, in 1923, Le Corbusier stated, “the house is a machine for living” and saw mass-produced architecture as the answer to social ills, setting up a construction system that was based on rationalization through standardization. Although none of Le Corbusier’s buildings were constructed employing prefabricated methods, his ideas about using the manufacturing industry were common practice for architects of the time [9]. In 1932, the term "assembled house" was first used by Frank Lloyd Wright. These houses consisted of modular units which became the spatial building blocks defining the various rooms [9]. Wright’s Usonian homes of the late 1930s presented the rationalization. However, his methods never varied much from onsite construction, and his houses were expensive because of the high demand for quality in hand-crafted detail [9]. Following some ideas of Modernism, Richard Buckminster Fuller saw architecture as an applied technology, expressed in terms of energy, mathematics and rationality [21]. In 1928, he patented the Dymaxion house, which was developed further in 1945–1946 into the “Wichita House” prototype [9,21] (see Figure 1). The word “Dymaxion” denotes maximum benefit for a minimum energy input in order to gain control of climate conditions [21]. The prototype was fabricated in aluminum and fastened with rivets in a hexagonal plan followed by a fixed structural pattern. All the services were grouped at the center core. However, Fuller stopped the production claiming that it was not ready for large deliveries [9]. In 1942, Walter Gropius in collaboration with Konrad Wachsmann produced the “Prepackaged House” with prefabricated wood structure and panels [9,22]. The technique was also practiced by Mies van der Rohe who contributed to the societal acceptance of the steel and glass tower using prefabrication. The Seagram Building in New York City is a good example of this [9,13]. Many of their parts were standardized, although the assembly process was customized, making factory process cost savings insignificant [9].



(a) (b)

Figure 1. Richard Buckminster Fuller. (**a**) Wichita House, 1945–1946 [9]; (**b**) Dymaxion House project [16].

With soldiers returning from World War II (WWII), the housing market rose in the US. In 1946, the federal government of the US passed the Veteran Emergency Housing Act (VEHA), giving the mandate to produce 850,000 prefabricated houses in less than two years [9]. William Levitt benefited from the VEHA; producing homes in the factory systematized the onsite process and added a separation of construction planning and execution [9]. Similar to Levitt, Jean Prouvé produced French postwar housing. In Western Europe, the Marshall Plan was setting the stage for post-WWII rapid growth. Prouvé worked with Pierre Jeanneret to develop Packed and demountable family homes made entirely of timber—the Pavilions were 8 × 8 and 8 × 12 meters large (see Figure 2). These designs were lightweight, quickly erectable prefabricated shelters used as a temporary housing solution. Prouvé worked to minimize waste and maximize benefits [9,22]. The United Kingdom's post-war housing program mirrored the US, with the difference being that the houses were meant to be transitory, therefore focusing on speed instead of quality. Prefabrication was used to manufacture and erect them, utilizing factories and creating employment. All four main types of temporary bungalows were manufactured in the UK—the Arcon (steel frame), the Uni-Seco, the Tarran (both timber-framed) and the AIROH (Aircraft Industry Research Organisation on Housing) houses [9].



(a) **(b)**

Figure 2. Jean Prouvé's Pavillion. (**a**) Assembling the prototype Pavillion, 1944 [23]; (**b**) Prefabricated house type assembly diagram [16].

After WWII, in 1954, many companies that began as recreational mobile trailer manufacturers shifted into producing permanent portable housing in the US. Mobile homes were built entirely as a module on a chassis in a factory and then trucked to the site. The mobile home became a permanent housing increasing from a 2.45 meters to a 3.00 meters-wide trailer, offering more space [9]. During the 1950s, the idea of a mass-produced expendable component dwelling can also be seen in Ionel Schein's prefabricated hotel units, Alison and Peter Smithson's House of the Future at the Ideal Home exhibition of 1955, and the Monsanto Plastic House in Disneyland [24].

In the 1960s, the contribution of Louis J. Kahn to prefabrication was revealing a material and a system (precast columns, vierendeel girders and beams) as well as its method of construction for aesthetics and design [9]. During 1962–1964, the plug-in cities were set up by applying a large-scale network-structure containing access-ways and essential services. The plug-in city integrated the metal cable housing concept, a megastructure of concrete that placed removable house elements able to be updated as technology moved forward and adapt with the dweller as his needs changed. The Cook's Housing for Charing Cross Road in 1963 and the Chalk's Plug-In Capsule Homes in 1964 were good examples of the plug-in houses [24], (see Figure 3).

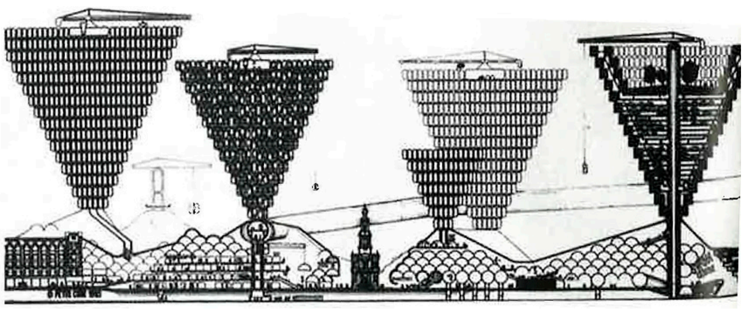


Figure 3. Peter Cook, Housing for Charing Cross Road, 1963 [24].

At the 1967 World Expo in Montreal, Moshe Safdie designed his first built project "Habitat 67" (see Figure 4). A housing complex, consisting of 158 houses, was constructed from 354 modular reinforced precast concrete units manufactured offsite. The units could be combined providing different sizes for the residents. The blocks were too heavy to be easily installed or relocated, had too many variations, and required specific tools, towering cranes and intensive labor [9].

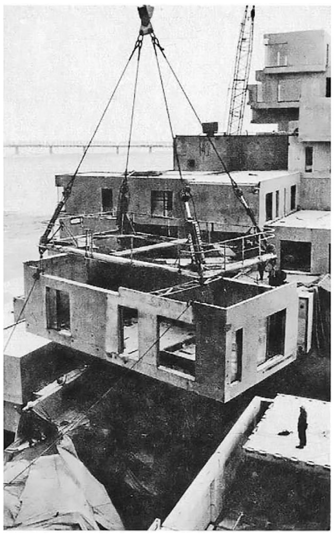


Figure 4. Moshe Safdie, Habitat 67, 1967 [9].

The 1960s also brought the Japanese Metabolists' manifesto published by Kisho Kurokawa and others [9,21,25]. The central idea was the individual capsule— movable, prefabricated and plugged into a structural service core. Kurokawa's Nakagin Capsule Tower located in Tokyo is a rare remaining example of Japanese Metabolism. It is comprised of two interconnected concrete towers and 144 individual, movable, and prefabricated capsules [9,21] (see Figure 5). Ironically, the building has never been changed or extracted from the core, and is deteriorated [9]. Kurokawa even claimed that his high technology "meta-architecture," with its notion of natural organic life-cycles, introduced an ecological system into architecture [9,25].

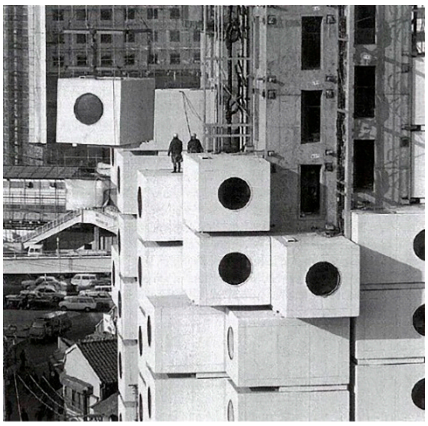


Figure 5. Kisho Kurokawa, Nakagin Capsule Tower, 1970–1972, Tokyo [26].

2.2. Ecological and Recyclable Buildings

Pursuing the history of prefabrication and adding to the high-tech and Metabolism era, the concern with the possibility of material depletion the consequent ecological movement started in 1970, at the US oil production peak. In 1973, an oil crisis forced a dramatic rise in the price of energy, products and services across the entire global supply chain [27]. In 1997, the Kyoto Protocol international agreement was signed to stabilize Greenhouse Gas atmospheric concentrations to prevent dangerous interference in the climate system [28]. As a consequence, projects started to focus on obtaining the maximum performance with the minimum of resources, which lead to the emerging of new architectural solutions.

The High-rise of Homes is a theoretical project by SITE in the USA from 1981 (see Figure 6). The building is a vertical community of private homes supported by a steel and concrete matrix, an alternative to the traditional housing design in the urban landscape, replaced by garden spaces and personalized architectural identity [29]. Inspired by SITE, Frei Otto saw architecture as a way to improve man's living conditions in harmony with nature, which led him to investigate the question of ecological building and making him one of the precursors of sustainability in architecture. Through the research, he arrived at a new form of natural, adaptable and flexible lightweight construction, as a way of building with minimum consumption of material, energy and economical means [11,21]. In 1990, Otto applied these principles in the Ökohäuser (Ecological houses) in Berlin, which is a vertical structure, composed of three residential houses with a concrete skeleton positioned on solid pillars (see Figure 7). The inhabitants themselves customized the open and raw structure with the architect's support and guidance. Initially, new families were supposed to demolish the oldest and to start over again, but this has never been the case [30]. The project opens the discussion about flexibility, individual housing in a community, and ecology—even though there is no guarantee that, in the end, it will be affordable, and the families will keep the concepts.

Figure 6. SITE, High-rise of homes, 1981 [29].

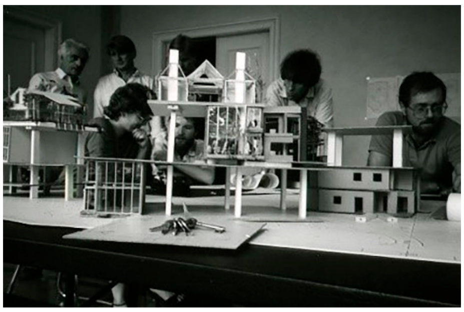


Figure 7. Frei Otto, Ökohäuser, 1990, Berlin [30].

In the late 2000s, the Tiny Homes movement started in North America with the housing market crash. These tiny homes were usually 37 square meters or less, meaning the homeowners were able to build them themselves. The smaller footprint meant it cost less, required fewer materials, reduced construction waste and was generally more energy-efficient in the long run to maintain. Their low energy requirements were based on solar power or other alternative forms of energy. Many were also built on wheeled trailer bases to make them portable. Tiny houses are symbols of a simpler lifestyle where "less is more" [31].

Nowadays, architects are developing projects integrating prefabrication and ecological concepts. For example, Werner Sobek designed the R128 single-family house in 1998–2000 (see Figure 8). The exposed bolted steel frame was prefabricated offsite, and the triple glazing panel was modular. The bathrooms are comprised of pre-fabricated modules inserted into the building [13]. The assembly employing offsite pre-fabrication and modular systems can be dismantled, allowing its materials to be either reused or recycled [32]. Another example is R50—cohousing build in Berlin by the Heide and Von Beckerath office from 2010–2013 (see Figure 9). The project includes 19 individual apartments, one studio and shared spaces. The reinforced concrete skeleton is based on the sizes of apartments and the suspended balconies in steel construction connecting them on each floor. The modular timber facade with opening glazed door elements is independently combined with the reduced and partly exposed infrastructure. The internal surfaces are unfinished, and the open design allows for individual layouts and a standard grid for fixtures. This design enables resident participation in interior design [33].

Figure 8. Werner Sobek, R128, 1998–2000, Stuttgart, Germany [34].

Figure 9. Heide and Von Beckerath, R50 cohousing, 2010–2013, Berlin, Germany [33].

Technology improves the design and manufacturing processes through advances in robotics, lightweight materials and digital building information. The risks faced by earlier modular and prefabrication builders are becoming more manageable. Technology has driven many new companies, often through the use of precision modeling and robotic manufacturing, to lower costs and improve efficiency [35]. The idea to use analogous examples as references to obtain inspiration about some problems in the present is not new. Throughout history, architects have searched for techniques to increase the quality of both design and production and used modular housing to introduce and improve sustainability and quality control [9]. Each example offers insight into how prefabrication and recyclability should or should not be harnessed to deliver architecture.

2.3. Discussion

Prefabrication is evolutionary, not revolutionary. The solutions to problems are discovered through practice and failure, which leads to an understanding of what works or not. Prefabrication can be a tool by which architecture can impact the built environment, most significantly the housing. The offsite manufacturing processes can offer greater accuracy, shorter construction times, safer working conditions, better value, promote recycling and reduce waste. Although prefabrication can reduce waste materials, it gives no clear indication about the environmental impact of materials used in construction. Prefabrication seems to be a viable solution for buildings to be easily disassembled and reused as industrial supplies [9].

According to Smith [9], the prefabricated projects during history failed for many reasons: Firstly, the sheer cost of updating technologies, replacing components and the dependency on big infrastructures for intervention; secondly, a lower quality and durability of houses in comparison to commercial construction; and finally, the aesthetic impositions and specific ideas, styles and materials that are too complicated to adapt and change according to individual living patterns, since aesthetic preferences change over time. Equally important would be the fact that it is the lack of integrated process in the early stage of design in a building venture that is responsible for many of these failures. The implementation of prefabrication during the earliest stages of the design process encourages all construction collaborators to adapt an affordable, appropriate technology for the built environment.

A number of prefabricated architectural experiments throughout the history until today cover basic needs, but do not satisfy the needs for adaptation on demand which are generated more and more by a fast-evolving society [24]. A traditional family model strongly influences housing currently under construction, and the number of households meeting these criteria is decreasing steadily. Moreover, the current housing market does not expect a growing need for communal, hybrid and transferable activities. Our lifestyles require a more integrated relationship between living and working, individual and common, and urban and nature.

Building technologies were improved, they implemented concepts of modularization, prefabrication and recyclability, but were still mostly focused on the assembled process of the construction. The structures were assembled, covered and glued by other materials making them demountable and challenging to reuse and unsuitable for disassembling at the end of life. New building concepts should be created in the future, which can be redesigned, upgraded, or disassembled without generating waste. High-rise buildings should integrate mixed uses, including offices, houses, shops and common spaces. Repetition and standardization are the inherent qualities of the mass-production of a consumer-oriented society. However, parts can be changeable or interchangeable depending on individual needs and preferences, and could also be economically feasible [24].

The majority of the buildings are still constructed using concrete, generating a significant CO_2 emission and making recycling rather expensive. Concrete is a part of architecture culture and will stay one for years to come, therefore buildings should be designed to address this situation and integrate this material in the construction in a recyclable way. However, nowadays, cities require more sustainable, smart, recycable and green buildings concepts all together.

The projects mentioned in Section 2 are mostly unitary residential projects. The idea of a temporary building introduced in Futurism should be taken into consideration and translated to the present. The temporary building concept can be achieved using bolted structures as applied for instance in the project of Fuller's Dymaxion house, the Prepackaged House of Gropius and Wachsmann, Prouvé's Pavilions and Sorbek's R128 house. They can be assembled and disassembled easily, although they are only implemented on a small scale. Their concepts can be used to design high-rise buildings nowadays. From the projects of Le Corbusier, Wright and Mies van der Rohe, the rationalization translated into modularity can be highlighted, even if the prefabrication methods required a lot of manual work onsite. These ideas must be brought to reality, but the prefabrication process during the construction must be improved without generating additional costs and manual labor. Furthermore, the high-tech movement and the metabolism manifesto serve as an inspiration to the large, open and exposed infrastructures allowing different layouts and uses besides plugged-in and -out housing capsules. The plug-in concept can be improved by combining ideas of the Mobile Homes and the Tiny House and as well as the idea of one housing unit which can be transported and installed in a different infrastructure. The challenge of today would be updating these strategies while integrating the ecological strategies used by Otto and SITE in combining nature and the built environment and adding to the reduced use of materials and waste production.

Infrastructure and existing buildings should be seen as a valuable cultural, social and architectural resource for shaping our future. The conversion of waste into valuable materials is one example of a positive attitude that needs to be adopted towards the existing stock. The international environmental movement's slogan "Reduce/Reuse/Recycle" incorporates the waste hierarchy. "Reduce" is aimed primarily at minimizing and avoiding waste. "Reuse" is a direct approach to waste management. "Recycle" comes third on the list as a way of processing material. The less the original waste product needs to be altered, the better is the process. The "3 Rs", Reduce/Reuse/Recycle, have been applied to architecture to create a hierarchy for strategies of change: the fewer interventions and the less energy expended, the more effective the process [8]. Recycling should be considered another ecological requirement that remains unfulfilled in the actual residential model. The sustainability of the built environment is often limited to the building's lifecycle, neglecting the grey energy and CO_2 emissions produced during the construction and demolition of these buildings. A switch in the architectural culture is necessary, which must take into consideration a broader comprehension of the multiple structural cycles, as well as the evolution of uses and users to create genuinely great solutions to the problems of the present day in a culture of collaboration [9].

3. Proposed Architectural Typologies

With the matters discussed above, it is necessary to design buildings to increase their suitability for recycling and future use. Thus, new designs should be capable of addressing ecological challenges and social changes. People's habits, as well as commodities, are changing at every social level, which eventually impacts the way of living [24]. Architecture should serve the public's needs, characterized as common and free spaces for the public in the cities, improving the quality of life and the buildings with the implementation of highly developed technology. It is the social questions about the use of the ground and the sum of human needs that constitute the functions that determine the form of a building. The first aspect can be reached by allowing the smallest footprint possible in order to give the population free access to the common ground. Regarding the second aspect, the shared space should be designed as an extension of the house, integrating people with different habits, and providing different activities. It would give residents the possibility to live, work and rest within the same space [21]. The adaptation of the building layout should be considered at the beginning of the design phase [36]. Adaptability relates to the technical performance of parts of the building. In this respect, adaptability is seen as a physical change with the purpose to increase the flexibility-in-use [37]. A large number of modular systems are designed to be manipulated, added, and maintained during their lifecycle, aiming for a building that can be reconfigured, relocated or disassembled for reuse [9]. Taking into the account the different needs of the current society, different conceptual typologies, which implement in the early design stage the possibility of the construction to be adaptable, demountable and recyclable in accordance with the needs of the future society, were developed in this research. The design of buildings is not only a professional practice but also a form of inquiry and research [38]. The different ideas, forms, uses and techniques related to prefabrication and recyclability of historical architectural buildings presented in Section 2 served as a starting point for the design principles of the building prototypes developed and discussed at the core of the ECON4SD project. The following sub-sections present the design principles that guided the development of this research and the details of each developed prototype.

3.1. The Principles

The construction of high-rise residential blocks is intended to increase the density of the population in the city center, at the same time creating open public and sharing spaces. The profile of the occupants in these buildings is the new generation of young workers living alone, or young couples with possibly one child. Therefore, the house units and apartments were designed to adapt to all kinds of use and to be affordable for all social classes, giving the population equal power for choosing how they want to live.

The buildings can be designed to provide flexibility, allowing different uses during their foreseen lifespan and the possibility to demount and remount the components in another place. This research aimed to produce alternative generic models, which would allow functional flexibility through time. Therefore three different recyclable architectural conceptual typologies were developed to have a more significant advantage of each system realistically and feasibly. They were named Slab, Tower and Demountable according to their stronger characteristics. The main principles for these building designs are: the possibility to be disassembled and recycled at the end of their life; the use of large-scale structures for flexible usage in a variety of types of modular and prefabricated construction methods; a highly effective space with a minimal footprint; and the integration individual types of accommodation with communal activities. For every different architectural typology, a structural, functional, spatial, constructive and aesthetic coherence was developed.

The first step in designing recyclable buildings is to consider their life cycle. The construction elements at the end of their service life should be transformed into resources for other buildings, closing loops in industrial ecosystems and minimizing waste. The structures were conceived to be disassembled and reconfigured throughout the lifecycle of the building. The exposed structure can facilitate the process of disassembly, consequently reducing the waste remaining at the end of the life cycle of the building. Therefore, the entire building structure or some parts, such as beams, slabs and pillars, among others, can be recycled, either to relocate the building, reuse components to build a new structure or to recycle the materials to create new ones. Furthermore, the structure and internal layout can be reconfigured for different functions, e.g., the same area transforming into a house or an office, depending on the necessity of the society.

The rationalization of the massive structure, both internal and external, was achieved by using grid systems, prefabricated components and modular units, which optimize the disassembly and the reconfiguration. Furthermore, the mega and prefabricated structures allow the most extended spans that provide more flexible uses and different layouts according to the user's needs. In addition, modular structures or modular buildings increase the possibilities for building expansion.

In order to have a highly functional space with a minimal footprint, reducing the area which provides access to the building should be put into consideration. A central core is one of the solutions adopted to reduce the structure on the ground floor, which can include the elevators, stairs and technical shafts. The smallest footprint and the most opened space generate public zones that can be explored such as shops, gathering spaces, and urban gardens.

The buildings offer places where the residents can have moments to be on their own and moments to meet others. The housing units were designed to reduce the space necessary to live, including cooking, eating, sleeping, taking care of hygiene and working, already proclaimed by Le Corbusier in "Vers Une Architecture." The dwelling can adapt according to the needs of contemporary families, while the buildings can receive more than one type of residential layout. As an example, the dwellings can reduce and increase their size for one resident, a couple, and a couple with kids.

Finally, all the prototypes have public space and communal areas to improve residents' life, with more facilities at the same location, which satisfy the group activity needs. These spaces are the extension of the housing and users' life. The shared zones were variously placed on the ground floor, on the rooftop and were also given by the circulation on the different floor levels. The activities can be selected initially and then adapted through time according to the needs of the residents or the city neighborhoods—for example, swimming pools, saunas, sports facilities, urban gardens, kindergartens, libraries and markets. Some buildings function as an independent module in and of itself, however they can also be combined with other modules to provide more than one type of activity.

To conclude, the prototypes have the capacities to be in a continuous evolution from one state to another. They are complete but always in transition to adapt to the users' needs. The design and execution methodology focused on the efficiency of use and implementation, attempting to leverage existing methods of residential prefabrication. The research by design methodology was implemented to reach the final shape of the three prototypes. Drawing, plans and 3D models were tested, analyzed and the feasibility and construction was demonstrated. Section 3.2 describes in more detail and individually each one of the final designs for three prototypes.

3.2. Prototype 1: Slab

The main objective of the Slab prototype is to increase density by providing more housing with shared spaces. The building is designed to allow different arrangements of the dwellers giving flexibility to house units to grow hosting different families' numbers and residents. Furthermore, to reach these concepts, the building has a reduced footprint providing more space for public use, and the rooftop is a common area.

The prototype is an 11-story building consisting of a primary reinforced concrete structure and connected wooden housing units, as shown in Figure 10. The shelf-structure provides a stable slab with a structure extending over two floors for standardized, prefabricated and portable housing modules. These modules offer a living space designed for either a single person or a couple. A housing unit plan was developed from one to four configurations, capable of expanding and shrinking as needed, as presented in Figure 11. For each one of the housing units, there is also a common area, which adds up to a significantly below-average floor surface per inhabitant as per standards. The modules are positioned in the main facade of the building, and they can be added or removed by a crane at any time. They can be transported by any standard truck, and can be quickly assembled and removed in rails.

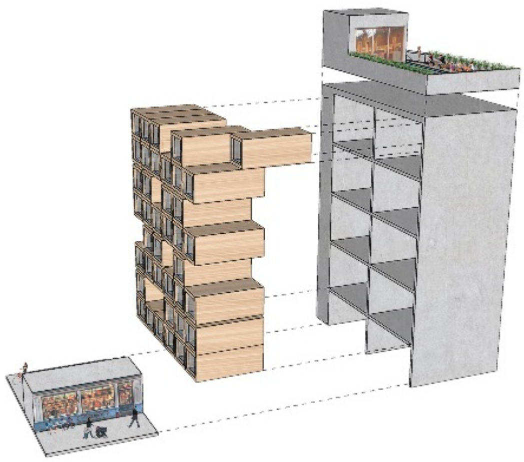


Figure 10. Prototype 1—Slab: diagram.

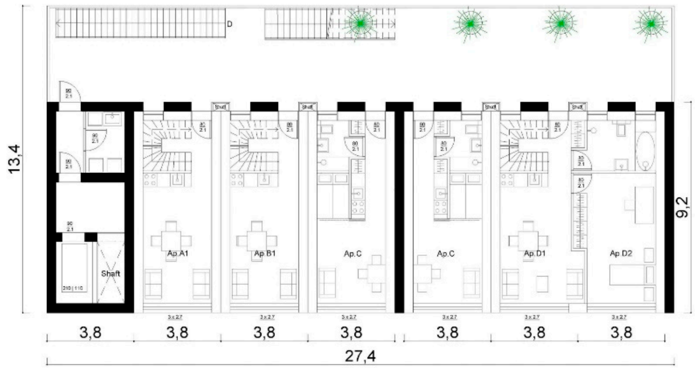


Figure 11. Prototype 1—Slab: 1st level floor plan.

One-side building orientation allows the dwellings to receive natural light on two facades. The modules are positioned in the main facade of the building. The stairs are integrated into the opposite facade, as seen in Figure 12, reducing the vertical core and creating an open corridor that becomes a large sharing balcony in front of the doors and compensates for a reduced size of the housing units. The vertical core is positioned on one side of the building to access the elevator and shafts, integrating some facilities such as small laundries.

The optimization of the housing surface area is associated with a range of communal activities on the top floor. These activities are theme-oriented, from a recreation area with a swimming pool, through a shared analog lounge, all the way to a collaborative workspace. This space will be designed according to the local needs. The ground floor offers an envelope that can be occupied according to the location of the building: in urban situations mainly by shops, in suburban cases more by offices or workspaces.

(a) **(b)**

Figure 12. Prototype 1—Slab 3D model: (**a**) frontal facade; (**b**) back facade.

Figure 13. Prototype 1—Slab: 3D simulation extension.

The building itself is a module that can be extended depending on the terrain and demand. Figure 13 is a simulation of this extension, integrating more than one module. Its structure allows the development of land that is difficult to build on. In addition, the Slab building represents an infrastructure that can be placed in many neighborhoods or cities, and the housing units can move with their owners by truck and plug-in into another Slab infrastructure. We can say that the typologies are a mix of ideas such as rationalization, modularity, prefabrication, plug-in and recyclability to reach the circularity in the construction. The concept of the housing unit that can be added in or out of the structure responds to the demands on a circular building. Since the housing units are made of timber, the maintenance and replacement through time are simplified. As this material is not exclusive to one industry, if a change occurs in the local economy, similar modules still can be fabricated by different companies.

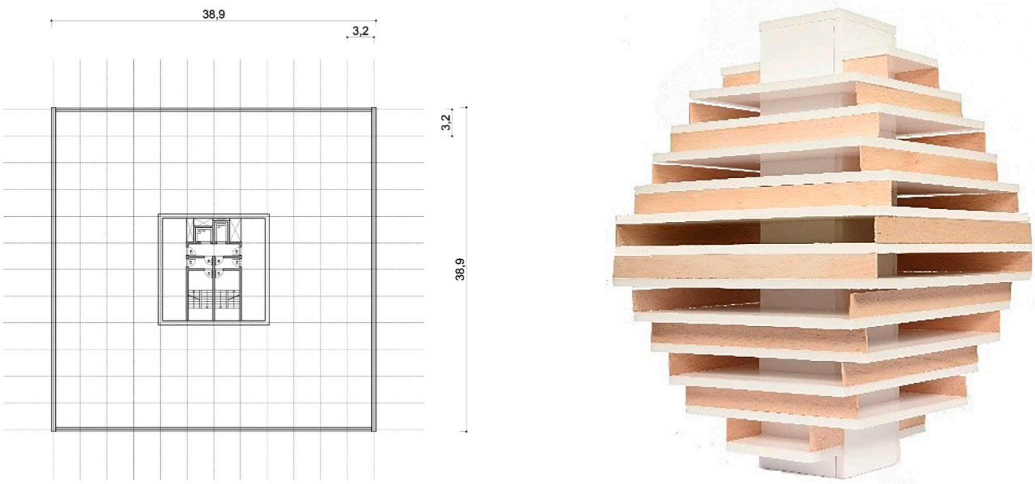
3.3. Prototype 2: Tower

The second prototype is a mixture of uses with different possibilities of floor organization, which may include different dimensions of apartments for different social classes combined with community facilities and sharing spaces. The project's ambition is towards an architecture with a minimal structure that implies open space and recyclability.

This typology refers to a 25-story tower, with a wooden structure wrapped around a reinforced concrete core. The building structure remains visible and will be fully prefabricated and recyclable, as shown in Figures 14 and 15. The form strives to reduce the footprint to a minimum, aiming to support a variety of shared activities, e.g., urban farming, which brings the community together, added to the reduction of the unnatural ground. The building is designed on a grid of 3.2 × 3.2 meters, as shown in Figure 15, to facilitate the process of prefabrication by rationalization of elements. The variations of slab sizes enables different uses and diverse housing unit layouts. The two lower and upper floors accommodate other community facilities such as a pre-school, living room, kitchen and sports venues. The central floors, with a large surface area, are dedicated to collaborative workspaces, while the intermediate levels are reserved for residence. The internal arrangement of walls, bathrooms and kitchens are adaptable since the infrastructure services are integrated into the ceiling. Through the varying categories, these housing units allow the integration of a diversified population. Therefore, the building complex seeks a mixture: between living and working, various social classes, private and common activities. A diagram with the different inside uses of the Tower is presented in Figure 14.

(a) **(b)**

Figure 14. Prototype 2—Tower: (**a**) prototype 1: 3D simulation; (**b**) prototype 1: section showing different uses.



(a) **(b)**

Figure 15. Prototype 2: (**a**) Tower: grid of 3.2 × 3.2 meters, 10th level; (**b**) Tower: 3D model.

3.4. Prototype 3: Demountable

The idea of a complete disassemblable and recyclable building is implemented in the third prototype named Demountable. The building is flexible in many situations, adjusting the interior layout, prolonging, shifting and reconfiguring the exterior format, being disassembled and reassembled in another place to adapt to future needs. Since the structure or its parts can no longer be reused, they must be recycled into new materials. As a result, we close the loop, and the construction life becomes circular. The building starts from a prefabricated basic standard block that can grow in all directions, adding more components or whole blocks if needed to facilitate the disassembly process, as illustrated in Figure 16. The structure is adaptable for steel or timber components. The internal span length of the generic model allows different layouts for housing units, offices, cars, gyms and saunas, for example. The replication and combination of these generic models offer the possibility to design buildings with different uses, such as parking, public facilities, shops, offices and housings, and sometimes a mixture of them.

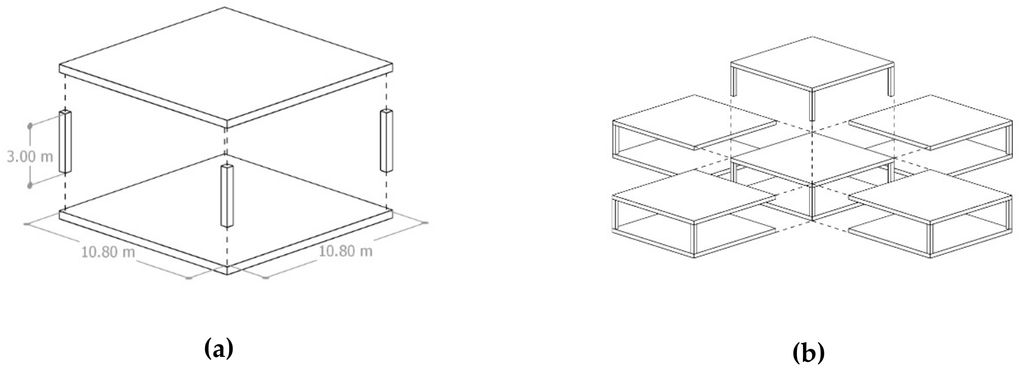


Figure 16. Prototype 3—Demountable: (**a**) architectural concept for the standard block; (**b**) the blocks' expansion.

This study presents two scenarios for this typology. The first configuration is a car parking building with public space on the rooftop with a swimming pool, sauna, gym and sports courts, as shown in Figures 17 and 18. Vertical access is added as an external structure to keep the main structure as free as possible. Through time, the constructed environment can be adapted to accommodate future demands while keeping the same structure. Some parking floors can be transformed into offices and others into housing, adding interior walls. Moreover, the ground floor can become shops, leisure spaces or a covered square that bring citizens together.

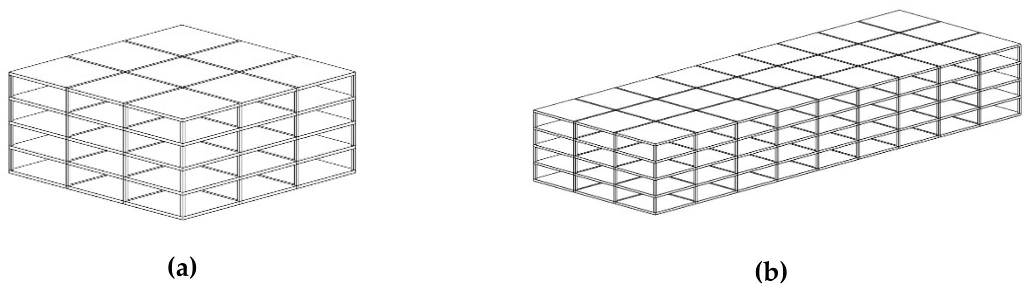


Figure 17. Prototype 3—Demountable: (**a**) the first configuration: mix using public facilities and parking, housings and offices; (**b**) the building extension.

(a) (b)

Figure 18. Prototype 3—Demountable: (**a**) 3D Simulation; (**b**) 3D model.

The second configuration is shown as a continuation of the building life-cycle. The structure needs to be disassembled and relocated. The building can maintain the same form as before or can be adjusted to other needs as a housing complex or an office building with different heights and numbers of blocks, as shown in Figure 19. All remaining parts from the old structure should be reused in other construction or recycled, producing new materials.

(a) (b)

Figure 19. Prototype 3—Demountable: (**a**) housing complex/office building; (**b**) their expansion.

3.5. Discussion and Benefits of the New Recyclable Prototypes

The aim of the prototypes is to examine the relevant issues of recyclable strategies and prefabricated and modular systems in construction so as to increase flexibility, adaptability and disassembly in the architectural design. The results presented in this paper are innovative tools and approaches which are to be implemented at the beginning of the design process and that can be adapted to other buildings.

The architectural typologies introduced in this paper bring direct solutions, combinations or improvements of designs and prefabricated and modular systems from constructed buildings presented in Section 2. In order to validate the viability and to highlight the improvement of the three prototypes, a comparison is made between them. The main difference is the fact that the three prototypes are high-rise buildings designed to be adaptable through time and disassembled at the end of their life through prefabrication and modulation, at the same time providing a large amount of housing units combined with more shared and public areas. The Slab buildings are focused on the housing expansion and plug-in concepts, accommodating 48 portable housing units; the floors of the Tower prototype can be divided to configure 140 apartments emphasizing the internal flexibility of the structure; and the prototype Demountable is designed to comprise 58 single housing units per floor (three single housing units in one standard block) focusing on the complete disassembly. Even though the other buildings integrated the prefabrication and modular system, they focused on the assembly process and not on the disassembly, making it more difficult to reuse or recycle, which generates more waste. Until the 1960s, the prefabrication and modular systems were widely implemented in the individual homes. The three prototypes took advantage of this rationalization on a small scale and translated it to a large scale, using grids to design high-rise buildings, demonstrating that the implementation of prefabrication and modularity in large buildings facilitates the process of construction disassembly and the adaptation of the structure for different uses. The concrete blocks of "Habitat 67" were combined to build a building, nevertheless they were too heavy to be easily installed or relocated. The "Nakagin Tower" also has modules, capsules attached to a core, but the layout was concise for the essential needs without the possibility to combine them to create big units. From "Habitat 67" and "Nakagin Tower" the concept of housing modules and plug-in systems mixing with the portable houses—Tiny House and Mobile homes—were brought to the Slab building, improving the possibility to extend the residence and to be connected in more than one infrastructure, since it employs timber, a lighter structure than concrete. The Archigram studies were focused on creating a discussion and theory in architecture with images and propaganda. Added to the opening of the debate on recyclability, the Slab, Tower and Demountable prototypes are realistic and provide more details and concerns about the feasibility of the construction. The ecological and recyclable examples inspired the integration of nature, the lightweight and exposed structures with open slabs in the construction showing that it is possible to easily modify internal layouts, extend and change the built environments throughout their useful life. However, they do not guarantee the environment's effects of the building at the end of life. By contrast, the three Recyclable Architecture typologies are designed from the beginning to reintegrate the materials into the life cycle in other buildings.

These typologies can be built in many neighborhoods or in many cities where new construction is required to provide residential, commercial, shared and public spaces while enabling the adaptation to social and future needs, reducing the use of resources and construction waste. The projects of the buildings can be adapted to the regulations of each region while keeping the same typology. To illustrate, the prototypes' height can be changed, adding or reducing some levels. More staircases can be connected to the Demountable typology. The dimensions of the Tower building can be expanded in proportion. The number of modules of the Demountable and the Slab building repetition can be related to the dimensions of the terrain. Moreover, the Slab, Tower and Demountable prototypes and concepts intend to serve as a guideline for other building projects. Therefore the prefabrication and modularity can be used in different manners to increase the flexibility and disassembly of the building. The design of these three prototypes brings several benefits to the construction field. They are listed below:

- The design brings more value to the construction and to the life of the residents. As an example it could be mentioned that this design provides more communal space inside the buildings. In the Tower prototype, the common areas are localized in the upper and lower floors. In the Slab prototype, the rooftop and corridors are the shared spaces. Moreover, the Demountable prototypes have a public access rooftop, and the ground floors of all Prototypes are public spaces. These strategies integrate living, working and leisure in the same building.
- The open design enables home expansion according to the needs of the resident. In the Slab building, the modules can be pluged in and out and connected. In the Tower and Demountable buildings, the open slabs without walls can change the layout easily. As a result, the floors can be adapted to different uses, e.g., the slabs can accommodate apartments and later on the interior layout can be changed to become offices.
- The use of primary resources and waste is reduced by proposing in the earliest stages of architectural design, for all the three prototypes, the use of recycled materials, and by predicting changes and disassembly that may occur over the useful life of the building or at the end of the first cycle.
- To complement the above, the transition of structure reconfiguration, additions, and subtractions through time is facilitated because the structure is separated from the liming. The housing modules are separated from the infrastructure in the Slab typology, and the walls are separated from the bolted structure in the Tower and Demountable.
- All prototypes serve as material banks for the construction of future buildings, considering that from the beginning, all the elements of the buildings can be traced and are designed to be separated and reused in other constructions, by adopting raw materials, exposed structures, and systems that can be plugged in and out, which keeps the loop of materials closed. For example, the Slab housing modules can be used in other building and their wood reused in other

structures. Secondly, the structure of the Tower can be demounted and reused since it is build entirely in timber and the walls can be relocated. Finally, the Demountable prototype was designed to be entirely demountable, so beams, walls, slabs and walls can be reused in different constructions.

- Parallel disassembly is allowed to minimize time onsite, for instance, the removal of modules or prefabricated slabs where parts can be detached later.
- Mechanical, electrical and plumbing systems are consolidated into core units to minimize runs and hence unnecessary entanglement.

To conclude and summarize the advantages of the conceptual typologies, the main idea of a Recyclable Architecture by using the proposed typologies can be reached. The Recyclable Architecture concept is defined as a modular and disassemblable construction that allows functional flexibility through time and reusability and recyclability of materials at the end of life, while integrating public and shared spaces according to the needs of society.

4. Conclusions

Architects keep designing in the same manner as before for a permanent building. By contrast, the concepts of Recyclable Architecture at the beginning of the construction project are extremely necessary to address the huge demand for additional buildings required to accommodate the new generations while at the same time reducing the use of natural resources and minimizing the materials wasted during construction. Prefabrication and modularity were important in the history of architecture for understanding these methods of implementing and improving them, simplifying the process of disassembling at the end of the first building's life cycle. Consequently, the concept of Recyclable Architecture has to be established and widespread.

This paper briefly examined prefabricated and recyclable building in architecture and proposed three new typologies. The aim of this research can be reduced to how the building can integrate the concepts of recyclability and disassembly realistically and feasibly. The three buildings prototypes presented in this article differ from other buildings as the concepts of Recyclable Architecture were implemented at the beginning of the design process, foreseeing what would happen after the useful life of the building and proposing solutions for them to be entirely or in parts recycled. Moreover, the typologies are a combination of a recycled building that provides different uses offering more generous spaces as public and communal areas for the inhabitants and society. The prototypes prove that a recyclable architecture with the current technologies is viable and can be built in any location where there is a demand to implement new buildings while reducing waste. In addition, after the life cycle the buildings can be adapted for the new demands or be disassembled to give a space for other typologies using the same materials, thus saving energy from product manufacturing. To summarize, the proposed typologies give the options and freedom for the future society to decide what they want to do with the building. In other words, the architecture of today can be made to serve the needs of the future.

To conclude, the study presents limitations: more architecture and structural details and technical issues should have to be considered in order to reach a more advanced generic model, as they can have an impact on the final design. In addition, the lack of quantitative data in the architecture field is an obstacle and should be tackled by researchers. However, the main benefits of implementing these prototypes in the urban fabric are the increased life span and usability, avoiding demolition and reducing waste to zero. In addition, they change the architecture perspective and construction from a permanent to a mutable building, through space and time and from linear to a circular process. As future efforts for this research project, quantitative data on building materials will be collected and analyzed in order to establish metrics for buildings' modularity, recyclability, and disassembly.

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M.F.S.; Writing—original draft, M.F.S.; Writing—review and editing, L.B.J. and D.W. All authors have read and agreed to the published version of the manuscript.

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