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CIRCULAR ARCHITECTURE: MODELS AND STRATEGIES TO REUSE AND RECYCLE BUILDINGS

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ABSTRACT

How we design, construct and live in our houses as well as go to work can mitigate carbon dioxide (CO₂) emissions and global climate change. Furthermore, the complex world we live in is in an ongoing transformation process. The housing shortage problem is increasing as the world population and cities are increasingly growing. Thereby, we must think of all the other issues that come along with population growth, such as increased demand for built space, mobility, expansion of cities into green areas, use of resources, and materials scarcity. Various projects from history have used alternatives to solve the problem of social housing, such as increasing density in cities through housing complexes, fast and low-cost constructions with prefabricated methods and materials, and modularisation systems. However, the current architecture is not designed to meet users' future needs and reduce the environmental impact. A proposal to change this situation would be to go back to the beginning of architecture's conception and to design it differently. In addition, nowadays, there is an increasing focus on moving towards sustainable and circular living spaces based on shared, adaptable and modular built environments to improve residents' quality of life. For this reason, the main objective of this thesis is to study the potential of architecture that can reconfigure spatially and temporally, and produce alternative generic models to reuse and recycle architectural elements and spaces for functional flexibility through time. To approach the discussion, a documentary research methodology was applied to study the modular, prefabricated and ecological architectural typologies to address recyclability in buildings. The Atlas with case studies and architectural design strategies emerged from the analyses of projects from Durant to the 21st century. Furthermore, this thesis is a part of the research project Eco-Construction for Sustainable Development (ECON4SD), which is co-funded by the EU in partnership with the University of Luxembourg, and it presents three new generic building typologies. They are named according to their strong characteristics: Prototype 1 - Slab typology, a building designed as a concrete shelf structure in which timber housing units can be plugged in and out; Prototype 2 - Tower typology, a tower building with a flexible floor plan combining working and residential facilities with adjacent multi-purpose facilities; and Prototype 3 - Block typology, a structure characterised by the entire disassembly. The three new typologies combine modularity, prefabrication, flexibility and disassembly strategies to address the increasing demand for multi-use, reusable and resource-efficient housing units. The prototypes continually adapt to the occupants' needs as the infrastructure incorporates repetition, exposed structure, central core, terrace, open floors, unfinished spaces, prefabrication, combined activities, and have reduced and different housing unit sizes, in which parts can be disassembled. They also densify the region that they are being implemented in. Moreover, the new circular typologies can offer more generous public and shared space for the occupants within the same building size as an ordinary building. The alternative design allows the reconversion of existing buildings or the reconstruction of the same buildings in other places reducing waste and increases its useful lifespan. Once the building is adapted and reused as much as possible, and the life cycle comes to an end, it can be disassembled, and the materials can be sorted for reusable or recyclable resources. The results demonstrate that circular architecture is feasible, realistic, adapts through time, increases material use, avoids unnecessary demolition, reduces construction waste and CO₂ emissions and extends the useful life of the buildings.

CHAPTER 1. INTRODUCTION

As the architectural profession takes on new global ambitions and responsibilities, the scope of this research aims to propose new architectural conceptions for the current and future environment through recycling endeavours. The challenge is to shift to a more sustainable growth model that relies less on natural resource extraction and more on flexible and adaptable environments as people spend most of their lives in buildings.

The interest in recyclable and reusable architecture originated from the initial research conducted on energy efficiency, human comfort and the need to improve the building designs to fit the ecological constraints of the world rather than redesigning nature to accommodate human desires. Buildings are essential for human beings as climate protection and they form the foundation of cities in which communities strive. Therefore, buildings should receive more attention. How we design, construct as well as live in and go to work from our houses can mitigate CO₂ emissions and global climate change. Furthermore, the complex world is currently in an ongoing transformation process. The constant interaction between natural forces and humans will result in an immense diversity of genetic and natural phenomena¹. Nature, social groups, lifestyles, human feelings and the world's understanding continuously change. In 2018, 1.7 billion people resided in cities with at least 1 million inhabitants, which is 23% of the world's population². Projections show that the world's population will increase from 7.7 billion people in 2019 to 9.7 billion in 2050³ and, therefore, city populations will also continue to grow. In addition, the number of people within the working age group is growing faster than in any other age group⁴. The population is getting older, the divorce rate is increasing and there is an increasing demand for larger detached houses in the suburbs and high-density compact houses in city centres⁵. This movement is creating a window of opportunity for rapid economic growth. These abrupt changes may explain the disconnect among built-up areas, population growth and the changing urban form⁶.

The current human relationship with the environment is on the edge of a readjustment process, where environmental homeostasis on a planetary level is required for us to survive⁷. It should be a requirement that social groups and individuals have the opportunity to develop life forms and environments of their choosing. This will in turn establish the desired human environment to include maintaining an ecological balance, economically managing natural resources and controlling physical and mental health. The ever-growing population is spurring the growth of high-rise constructions and land occupation around cities which will provide work and habitation, but the current architecture is not designed to meet users' future needs or to reduce its environmental

1 Ward and Dubos 1972.

2 United Nations 2018.

3 United Nations 2019.

4 Ibid.

5 Ibid.

6 Kepes 2017; OECD 2017.

7 Kepes 2017.

impact. As the world's population continues to grow, the available resources will decrease as the materials are limited. A proposal to change this situation would be to go back to the beginning of a building's conception and design it differently. It is essential to think about the design process, what will happen to a building when it comes to an end or its subsequent period of use, or even how to reuse its components.

The building industry is undoubtedly responsible for the significant global consumption of natural resources and waste generation, which as a result impacts the environment and demands more natural resources⁸. For instance, the construction industry represents over 50% of global energy use and more than 35% of the world's CO₂ emissions⁹. Therefore, resource efficiency improvements (such as demolition, new construction, building operations and shipping) throughout the whole building's life cycle can drive competitiveness in the construction sector while reducing material use and environmental impacts associated with the built environment¹⁰. Furthermore, building construction and operation improvements can influence 42% of the final global energy consumption, 35% of the world's total greenhouse gas (GHG) emissions and 50% of the materials harvested¹¹.

A building is to be demolished when it no longer meets expectations and surpasses its service life, making this partition of the building industry the largest resource consumer and waste stream¹². The fact that existing buildings contain large amounts of embodied energy, materials and resources should be highlighted beyond just the contribution of identity and memory of communities¹³. Once demolition is replaced by disassembly, materials can be sorted for reusable or recyclable resources. Effective waste management and the integration of reusable and recyclable processes can reduce environmental construction impacts, depletion of natural resources and energy as well as landfill requirement costs¹⁴. In addition, recycling adds a positive influence on material production as less waste production is beneficial for the environment, as opposed to the building industry's total development consumption¹⁵.

In looking at the European Union (EU) conditions, it can be seen that it is facing challenges from growing energy import dependency, limited energy resources and the mitigation of climate change¹⁶. As a result, policies were invoked at the EU and Member State levels to address building energy efficiency. These specific policies for building materials or strategies that cover a broad urban environment have as a result indirectly influenced sustainability. However, the regulations that impact sustainable buildings or broader life-cycle environmental performance have yet to benefit from prolonged policy action, thereby emphasising the need to incorporate a broader spectrum of resource

8 Abd Rashid and Yusoff 2015; Ellen Macarthur Foundation 2017; Kibert 2003.
9 Abd Rashid and Yusoff 2015; Ellen Macarthur Foundation 2017; Kibert 2003.
10 Herczeg et al. 2014; Petzet and Heilmeyer 2012.
11 European Commission 2011; Herczeg et al. 2014.
12 Šijaković and Perić 2014.
13 Ibid.
14 Akbarnezhad, Ong, and Chandra 2014.
15 Herczeg et al. 2014.
16 European Commission 2012.

uses and environmental influences¹⁷. The constant expansion of the built environment can be a viable option if the volume of materials is reduced and available for reuse¹⁸. Materials and methods impact the environment as much as the design of the building, which can impact its entire life cycle and future use¹⁹.

Just as the design of a building impacts its use, so does its functionality. In this context, 75% of the building stock in Europe is residential buildings, trailed by wholesale, retail and office buildings. Furthermore, it is calculated that 88% comprises private buildings, and only 12% of the building stock comprises public buildings²⁰. Therefore, any focus on sustainable housing and lifestyle must engage with the broader social, economic and environmental contexts for sustainable private household practices²¹. Considering the construction industry's responsibility and influence on the environment, new architectural typologies and concepts should be designed to adapt to posterity²². Furthermore, in order to improve resource efficiency, the growing resource constraints should go hand in hand with the increasing demand for affordable housing worldwide²³. Architecture over the years has been transforming its traditional independent, heavy and solid position into a dynamic and interdependent structure, responding to humans' growing need for change²⁴. This transformation should be driven by the necessity to improve recycling-friendly methods and minimise the production of grey energy from fossil fuels²⁵. Henceforth, buildings should be updated, transformed, disassembled, reused and recycled with the aim to reduce construction waste and increase the building's useful lifespan. The flexible, mobile and open lightness can significantly contribute to humans' liberation from the closed, fixed space²⁶.

In addition, nowadays, there is an increasing focus to move towards sustainable and circular living spaces based on shared, flexible and modular built environments which can improve residents' life quality and minimise virgin material use²⁷. These life cycle changes can address obsolescence, adaptation, addition, technology upgrades, wear or simply the user's needs²⁸. Prefabrication is one alternative in building design to diminish waste during the construction²⁹ and deconstruction stages. Manufacturing processes offsite can offer better precision, higher value, faster build times, more secure labour settings, an increase in recycling avenues and a reduction in surplus for building materials³⁰. However, it can also create a monotonous landscape if not

17 Herczeg et al. 2014.
18 Chen, Burnett, and Chau 2001.
19 Eurostat 2019.
20 Herczeg et al. 2014.
21 Nelson 2018b.
22 Ferreira Silva et al. 2020.
23 Kepes 2017.
24 Ibid.
25 Heinlein and Sobek 2019a.
26 Kepes 2017.
27 Ellen Macarthur Foundation 2017; Ferreira Silva et al. 2020.
28 Correia 2017.
29 Jaillon, Poon, and Chiang 2009.
30 Smith and Timberlake 2010.

studied and explored³¹. To break it down, new ways of design and buildings should be proposed that include rationalisation and the same time architectural variations.

New buildings are still needed to accommodate for the population growth and currently many existing buildings are not suitable for reuse. With this in mind, demolitions should not be prohibited but rather evaluated for certain building typologies to determine whether they are useful as models for certain forms of reuse. Complementary to that, ecological needs require a global and integrated way of thinking, living, designing, caring about the environment, offering more habitation and optimising construction resources³². Considering that the world is striving towards affordability while also taking into account the environmental restrictions, this thesis proposes generic architectural typologies and strategies that have the potential to reconfigure space use, spatially and temporally, explore functional flexibility through time, compact and shared lifestyle and encourage the down-cycle of CO₂ emission rates and construction waste for future housing units. Furthermore, this research examines the benefits and challenges of creating reusable, recyclable, more efficient and sustainable living spaces through the use of modular and prefabricated technologies.

The present thesis, fuelled by the ECON4SD research project and co-funded by the EU in partnership with the University of Luxembourg, presents three new generic conceptual building typologies that aim to reduce generated construction waste and answer social problems. The three concepts are named according to their strong characteristics: Prototype 1 - Slab, Prototype 2 - Tower and Prototype 3 - Block. As an alternative to conventional building procedures, disassembly concepts and prefabricated and modular systems were applied at the early design stage to address the housing shortage as well as recyclable architectural concepts. To approach the discussion, a documentary research methodology was applied to study modular, prefabricated and ecological architectural building types to address recyclability in buildings. In addition, the building projects served as a reference to develop the prototypes through the research by design methodology.

The three new typologies combine modularity, prefabrication, flexibility and disassembly strategies to address the increasing demand for multi-use, reusable and resource-efficient housing units. The prototypes continually adapt to the occupants' needs as the infrastructure incorporates open spaces, exposed structures and raw materials that will minimise the primary resources but still offer different applications for the same site. The new typologies can offer more generous public and shared space for the occupants, within the same building size as an ordinary building. After the maximum reuse of space and the first building life cycle comes to an end and is no longer suitable, the typologies can be dismantled instead of demolished and the components and materials can be either reused or recycled for future buildings. Once the demolished building's components are separated, there can be tracking, reconditioning, recycling and reselling, for future building use. In addition, materials from other construction sites can be implemented in new typologies. The results show that the implementation of disassembly, reuse and recyclable strategies in the design process reduces resource

31 Ferreira Silva et al. 2020.

32 Otto and Songel 2010.

and energy use throughout the building's life cycle. This demonstrates that recyclable architecture is feasible, realistic, adapts through time, increases material use, avoids unnecessary demolition and reduces construction waste and the CO₂ emissions. The following sections critically address different resource problems, ecological concepts and Luxembourg society challenges through a sustainable and recyclable architecture avenue.

1.1. The resources problem and climate change

Humans' rapid growth has resulted in the reduction of viable living space. There are contaminated rivers and lakes as well as toxins in the atmosphere, sea and land due to the unrestricted dumping of human and industrial waste³³. This way of life will eventually lead to diminished space for humans. Furthermore, the faster non-renewable resources are expropriated and consumed, the fewer resources there will be which become available, the more pollution which will be created and the higher the costs will be for material along the supply chain³⁴. Therefore, measures must be taken to handle material wisely, reduce building pollution and promote component reusability. For this reason, it is essential to understand that natural resources are finite, part of our environment and economy and so we need to increase awareness of the impact of overexploitation, climate change and pollution.

Redundant material use causes environmental effects, supply uncertainty and price volatility³⁵. This concept of wastefulness tracks back to World War II (WWII), when reusing items was not encouraged and had little to no value for most Americans. In 1955, the popular Life magazine featured an article titled "Throwaway Living" that encouraged wastefulness, suggesting the single-use of items instead of cleaning it every day³⁶. As a solution to the abundant amount of waste created with single-use, and in order to control the odour and the flies, city trucks picked garbage up and compacted down the trash mounds and covered the mounds with soil daily. This allowed people to pay little to no attention to their consumption rates³⁷. However, over time, the garbage that rotted under the layers of earth released gases and toxins resulting in unpredictable fires and polluted the groundwater in rivers, drinking water supplies and people's homes. These issues did not come to public attention until the environmental movement of the 1960s and 1970s³⁸. Simultaneously, natural resource usage gained further attention in the 1970s, when US oil production reached its peak and then declined affecting the world's supply network and resulting in an oil crisis. As a consequence, the cost of goods, energy and services rose dramatically, and ecological movements emerged³⁹. Since 1980, material extraction has increased by over 200%, mainly due to building construction and industrial minerals⁴⁰. Until the 1990s, instead of a new form of communication and energy production, the population accumulated wealth from the four decades following WWII leading to economic growth with addictive buying and mass collective consumption habits⁴¹.

The global economic activity used the available energy in nature and converted it into

33 Kepes 2017.
34 Rifkin 2011.
35 OECD 2017.
36 Byers 2018.
37 Ibid.
38 Ibid.
39 Rifkin 2011; Silva 2020.
40 OECD 2017.
41 Rifkin 2011.

goods and services to be consumed, rejected and recycled, which resulted in long-term energy costs and losses⁴². Economic activities such as the extraction of raw materials, material manufacturing, material transport, material consumption and material disposal in landfills or incineration emits greenhouse gases such as CO₂, thereby generating economic, environmental and social consequences worldwide⁴³. The extraction, processing and use of materials cause half of the world's greenhouse gas emissions⁴⁴. The CO₂ from fossil fuels and biomass combustion already accounts for 90% of GHG emissions worldwide⁴⁵. The increase of CO₂ emissions in the atmosphere is considered the leading cause of climate change, an indicator in the building material life cycle and is difficult for countries to regulate and cope with⁴⁶. Environmental adjustments can lead to climate change that bring global awareness and change to ecosystems, agriculture, human welfare, socio-economic activities, and the frequency of extreme weather events worldwide⁴⁷. The earth's biosphere wholesale destruction questions the existing linear economic model⁴⁸.

As a result, political action is required in response to the increasing pressure on the Earth and ecological concerns. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) provided the basis for multilateral action to tackle climate change and its consequences for humanity and ecosystems⁴⁹. The 1997 Kyoto Protocol and the 2015 Paris Agreement were established to "stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"⁵⁰. By 2000, the EU sought to decrease its carbon footprint and to transition to a sustainable future. In May 2007, the European Parliament supported the Third Industrial Revolution, which proposed renewable energies instead of fossil fuels, as an economic vision for the EU⁵¹. In addition, in 2009, 192 national government leaders and scientists assembled in Copenhagen to face the challenge of industry-induced climate change. It was reported that the temperature of the Earth will rise at least three degrees Celsius before the century's end eventually leading to the extinction of plants and animals and complications with the water cycle⁵². The EU proposed that the world's nations should restrict global CO₂ emissions by 2050 and expect the rising temperature to be kept to two degrees Celsius⁵³.

Although a growing number of people are worried about the depletion of natural resources and realise the urgent need for change, without proper guidance, cities

42 Third Industrial Revolution Consulting Group LLC 2016.
43 European Commission Eurostat 2014; Hillebrandt and Seggewies 2019; OECD 2020.
44 OECD 2020.
45 OECD 2017.
46 Hillebrandt and Seggewies 2019; OECD 2017; Third Industrial Revolution Consulting Group LLC 2016.
47 OECD 2017; Rifkin 2011.
48 Third Industrial Revolution Consulting Group LLC 2016.
49 United Nations 1992.
50 UNFCCC 2020.
51 Rifkin 2011.
52 Ibid.
53 Ibid.

have continued to grow and the dynamic population is still driven by the linear “take-make-dispose” model⁵⁴. The more cities grow and countries become prosperous, the more waste will be produced⁵⁵. In 2019, the world population totalled 7.7 billion people and projections indicate that the world population will be around 8.5 billion in 2030, 9.7 billion in 2050, and 10.9 billion in 2100⁵⁶. According to the United Nations (UN), 1.7 billion people, 23% of the world’s population, lived in a city with at least 1 million inhabitants in 2018⁵⁷. In total, 54% of the world’s population lives in urban centres making the cities more susceptible to environmental risk due to high economic activity, pressures on urban infrastructure, and centres for steep resource consumption⁵⁸. City activities are responsible for the consumption of 70-75% of natural resources worldwide, impacting the availability of resources and ecosystems in regions that extend the urban perimeter⁵⁹. City efficiency and resiliency will become even more challenging as population and economic expansion continue⁶⁰. In some countries, the number of people of working age will grow faster than other groups, from 35% in 2019 to 43% in 2050, opening up opportunities and accelerating economic growth⁶¹. As the population increases, more buildings need to be constructed due to the growing demand for housing. This quick demand will cause a critical housing shortage problem in the near future.

The construction sector is a critical contributor to the global consumption of resources and waste generation, which in turn impacts the environment and adds more pressure on natural resources⁶². To exemplify this, the building industry is responsible for over 50% of energy use and over 35% of CO₂ emissions worldwide⁶³. In Europe, the construction sector contributed to 36.4% of waste from domestic and economic activities in 2016⁶⁴. The construction phase accounts for nearly 20% of the total life cycle impacts⁶⁵. In terms of occupancy, residential buildings consist of 75% of building stocks followed by retail and office buildings where 88% of buildings are private and only 12% of buildings are public⁶⁶. The existing building stock incorporates enormous quantities of materials and stored energy in addition to contributing to communities’ character and memory⁶⁷. In addition, the difference between the public and private as well as the purpose of the construction can impact the environment due to decision making and strategy.

54 Dodman, Diep, and Colenbrander 2017; Ellen Macarthur Foundation 2017; Kepes 2017.

55 Byers 2018.

56 United Nations 2019.

57 United Nations 2018.

58 Dodman, Diep, and Colenbrander 2017; Ellen Macarthur Foundation 2017.

59 Dodman, Diep, and Colenbrander 2017.

60 Ibid.

61 United Nations 2019.

62 European Environment Agency 2010; Abd Rashid and Yusoff 2015; Ellen Macarthur Foundation 2017; Kibert 2003.

63 Abd Rashid and Yusoff 2015; Ellen Macarthur Foundation 2017; Kibert 2003.

64 Eurostat 2019.

65 Herczeg et al. 2014.

66 Ibid.

67 Šijaković and Perić 2014.

When buildings no longer meet expectations, demolition is often a course of action, adding to the construction industry’s consumption of resources and waste stream⁶⁸. Alternatively, buildings can be dismantled rather than demolished, thus collecting components and materials for recycling or reuse within new and existing buildings⁶⁹. The building’s life cycle as a whole must be considered when addressing the issue of carbon emissions, as there is energy involved in demolition, new construction, building operations and transportation⁷⁰. The life cycle analysis of a product’s process goes hand in hand with demolition for later reuse. The life cycle assessment (LCA) of materials within construction, extraction and production show many environmental effects to include climate change, acidification, eutrophication, ozone layer depletion, photochemical oxidation and human and ecosystems toxicity⁷¹. This analysis helps select appropriate current building materials for a future building’s reuse and recyclability, leading to improved resource efficiency and lowered environmental construction impacts⁷². The primary objective must be reducing the materials’ widespread use and then choose construction materials that use the lowest initial energy in its production, usage, end-of-life and recycled phase for avoiding waste⁷³. In Europe, the aim is to achieve higher recycling levels and minimise additional natural resource extraction⁷⁴.

A change in attitude towards building reuse and discard has the potential to boost material recycling rates from 10-20% to 60-70% and decrease demolition waste by 50% yearly⁷⁵. This can be achieved through recyclable building element features designed to disassemble for reuse in later renovations once a building reaches its useful lifespan⁷⁶. The disassembly process is essential since a product is completely separated into elements and/or sub-modules in a non-destructive or semi-destructive manner⁷⁷. However, each item of recyclable waste is not entirely recyclable. When all the value has been removed, some material is often leftover and sent to landfills. Despite the advances in recycling in the 21st century, landfills have continued to grow and they are still the primary disposal method in several countries⁷⁸. More than half, 53.3%, of the total generated waste is treated in recovery operations within the EU, but still 45.7% of mainly landfill disposal⁷⁹. In addition, lots of construction and demolition waste is still used for backfilling⁸⁰. Once demolition is in progress, building products may be recovered for suitable reuse in other buildings, although the possibilities in this area are limited unfortunately. Another reason is that the recycling of construction materials

68 Šijaković and Perić 2014

69 Kibert 2003.

70 Petzet and Heilmeyer 2012.

71 OECD 2020.

72 Herczeg et al. 2014.

73 Hillebrandt and Seggewies 2019.

74 European Commission Eurostat 2014.

75 Kibert 2003.

76 Ibid.

77 Lambert and Gupta 2004, vol. 19.

78 Byers 2018.

79 European Commission Eurostat 2014.

80 OECD 2020.

is inhibited as users question the material's quality and renovation cycles resilience⁸¹. Nevertheless, there is an urgent need for a change in the demolition process handling and the need to propose other solutions after a structure's final use.

Sustainable recycling can be measured by the amount of old and repurposed materials used⁸². The process works full circle by breaking down the old to create a new substance with similar properties⁸³. Increasingly more residues are being shunted out of dumps into the economy through recycling, composting and incineration with energy recovery⁸⁴. Old structural elements and construction products can be suitable for reuse, or downcycling, but not for their original purpose and possibly with some quality downgrades⁸⁵. On the other hand, many materials can be recycled, such as aluminium, steel, concrete and wood⁸⁶. Recycling consumes less energy than manufacturing something from raw materials⁸⁷. For example, steel structures can be melted down and recycled an unlimited number of times to make the same quality products and it requires just a quarter of the energy required to produce new steel⁸⁸. Steel from recycled scrap consumes 60% less energy than manufacturing from iron ore⁸⁹. Mineral materials recovered from demolitions are usually used as downcycled material in the form of aggregate. However, recycled concrete and brick is commonly separated further into material layers⁹⁰.

Compared to steel and concrete, the environmental benefits of wood are greater since it replaces materials with potentially higher carbon footprints and it has a lower energy processing consumption⁹¹. Biotic materials are better than fossil-based materials at reducing air pollution since fossil-based materials take millions of years to stock CO₂ released by burning, while biotic materials sequester the same amount of CO₂ that they release during life ends when they rot or burn⁹². For example, wood is a sustainable building resource as it stores carbon and as building elements it can be reused or recycled for future reuse to ensure that the cycle carries on⁹³. The material recovery in construction maximises economic value, minimises environmental impacts and energy waste of excavation, manufacturing and transportation, improves waste management, cuts down on depleting natural resources and reduces the cost and energy usage of landfills through reuse, repair and recycle⁹⁴. Construction improvements and

81 Hillebrandt and Seggewies 2019.

82 Šijaković and Perić 2014.

83 Hillebrandt and Seggewies 2019.

84 OECD 2020.

85 Hillebrandt and Seggewies 2019.

86 Herczeg et al. 2014.

87 Byers 2018.

88 Hillebrandt and Seggewies 2019.

89 Byers 2018.

90 Hillebrandt and Seggewies 2019.

91 Green and Taggart 2017.

92 Hillebrandt and Seggewies 2019.

93 Green and Taggart 2017; Hillebrandt and Seggewies 2019.

94 Akbarnezhad, Ong, and Chandra 2014; Ellen Macarthur Foundation 2017; Guy and Ciarimboli 2005a; Herczeg et al. 2014; Mule 2012; OECD 2020; Šijaković and Perić 2014.

operations impact 42% of world energy consumption, 35% of world GHG emissions, 50% of materials mining and can save up to 30% of water usage in some locations⁹⁵. In addition, recycling keeps some of the waste out of incinerators where carbon dioxide and nitrous oxide are released and landfills where methane is dumped. Thus, recycling reduces global warming and also saves manufacturers money; producing products from recycled materials can be cheaper than raw materials and creates jobs⁹⁶.

As a response, new buildings should maintain carbon neutrality as they typically request more energy and CO₂. This is different from retrofitting buildings, which save more energy and release less CO₂ into the atmosphere⁹⁷. So when comparing the energy efficiency of existing buildings to new ones, original construction energy consumption must also be considered because energy is involved in demolition, production, new construction, operation and mobility⁹⁸. The circular economy changes and reacts to the linear economy aiming to maximise the materials' value, decoupling growth from the consumption of finite resources, and designing out waste and pollution through restorative and regenerative methods⁹⁹. The mindset change of taking into account the energy consumption cycle of a building's life can bring environmental benefits and reduce impacts in construction and demolition waste¹⁰⁰. Therefore, any focus on sustainable housing and lifestyle must engage with the broader social, economic and environmental contexts for sustainable household practices¹⁰¹. Consider buildings from a purely material level; each one consists of either recyclable or waste materials. Whether recovered materials need to be resold later or disposed of now, this idea must be resolved during the planning phase¹⁰². Amidst climate change issues such as natural disasters, scarcity of materials, and increase of greenhouse gas emissions, many ecological concepts and terms as well as architectural discourses have emerged from ecology movements. These movements bring attention to the problems of material shortages, a growing population and overconsumption. With this in mind, the next section is an overview of this scenario.

95 European Commission 2011; Herczeg et al. 2014.

96 Byers 2018.

97 Rifkin 2011.

98 Petzet and Heilmeyer 2012.

99 Ellen Macarthur Foundation 2017; OECD 2020.

100 Ghisellini, Ripa, and Ulgiati 2018.

101 Nelson 2018b.

102 Hillebrandt and Seggewies 2019.

1.2. The ecological concepts and trends in architecture

The study of ecological architecture is essential to understand how humans interact with nature through the built environment and society's strategies. The ecological aesthetic sciences contribute to the multi-sensory awareness of the environment¹⁰³. Furthermore, concepts and terms that support environmental discourse in the architectural field eventually bring change¹⁰⁴ and potential design strategies and tools to improve building performance¹⁰⁵. This section explores the ecological concepts associated with architecture design and processes to open up discussion and brings a position in its different perspectives.

The word ecology was formulated in 1866 by Ernst Haeckel zoologist, and it is applied as the relation of the animal with both organic and inorganic environment¹⁰⁶. He also studied the structure and function of nature in synergy with organisms and their environment, including the interactions between other organisms, populations and the physical environment¹⁰⁷. By the beginning of the 19th century, attention was being paid to the conflict between population expansion and the Earth's capacity to supply food¹⁰⁸. The influences of ecology concepts in architecture can be seen after WWII. They reflected a holistic vision of the world taking into account space, form, structure and humans and then proposing architecture designs of basic landscape concepts of space, nature and energy¹⁰⁹.

On the first Earth Day in 1970, environmental activist events around the world garnered international attention and people sought out ways to eliminate or at least reduce pollution issues that were caused by copious amounts of waste¹¹⁰. Land, water and air resources are being devastated because people are not dealing responsibly with their waste¹¹¹. In addition to the waste problem, the concern with material depletion became more evident in 1970 with the peak of United States (US) oil production¹¹², which forced a dramatic price increase in 1973 in energy, products and services across the worldwide supply network¹¹³. By 1972, environmental awareness had reached a global level. The Club of Rome, an association of science and political leaders, emphasised the growing pressure on natural resources in their report *The Limits to Growth*¹¹⁴. At the same time, the UN Conference on the Human Environment in Stockholm led to

103 Demos 2017.

104 Basa 2009.

105 Cole 2012.

106 Demos 2017; Pimm and Smith 2019.

107 Pimm and Smith 2019; Scheiner and Willig 2008.

108 Pimm and Smith 2019.

109 Krufft 1994a; van Es 2016.

110 Byers 2018.

111 Ibid.

112 Colini and Eckardt 2011.

113 Rifkin 2011.

114 Donella H. Meadows et al. 1972; Colini and Eckardt 2011.

environmental agencies and the UN Environment Program¹¹⁵.

With time, the word "ecological" gained a different meaning associated with other words, and different concepts were interconnected. For example, the notions of 'sustainable,' 'green' and 'regenerative' bring qualitatively varied meanings¹¹⁶. Each ecological discourse tries to organise and adjust the architecture field based on its first aspect of concern¹¹⁷. For example, architecture can be categorised according to the different environmental topics, such as ecological architecture, sustainable architecture, green architecture, climatic architecture, organic architecture and smart architecture¹¹⁸. Clarifying these distinctions and relationships is necessary to understand how design approaches and tools may evolve in the future¹¹⁹.

The word sustainability has gained much attention nowadays and has been widely used and, therefore, it is a good start to understand the connection to architecture. The UN at Our Common Future Report (1987) defined "sustainable development" as "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"¹²⁰. This implies limits imposed by social organisation, technology and environmental resources, rational management of natural resources, biosphere's capacity to absorb the human activities impacts, and the implementation of interdisciplinary approaches¹²¹. Furthermore, sustainable development can only be achieved if population size and growth harmonise with the changes in the ecosystem¹²². Accordingly, "sustainable housing" is defined as "housing with a minimum of negative environmental impacts in terms of climate change (greenhouse effect); the quality of air, water, and soil; noise; stench; the stock of non-renewable materials; and biodiversity"¹²³. Thus, sustainability covers the continuous correlation between human and natural processes¹²⁴ and deals with the terms and conditions of human survival¹²⁵.

As the concept of sustainable architecture was still vast, the "green" trend started to appear as an attempt to have more specific strategies. Progress towards green growth can be assessed with CO₂ emissions from production and demand perspectives (footprint), decoupling achieved between GHG emissions and economic growth, and changes in atmospheric GHG concentrations¹²⁶. The "green architecture" concept can be associated with the term "green buildings" which was defined during the Kyoto Protocol international agreement (1997) as "healthy facilities designed and built in a

115 Colini and Eckardt 2011.

116 Cole 2012.

117 Basa 2009.

118 Ibid.

119 Cole 2012.

120 World Commission on Environment and Development 1987.

121 Ministère de l'Intérieur 2003a.

122 World Commission on Environment and Development 1987.

123 Priemus 2005.

124 Cole 2012.

125 Lemons 1992.

126 OECD 2017.

resource-efficient manner, using basic ecological principles,” i.e. refers to the quality and characteristics of the actual structure created using sustainable construction principles and methodologies¹²⁷. The agreement was signed to stabilise atmospheric concentrations of greenhouse gases and avoid dangerous interference with the climate¹²⁸. The performance attributes from a green building included damage reduction to natural sites during new construction, environmental damage from local and global emissions and waste, resource and energy usage as well as improved health conditions and comfort for building occupants¹²⁹. Complementarily, the term “green design” has been used to enhance the environmental efficiency of green buildings and constructions, which reduces the adverse effects of human activities on the integrity and health of ecological systems compared to typical buildings¹³⁰. Simulation tools that incorporate standards and plans are used during the design and planning phases of green buildings¹³¹. Indeed, green building success is typically described as listing the strategies and technologies used to achieve performance goals rather than illustrating how they work as part of an integrated system¹³².

To meet green sustainable concepts and trends, businesses with divergent fields are developing an array of new technologies, products and services, such as clean energies, green constructions, telecommunications, micro-generation, distributed grid IT, plug-in electric and fuel cell transport, sustainable chemistry, nanotechnology, zero-carbon logistics, and supply-chain management, etc.¹³³ In the middle of these changes, the term “Third Industrial Revolution” emerged in 2007 as an economic vision for the EU that emphasised the shift to renewable energy to be collected locally as a dual-purpose building habitat and micropower plant and then stored and shared with others through collaborative intelligent energy networks¹³⁴. With renewable energy generation, “green energy” and “energy efficiency” terms started to be applied. “Green energy” utilises the means of renewable energy production through wind, solar, water, biomass, geothermal technology and so on¹³⁵. The “Energy efficiency” can be seen as renewable energy generation or grid modernisation that develops smart battery technology¹³⁶. It improves the supply by reducing primary energy consumption and decreasing energy imports, thus reducing greenhouse gas emissions and cost-effectively mitigating climate change¹³⁷. The energy efficiency of buildings is also related to the user’s demand and human comfort level due to its high electricity consumption¹³⁸. That is why there is a search for building technologies that consume and produce less energy. When buildings

127 Kibert 2016.

128 Ibid.; UNFCCC 2008.

129 Cole 2012.

130 Ibid.; McDonough and Braungart 2010; Reed 2007.

131 Bauer, Möhle, and Schwarz 2010.

132 Cole 2012.

133 Rifkin 2011.

134 Ibid.

135 Ibid.

136 Ibid.

137 European Commission 2012.

138 Bauer, Möhle, and Schwarz 2010.

produce enough renewable energy for their own needs and then can generate even extra energy, they are called “positive power”¹³⁹ or “positive energy building.” However, the current green building tools that encourage an individual building’s performance do not deliver design solutions that enhance the physical, ecological and social contexts¹⁴⁰.

Similar to technological advancement, the strategy and tools that improve a building’s sustainability often focuses on its materiality. The carbon footprint is one of the indicators of sustainability that calculates environmental impacts of a particular product, company or organisation¹⁴¹. The carbon footprint represents a quantity of gas emissions relevant to climate change and related to human consumption or production activities rooted in the Ecological Footprint¹⁴². The urban carbon footprint calculation focuses on the emissions from processes that take place within the city limits¹⁴³. For example, focusing on the economic and ecological impacts of consumer goods, “cradle to cradle” originated in 2002 from the product design sector, integrating design and science of materials, water and energy in circular economies trying to remove the waste concept¹⁴⁴.

The world has experienced a new fusion among communication media, construction and energy frame. Renewable energies, green and sustainable strategies integrated with media, and intelligent technology have been deployed across the city, leading to the emergence of the “smart city.” A smart city has a good grip on performance, coordination and monitoring of its economy, governance, people, mobility, health and education programs, and environment. These aspects are built on the combination of intelligent computing technologies that make activities, services and infrastructure more innovative, interconnected and efficient as well as an awareness of social and urban growth¹⁴⁵. The smart city concept is dependent on the effective use of communication, electronic development and information technologies that increase hybridisation with the physical world¹⁴⁶. Developing a smart city with a technological approach promotes the urban life quality and sustainable development merge through better resource management and collection in addition to collaborative effort based on a holistic interpretation¹⁴⁷.

Up to this point, it can be seen that the environmental architecture aspects and economy have been driven by technology and energy improvements and not by architectural design. Whereas architects integrated passive design strategies, plants and terraces in the projects, as an attempt to reach the so-called green and sustainable buildings, the engineers were focused on technologies, materials and energy efficiency. However, both did not consider the design project as a whole or the overall impact on the environment. The environmental performance assessment of buildings relies on a

139 Rifkin 2011.

140 Cole 2012.

141 Pertsova 2007; Zubelzu and Álvarez Fernández 2016.

142 Pertsova 2007.

143 Rifkin 2011.

144 McDonough and Braungart 2010.

145 Ben Letaifa 2015; Hollands 2008; Rudolf Giffinger et al. 2007; Washburn and Sindhu 2010.

146 Picon 2015.

147 Deakin and Mora 2019; Picon 2015.

series of isolated design gestures rather than encouraging creative synergies, closing loops and responding appropriately to local ecological and social contexts¹⁴⁸. The green building evaluative tools can bolster regenerative design but require a qualitatively different design structure¹⁴⁹. When all the previous concepts and trends did not work separately, a new way of thinking and integration became necessary. The emergence and use of integrative design methods have more recently occurred and there is a more cooperative professional exchange between the members of the design team.

The circular economy has opened the way and holds promise for a restorative and regenerative design production and consumption model¹⁵⁰. The circular economy involves the built environment, i.e. cities, to increase people's quality of life and reduce the use of virgin material by shared, flexible and modular spaces¹⁵¹. The main challenge is improving resource efficiency at all the material life cycle phases, to include waste management and prevention¹⁵². Four Strategies for conserving resources and avoiding waste can be pursued in order to achieve a real circular economy system: avoid waste, reuse, recycle and downcycle to a limited extent¹⁵³. Rooted in the same concept, the environmental movement's international slogan "Reduce/Reuse/Recycle" (3Rs) incorporates the waste hierarchy, classifying and evaluating methods according to energy consumption and loss¹⁵⁴. Reduce aims to avoid and minimise waste, reuse re-evaluates an object's original purpose and recycle processes material to create a new product¹⁵⁵. Further recovery refers to both reuse and recycling¹⁵⁶. In architecture, the 3Rs create a possible hierarchy of strategies with fewer interventions and less energy expended, from demounting newly built extensions and converting disposed material into valuable material to merely extending, adapting and continuing what is already there¹⁵⁷. The thinking is that the building can be demountable, which is the term "design for disassembly" (DfD) that emerged in the early 1990s¹⁵⁸ and refers to design principles that ensure and facilitate building a component's reuse and recycle¹⁵⁹. It must be considered at the design stage to be effective¹⁶⁰. The DfD reduces the physical interdependence and increases the simplification of systems through material consumption, cost and waste reduction in the construction, renovation and demolition phase. Moreover, it extends buildings' service life and supports the material banks for the future¹⁶¹. Existing cities' infrastructures and buildings should be seen as a crucial

148 Cole 2012.

149 Ibid.

150 Ellen Macarthur Foundation 2017.

151 Ibid.

152 OECD 2020.

153 Hillebrandt and Seggewies 2019.

154 Byers 2018; Petzet and Heilmeyer 2012.

155 Lambert and Gupta 2004, vol. 19; Petzet and Heilmeyer 2012.

156 Lambert and Gupta 2004, vol. 19.

157 Petzet and Heilmeyer 2012.

158 Kibert 2003.

159 Jaillon and Poon 2014.

160 Kibert 2003.

161 Guy and Ciarimboli 2005a; Heinlein and Sobek 2019a.

social and architectural resource for shaping the future¹⁶².

To conclude, although the terms and concepts simplified the problematic environmental situation, they also helped understand the priorities and general ideas. While ecological sustainability emphasises the importance of the resilience of natural systems by maintaining their functions, processes and biodiversity, technological sustainability on the other hand emphasises technical and engineering efficiencies that encompass green building practices¹⁶³. Waste reduction, recycling, burning for energy recovery and landfill are all part of the solution¹⁶⁴. The notion of "sustainability" is a more suitable informative strategic approach to planning and redesigning the built environment¹⁶⁵. Thus, a building can support sustainable living patterns but in and of itself cannot be sustainable¹⁶⁶. The environmental and ecological qualities must be combined with aspects that respond to the market, flexibility, affordability and technical reliability demands¹⁶⁷.

Architects and engineers, as seen before, are reworking, restructuring, reusing or updating existing buildings. Repeatedly, it is assumed that, for a building to be sustainable, it was necessary to add technology once the project was complete, making it more expensive and less effective over its lifetime. However, to have sustainable architecture, more attention should be paid to the first architectural design stage, which is where innovations need to occur. This means we need to completely rethink how the process is carried out. In addition, the architectural design process should integrate solutions and strategies to bring comfort to the occupants, use fewer resources in construction, use recycled materials, reduce the carbon footprint and propose new reuse for most if not all materials and components once the building life cycle reaches the end. The technology should always be present from the beginning to map and monitor all the processes from design, construction, local energy production, occupancy and structure disassembly for future reuse. Thus, through the proposal of reusable and recyclable architecture, this research brings attention to the design phase and incorporates the circular economy, reusable concepts and technology. In the context of ecological and sustainable construction, the European research multidisciplinary project ECON4SD emerged and was developed from 2017 to 2022.

162 Petzet and Heilmeyer 2012.

163 Cole 2012.

164 EPA 1988.

165 Cole 2012.

166 Gibberd 2003.

167 Priemus 2005.

1.3. Eco-Construction for Sustainable Development (ECON4SD)

The traditional way of how architects and engineers design and build separately can no longer be followed if we want to be a part of the change and reduce waste and time¹⁶⁸. In this scenario of seeking change, the multidisciplinary project ECON4SD was created. The ECON4SD is a research project co-funded by the EU in partnership with the University of Luxembourg. This project aimed to improve the components and design models for energy and resource efficient buildings as well as enhance sustainable construction concepts based on concrete, steel and timber¹⁶⁹. Furthermore, the multidisciplinary team of architects and engineers from the University of Luxembourg developed alternative housing models, entirely recyclable from a material bank inventory, to address ecological-social issues. In addition, unique prefabricated structural components were developed within the project that allows for demolition-free, disassembly and reassembly in response to changing structural requirements, revitalisation and removal.

The project focuses on adaptability, flexibility and modularity with detachable connections for architectural buildings. These components should be easy to maintain, repair, remove and reuse. The aspects of structural elements and ageing material in a building's service life were considered. The initial goal was to reduce the energy and resources used over the whole life cycle by showing ways to use buildings as sources of materials and components. This project tries to incite a paradigm shift in the construction sector.

The team comprised six doctoral candidates, a postdoc and professors from the school of civil engineering and architecture divided into seven working packages (WP): architecture WP1, structure in steel and concrete WP2, structure in timber and concrete WP3, concrete ageing WP4, energy consumption WP5, BIM WP6 and material bank WP7. Figure 1.1 shows the WPs and the professor responsible for each one. Bringing attention to this thesis connection, Marielle Ferreira Silva and Prof. Florian Hertweck were responsible for designing generic alternative models for the ecological transition by investigating the reusability and recyclability of architecture. Thus, three architectural prototypes were developed in coordination with the adjacent engineering fields: Prototype 1 - Slab typology, Prototype 2 - Tower typology and Prototype 3 - Block typology. The design process and details are presented in Chapter 3 - Protocol. Workshops were organised to bring the group together to discuss all the matters of the project and the feasibility of the proposed typologies, with plans, drawings, 3D models and results.

Based on the prototypical design sketches, engineers from WP2, WP3 and WP7 analysed their viability and proposed steel, concrete and timber structures accordingly. WP5 explored the energy efficiency of those typologies and strategies for its improvement and the life cycle assessments for the Prototype 1 Slab typology. At the same time, the concrete age for the Slab typology structure was also analysed by WP4. The WP6

168 Pelsmakers and Newman 2021. editors Sofie Pelsmakers (author of Environmental Design Sourcebook

169 Ferreira Silva et al. 2020.

developed a 3D model for the Slab typology and explained how BIM could support the life cycle assessment and metric analyses for the demountable structure. Finally, the WP7 was responsible for bringing everyone together to discuss and address any difficulties, including developing the project's material bank.

The cooperation with external researchers and companies from the construction sector stimulated national research and innovation capacity through interdisciplinary, inter-sectoral and international partnerships. Since the project was based in Luxembourg, research was conducted in order to understand Luxembourg society's challenges and how ECON4SD concepts could be applied. In addition, since Luxembourg is situated in Central Europe, there were concerns about the future in terms of climate change and sustainable strategies.

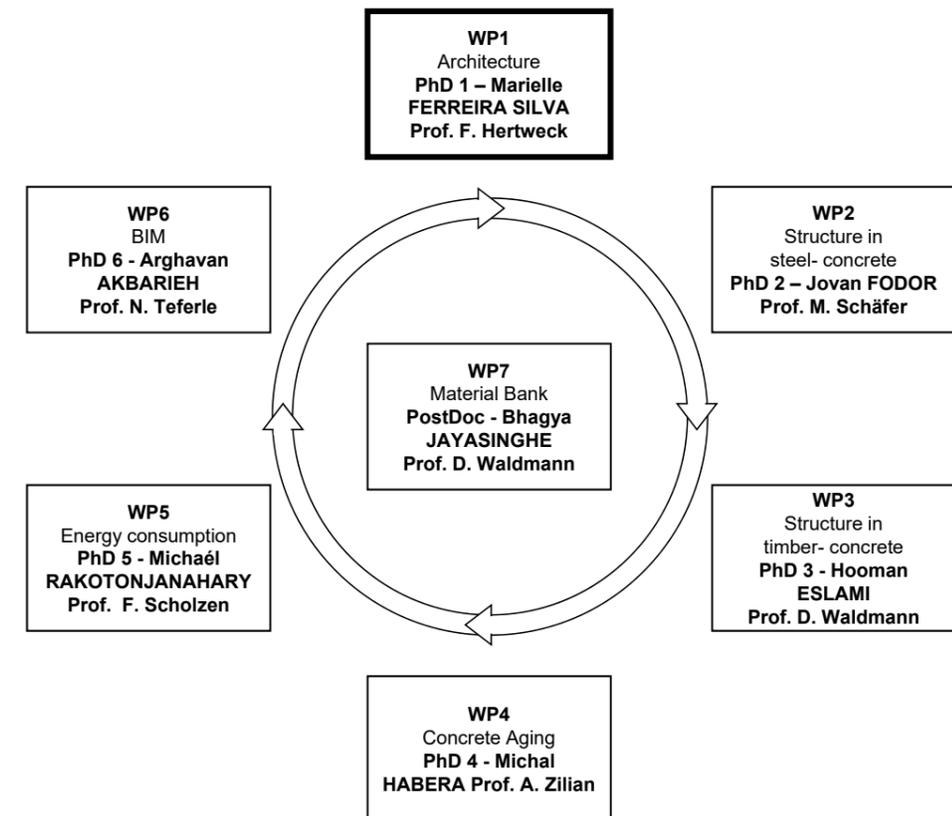


Figure 1.1: ECON4SD Project structure

1.4. The challenges of Luxembourg society

Over the last decades, Luxembourg has experienced exponential economic growth, impacting the construction sector and resource consumption. Luxembourg is situated in Central Europe, bordered by France, Germany and Belgium. As one of Europe's most important financial centres and home to several EU institutions, the country is experiencing exceptional demographic growth compared to other EU member states¹⁷⁰. Luxembourg follows the population growth trends globally, continuously experiencing an average annual growth rate of 2.34% between 2010 and 2017¹⁷¹ compared to the annual EU population growth of 0.1%¹⁷². Between 1981 and 2018, the population of Grand Duchy of Luxembourg increased from 364 597 to 602 005 inhabitants¹⁷³. This considerable growth has been concentrated mainly in the last thirty years¹⁷⁴. It is estimated that Luxembourg's population will reach 675 000 in 2030, 796 000 in 2050 and 1 million in 2100¹⁷⁵. Population growth allows building and expanding a new generation of efficient buildings, infrastructure and neighbourhoods to reduce marginal costs and ecological footprint¹⁷⁶.

Migratory balance is crucial in Luxembourg's population growth, distinguished by an unusually high proportion of foreigners¹⁷⁷. Between 2013 and 2018, the Luxembourg population increased per year, 2,130 people due to natural balance and 10,863 people between immigration and emigration¹⁷⁸. In 2018, 47.9% of the Luxembourg population was from 170 nationalities and only 52.1% were Luxembourgish. With 96,544 people, the Portuguese community is the largest foreign community in Luxembourg, followed by French (45,822) and Italian (21,962) communities¹⁷⁹. Continued immigration determines the population growth¹⁸⁰.

In Luxembourg, the population structure remains relatively young, mainly due to the working age of the immigrant population (~37 years old), which is "rejuvenating" the Luxembourg population (~41.6 years old) compared to that of the ageing EU and neighbouring countries¹⁸¹. From 1985 to 2001, the number of employees rose from 142,100 to 262,600. Simultaneously, the number of cross-border commuters from Belgium, France and Germany quadrupled from 16,100 to 98,800, and their share of salaried employment rose from 11.3% to 37.7%¹⁸². The cross-border occurrence is

170 STATEC 2019.

171 +ImpaKT 2021; Aménagement du territoire 2018.

172 Third Industrial Revolution Consulting Group LLC 2016.

173 STATEC 2019.

174 Ibid.

175 UN 2017, vol. 136.

176 Third Industrial Revolution Consulting Group LLC 2016.

177 STATEC 2019.

178 Ibid.

179 Ibid.

180 Ministère de l'Intérieur 2003b.

181 STATEC 2019.

182 Ministère de l'Intérieur 2003b.

attributed to the Luxembourg economy's attractiveness, which offers double the jobs in relation to the resident workforce¹⁸³. Consequently, since the beginning of the 1990s, the foreign presence (active residents and cross-border workers combined) on the Luxembourg labour market has exceeded 50%¹⁸⁴. This phenomenon affects transit where 40% of the commuters work in Luxembourg City and arrive in the Grand Duchy mainly by car, but also by train and bus¹⁸⁵.

In Luxembourg, the housing demand will remain high due to the continued population growth, traditional family break-up and changes in the housing structure¹⁸⁶. As the population of Luxembourg is expected to increase substantially by 2050, new residential buildings are needed in the country to provide a vast opportunity for sustainable building stock transition¹⁸⁷. The housing market is a complex system driven by the interaction of supply and free demand in which government intervention has focused on the regulation of land use sectors¹⁸⁸. Single-family homes, the most space-consuming construction, and homeownership dominate the housing market, supported by the housing policy in Luxembourg. This situation causes spatial and social segregation¹⁸⁹. The Grand Duchy of Luxembourg residential buildings in 2015, 82.9% were single-family houses, 10.9% were apartment buildings and 6.1% were semi-detached buildings¹⁹⁰. In 2016, apartments comprised 69.3% of residential buildings constructed¹⁹¹. The number of apartments in residential or semi-residential buildings has increased from 6 units in the 1980s to 9 units in 2016¹⁹². The average living area of a single-family house tended to increase over time from 181 m² (2007) to 195.6 m² (2016). Opposite to that, apartments decreased to 80.1 m² from 93.4 m². In 2016, the average residential area (including non-habitable areas) was 281 m² for single-family houses and 126 m² for apartments. The distribution of dwellings shows that approximately 30% of single-family housing have more than 7 rooms, while 56.4% of the apartments consist of a maximum of 3 rooms¹⁹³. The selling price per m² of an apartment mainly depends on the type of apartment, its surface and its location. In 2019, housing prices rose by 11% a year and on average an apartment under construction was between 15% and 20% more expensive than an existing apartment of comparable size. In 2019, the average price per m² of existing apartments was €6,057/m², and apartments under construction were €7,145/m². The average price of a single-family house was €789,474¹⁹⁴. In the private sector, projects are often designed to maximise the use of land with low ceiling height and load-bearing walls, which reduces future adaptive reuse and flexibilities in internal

183 Third Industrial Revolution Consulting Group LLC 2016.

184 Ministère de l'Intérieur 2003b.

185 Third Industrial Revolution Consulting Group LLC 2016.

186 Ministère de l'Intérieur 2003b.

187 Third Industrial Revolution Consulting Group LLC 2016.

188 Ministère de l'Intérieur 2003b.

189 Ibid.

190 Ferring, Peltier, and Licheron 2020; François Peltier 2015.

191 François Peltier 2019a.

192 Ibid.

193 Ibid.

194 Ferring, Peltier, and Licheron 2020.

layout options¹⁹⁵.

Once buildings do not accommodate the current requirement, they start to be demolished. In the majority of the cases, the renovation of old buildings can have a higher cost than demolition¹⁹⁶. Buildings built before 1945 in Luxembourg are the most commonly demolished, 69.1% of total buildings demolished¹⁹⁷. In 2016, 75% of the waste generated in Luxembourg was from construction and demolition, 61% of it was treated recovery and the 39% remaining was disposed of mainly in landfills¹⁹⁸. When these numbers are compared to the European Union, Luxembourg generated almost 39% more waste but also recovered 7.7% more.

Building construction, house offers and life circumstances are directly connected to land issues and determine the organisation and planning of territory. The consequences of population growth decide demographic projections, territorial development and rational management of space¹⁹⁹, impacting land consumption and artificialise²⁰⁰. The demographic and economic growth, the extension of urban structures, and the road infrastructure have resulted in a considerable increase in Luxembourg's urbanised areas. Natural spaces and structures on the periphery of large conurbations are the most affected by urban growth²⁰¹. The highest population concentrations and commuters working in the agglomeration are found in the municipalities that compose of the three major urban centres, Luxembourg city, the former mining area in the south and southwest (Esch-sur-Alzette, Differdange and Dudelange) and municipalities in the north named as Nordstad (Bettendorf, Diekirch, Erpeldange-sur-Sûre, Ettelbruck, Schieren and Colmar-Berg)²⁰². Private and shared land and soil resources are essential components of the economy and ecosystems' natural asset base. The market value of the land varies according to location, demand and abundance. Many land demands and the desire to maximise market value lead to relative scarcity and increase the land price²⁰³. In Luxembourg in 2016, 72.5% of the total area available for housing was held by individuals, 14.9% by private companies, 11% by public entities and 1.6% by other types of legal entities²⁰⁴. The average sale price of lots located in residential or mixed-use areas was approximately 58,312 €/hectare between 2010 and 2017²⁰⁵. The residential land prices for construction increased on average 6.1% per year between 2010 and 2017²⁰⁶. The land occupation and city expansion did not consider the land's ecological value, leading to the irreversible destruction of natural spaces, deforestation and loss of habitat by increasing the exploitation of natural resources, urban expansion,

195 Jaillon and Poon 2014.

196 Third Industrial Revolution Consulting Group LLC 2016.

197 Ibid.

198 European Commission Eurostat 2014.

199 Ministère de l'Intérieur 2003b.

200 +ImpaKT 2021.

201 Ministère de l'Intérieur 2003b.

202 STATEC 2019.

203 OECD 2017.

204 Paccoud 2019.

205 Licheron 2019.

206 Ibid.

agricultural lands and transportation infrastructure²⁰⁷. The main challenge is to balance the economic, social and environmental objectives focusing land development away from greenfield and biodiversity-sensitive locations²⁰⁸. Furthermore, the concept of ownership can be transformed to give more access to social networks and common shared spaces with others.

Analysing the context in Luxembourg, the two major problems for the housing sector are the inadequacy of the spatial dynamics and the mismatch between supply and demand of the number and size of dwellings²⁰⁹, leading to a yearly steady 4.5 % rise in housing price²¹⁰. These problems are linked to Luxembourg's demographic changes over the past 30 years and will probably continue to increase²¹¹. The City of Luxembourg and the Southern municipalities have absorbed a large part of the population growth. In addition, artificialisation is developing throughout the territory and contributes to more significant natural and agricultural environment fragmentation. Luxembourg has also been experiencing a reduction in the households' average size²¹². These factors have thus contributed to an increased demand for housing that the market has not been able to satisfy, leading to increased land and housing prices. By 2060, the potential demand for housing would vary from 243,000 to 324,000 units. Luxembourg would, therefore, need 5,600 to 7,500 more houses per year depending on the scenario²¹³. Therefore, it is urgent to reduce the housing shortage while offering more low-cost and low-rent housing to avoid people paying the exorbitant prices demanded by the current housing market. In general, urban density should not be associated with a necessary evil, but instead opportunities, such as close access to facilities, more social interaction and a better supply of services. However, a shift to a more parsimonious land use requires a change in the model of a large house in the middle of it.

At the governmental level and in a broader vision for the future, in June 2018 the EU Member States, the European Parliament and the European Commission made a political agreement envision 2030. This agreement aimed for a 40% reduction in greenhouse gases (GHG), a 32% of renewables energies production, a 32.5% for energy efficiency and a review clause for an increase in the percentages in 2023. More specifically, Luxembourg aims to reduce GHG emissions from industries by 55% by 2030 compared to the emissions released in 2005²¹⁴. Furthermore, Luxembourg's vision proposes the expansion of the digital economy and the use of Big Data and algorithms to aggregate efficiency and productivity in order to reduce the ecological footprint and cost of production and the distribution of goods and services to make the economy more attractive and competitive in an emerging low-carbon world²¹⁵. The construction sector aims for a cradle-to-grave approach without waste generation by

207 Ministère de l'Intérieur 2003b; OECD 2017.

208 OECD 2017.

209 Aménagement du territoire 2018; Ferring, Peltier, and Licheron 2020; Licheron 2019.

210 Ferring, Peltier, and Licheron 2020; Licheron 2019.

211 Aménagement du territoire 2018.

212 Ibid.

213 François Peltier 2019b.

214 Governance of the Energy Union and Climate Action 2019.

215 Third Industrial Revolution Consulting Group LLC 2016.

integrating smart and green concepts. These concepts would aim to create a flexible design with a zero energy construct that serves multiple functions in an optimal, shared and attractive district filled with lively public spaces, art and culture²¹⁶.

To summarise, the construction market growth is driven by the increased need for office space due to augmented workforce. The housing stock is not very diversified and specified sector needs have yet to be developed. Certain household categories that do not want to settle permanently in Luxembourg prefer to rent accommodation which increases rent prices. The inflation in rent and land market prices have made new construction expensive and difficult to access adequate housing. Therefore, the subsidised housing market will have to be further developed and explicitly oriented for the rental sector. The lease should no longer be exclusive to meet the needs of low-income families, but also for other categories of the population with limited financial resources, such as young families at the beginning of their professional career and the elderly who do not wish to have their own home or prefer to rent properties. The lease should also be favourable to specific temporary population due to residents' renewal. In addition, buildings are often demolished due to conversion or architectural alteration and not structural decay. These structures are almost intact and undamaged and demolition of these properties lead to large amounts of landfill waste. As a result, the construction sector generates substantial CO₂ emissions, resource consumption and waste.

The challenge for Luxembourg is the question of space and affordable accommodation for future generations while also integrating immigrants and reducing the production of waste and exploitation of raw natural materials. These challenges are not only faced in Luxembourg but also by other countries. Given the construction sector's high resource intake and high CO₂ emissions, a sustainable building with cutting-edge concepts would have a tremendous impact on the economy and prepare Luxembourg's society for a population increase. The design of cities and towns will need to follow a different path in order to reduce space consumption, increase density for the growing population and take into account the specific regional context²¹⁷.

216 Third Industrial Revolution Consulting Group LLC 2016.

217 Ministère de l'Intérieur 2003a.

1.5. The research questions, aims and significance

There are many aspects that can impact the physical world that should be considered to protect nature and sustain future generations. The first aspect is population growth and how it affects country population growth and dispersal. The second aspect is the resource and finite material problem. There is a need to find new materials and reduce or even eliminate material exploitation. The third aspect is the material waste used just once and disposed of in landfills. The fourth aspect is the gas emissions into the atmosphere. CO₂ emission is a result of every activity and the balance at finding a way to reduce, consume and have zero emissions needs to be considered. If not treated significantly, these four aspects can lead to pollution and climate change that leads to global temperature rise and destroys nature within the ecosystem. Each of these aspects are influenced by the other in a complex relation. Therefore, it is hard to choose the most important aspect to act on, but there must be a best practice approach to propose solutions that target as many features as possible.

Within the architectural field, the problem is that architecture has not been designed to meet the users' future needs as well as reduce the environmental impacts that result from population growth and limited resources. Generally, architects and builders are solely focused on building refurbishments that reduce material cost and create permanent fixtures without provisions for future disassembly²¹⁸. Consequently, buildings and their components have not historically been designed to be recycled or reused, much less disassembled²¹⁹. A change is needed in architectural design thinking. Just as existing buildings must be renovated and building materials need to be recycled or reused, new buildings must be designed to anticipate future changes, reusable, recyclable and even transposable to other places. As a result, architects should design and construct buildings forecasting that other architects and users will remodel them, reinterpret them and use them for different purposes. This brings this thesis to the main research question of "What kind of building design and typology allows architectural cycles?" Subsequently, climate change, the shortage of resources and housing space as well as the social mutations that the world and Luxembourg are confronted with pushes one to rethink the house manufacturing process. Ultimately, this raises relevant questions such as the following: "How to reduce living space while offering shared and generous spaces?" "How to reduce the footprint while increasing density?" "How to design a more collective housing building prefabricated without compromising architectural quality?" "What happens when buildings come to the end of their useful life cycle?" "Can there be a way to design a building from the beginning without generating waste at the end of its use?" and "Can buildings be designed for their future reuse and recycling?" Considering all these questions, it is crucial to develop innovative concepts that have a better understanding of available resources and promote new eco-design and flexible building lifecycle approaches.

For this reason, the main objective of this thesis is to study the potential architecture that reconfigures, spatially and temporally, and produces alternative generic models that

218 Chini 2005.

219 Kibert 2003.

reuse and recycle architectural elements and spaces for functional flexibility through time. As the population increases, the need for more housing becomes a bigger issue and the housing shortage becomes even more critical. Moreover, buildings need to be built to accommodate future generations. Modular, prefabricated and ecological architectural projects were examined and new architectural typologies proposed focused on recyclability and reusability aligned with current environmental and social challenges. The architectural projects emphasised the profession's responsibilities towards global environmental requirements. The prototypes combine architecture with science, technology, nature and ecology. To change how buildings are constructed, there is a need to go back to the beginning of an architecture's conception and develop it differently. The design process considered the material and space's final usage and how they could be reused as much as possible before the materials go to recycling. From the beginning, the typologies were designed to allow the entire building's reusability, dismantling and recycling. After the first building lifecycle, the components can be reused in another place, depending on their necessity. A lifecycle analysis was proposed to validate the typologies throughout the material and space usability.

This thesis is significant as there is a high interest in producing new recyclable materials, waste management processes and more energy-efficient methods. However, in order to achieve a zero-carbon or green building goal, the design process and the construction milestones are sectioned into design, materials, technology, economy and punctual strategies. Thus, recyclable architecture is the solution for sticking everything together for targeting global population growth, technology integration and high quality living. Furthermore, architecture can be in close alliance with politics, industry and the sciences, thereby helping develop strategies to avert issues such as climate change and the exploitation of natural resources. Despite different ideologies, the concept of recyclable architecture has remained essential to architectural evolution for many academics and practitioners of the field. As such, this research contributes to the current knowledge by providing an insight into prefabrication, modular and ecological typologies and leading towards circular architecture²²⁰. Furthermore, the provided solutions achieve a circular architecture process and intend to serve as an inspiration and model for other construction projects. This helps the architect, design and construction industry in decision-making²²¹.

Consequently, this research presents new architectural typologies that offer solutions to reduce natural resources and construction waste while adapting to social needs. The development of prototypes offered the possibilities to test different solutions towards a better one and understand the limitations of the projects and the importance of choices made in the design stage. This includes material choices and combinations, 2D or 3D aesthetics, the functionality of spaces and elements, and how easily they can be reused, disassembled or recycled. It also includes the way designs will interact with people along their journey. Applied at the early stage of the design process, disassembly concepts and prefabricated and modular systems address the housing shortage while discussing recyclable architectural concepts. Implementing deconstruction and flexible concepts in the design phase is the beginning of a sustainable strategy for the built

220 Ferreira Silva et al. 2020.

221 Silva 2020.

environment.

The innovation is given by the combination of different strategies from previous projects and concepts in prototypes and displayed recyclable and reusable architecture. The new influential typologies, both conceptual and physical, contain essential aspects of new human perspectives. The more flexible the constructions are, the more interconnected people will be to the environment and internal capacities. The generic architectural prototypes presented in Chapter 3 were developed during this research and respond to the problems in Luxembourg that also affect the wider world. They can be adapted to other cities' and regions' regulations and users, keeping the same typology for new shared and public construction needs while adapting to changing social and environmental climates. For example, the typologies' height can be changed by adding or reducing floors. The Slab, Tower and Block prototypes and concepts are intended to serve as a guideline for other building projects. It may help architects, designers, decision-makers, policymakers, clients, developers and the construction industry better understand recyclable architecture and adopt appropriate strategies to overcome the identified challenges. This proposal is part of the solution to face global warming and can reduce the consumption of natural resources and CO₂ emissions. Designing a building that can be disassembled can make a difference to the construction waste's volume and impact on the environment. From the urban design point of view, new recyclable prototypes can change the city, piece by piece and transform the scenario in the future by giving a new city perspective.

1.6. Research frame and methodology

This study approaches architecture as a complex product consisting of built form, innovation, written and visual expression. It is thus based on a wide range of sources, built architectural projects, professional journals, popular magazines, newspapers, books, laws and regional planning and regulation. The thesis was separated into three main chapters, deliverables and conclusions.

Chapter one: Introduction. This chapter brings a literature review and an overview of the entire research. A systematic literature review is a structured procedure for identifying the relevant sources and build a comprehensive overview of the literature published answering a specific research question²²². Based on the topic, ECON4SD project proposition and research questions, relevant keywords were identified. Section 1.1 is a global collection of resource problems and the concerns about climate change. Section 1.2 presents the trendy terms and concepts linked to the environment nowadays and build the knowledge basis that this research is built upon. Section 1.3 shows the relation between the thesis and the ECON4SD project. In Section 1.4, since the project and the research were based in the Grand Duchy of Luxembourg, a survey was done to understand the country's challenges. Finally, in Section 1.5 and 1.6, the main research question is formulated, its objectives and relevance are discussed and the specifics of how the study was conducted and its methodology are presented.

Chapter two: Atlas. This chapter presents modular, prefabricated and ecological architectural projects through documentary research. In order to establish a starting point, the view of eminent people in the field on the topic at hand is examined²²³. Modular and prefabricated architecture is not new, and the aspects of history in which it was most relevant often reflect today's circumstances²²⁴. Architects, engineers and contractors need to improve their understanding of prefabrication and pragmatics to develop and implement these architectural production methods²²⁵. In architecture, invention and new ideas are stimulated and grow when building designs are exposed and compared to existing buildings with a similar programme and functions and site conditions. In the present study, the analogous building becomes a model for discussion²²⁶. Thus, a documentary research methodology was applied to create a narrative from the literature reviews on modular, prefabricated and ecological buildings to approach recyclable buildings on architecture and construction journals, books, newspapers, reports and websites. From Durant to the 21st century, the hypothesis was to analyse modularity and prefabrication's contribution to developing a consistent perception of contemporary housing reusable design, spatial organisation, dimensions and construction. Drawings and project documentation were collected and an atlas emerged from the literature review and organised into the three main topics of modularity, prefabrication and ecology. Representatives' example of housing units' typologies was

222 Potrč Obrecht et al. 2020.

223 Hensel 2012.

224 Ferreira Silva et al. 2020.

225 Smith and Timberlake 2010.

226 Sherwood 1979.

selected to study in-depth and analyse the dimensions, grid, layout and materials. Building case studies were selected because of their importance as prototypes that set the standards and patterns of what was and is to follow. Other considerations were diversity and architectural quality so that a wide range of building types and problems would be represented²²⁷. Without design determinants, an analogous reference, or the study and adaptation of a similar solution or problem, can give a new design vision and be used as a simulation technique to clarify the problem²²⁸. As a reference to learn from, the better solution, principles and applications of construction and systems were examined, translated and combined to develop new typologies.

Chapter three: Protocol. This chapter presents three new alternative generic prototypes to address the housing shortage and ecological problems – Slab, Tower and Demountable typologies. They were developed through research and design methodology, as part of the ECON4SD experimentation project, with architects and engineers from the University of Luxembourg over five years to answer the main question of this research. The use of a prototype was essential for the process of discovery and invention related to problem-solving²²⁹. Prototypes have crucial roles within the design thinking process. They unite the process and can be interpreted as a creative, systematic and collaborative approach to identifying and creating hypotheses that solve problems and map the needs to concepts and ideas²³⁰. The prototypes combined several aspects from the projects within the Atlas. The design methodology proposed and used a prototype to encourage prefabricated methods in residential buildings, improving strategies and design for reusability. As part of the study, drawings, plans and 3D models were developed, tested and analysed in the ECON4SD workshops. After each presentation and proper feedback, better propositions emerged and new solutions were tested to improve a better final version of each typology. Section 3.1 presents the design principles that guided the process. They were developed according to the circular economy principles to produce socio-ecological, climate-adapted and sustainable housing by limiting the consumption of resources and the production of waste during their life cycle. Section 3.2 presents Prototype 1 the Slab typology, a building designed as a concrete shelf structure in which timber housing units can be plugged in and out. Section 3.3 presents Prototype 2 the Tower typology, a tower building with a flexible floor plan combining working and residential facilities with adjacent multi-purpose facilities. Section 3.4 presents Prototype 3 the Block typology, a structure characterised by the entire disassembly. The Block architectural typology, as it is the most integrative design, was analysed using quantitative methodology through a Life Cycle Assessment (LCA). LCA's methodology evaluates the impacts of a product, process or service on the environment throughout its lifecycle, taking inventory of material resources, energy inputs and environmental issues through a cradle-to-grave approach²³¹. Section 3.5 explains the interaction of the ECON4SD project among the architecture WP and other WPs in the design process. Finally, Section 3.6 presents the

227 Sherwood 1979.

228 Ibid.

229 Ibid.

230 Griffin et al. 2015.

231 Valero Delgado 2014.

final discussion and valuable findings.

At the end of this thesis, the deliverables show the events, conferences, projects and exhibitions that this research was presented at and a part of. The conclusion reflects the entire trajectory of this research to include the limitations and future continuity. The research development was complex and non-linear. Learning throughout the entire process, the Atlas and Protocol were reviewed and refined in order to find the best existing solution that improves the prototypes' design. Figure 1.2 presents the methodology diagram and the interaction between the documentary research and research by design as a circular study.

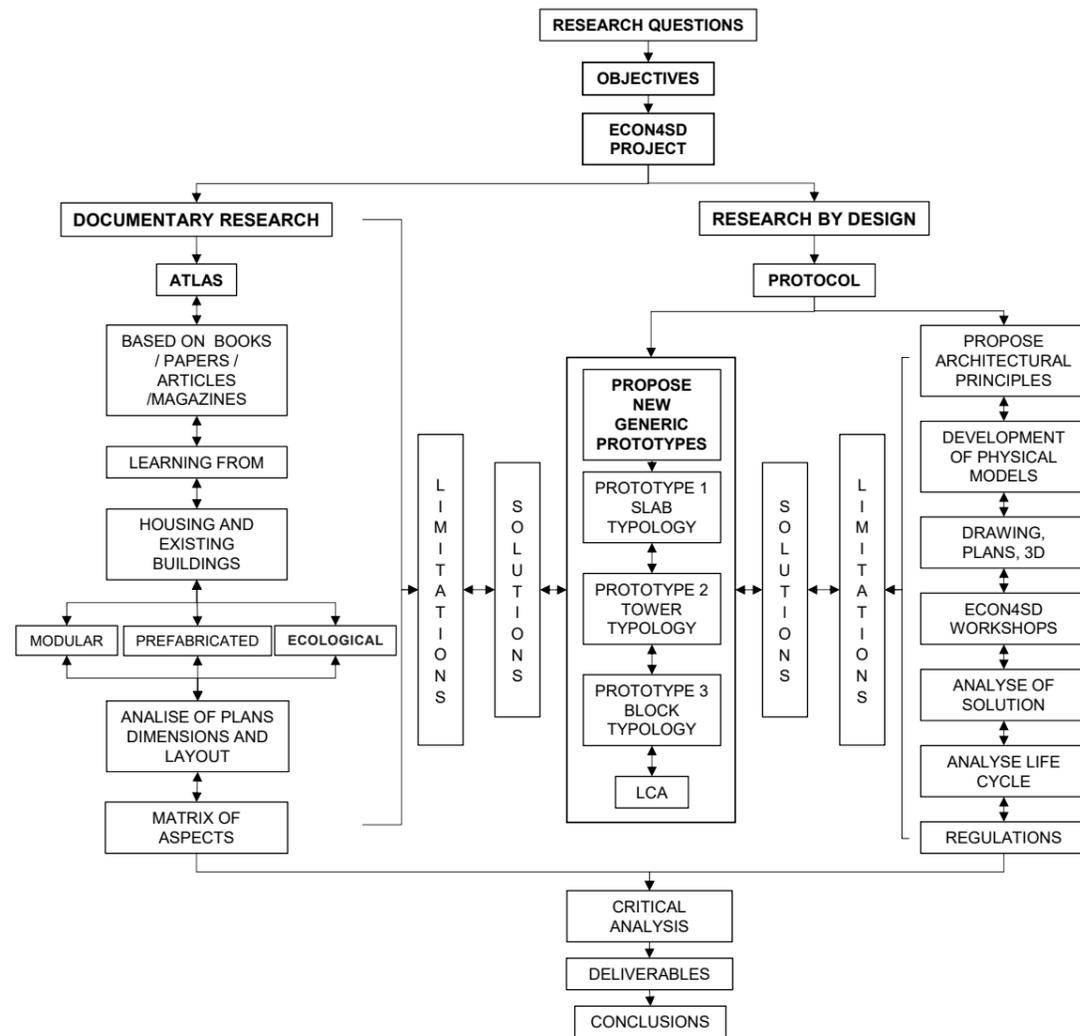


Figure 1.2: Methodology diagram

CHAPTER 2. ATLAS: FROM MODULAR, PREFABRICATED AND ECOLOGICAL TOWARDS REUSABLE AND RECYCLABLE ARCHITECTURE

The habitat and built environment, which house humans and influence their actions, are an ongoing theme that connects many buildings and ways of thinking beyond architecture²³². The concern with social needs and improvements in housing to what was produced by society emerged after the post-war period²³³. Construction activity has grown exponentially due to the ever-increasing population²³⁴. However, the housing crisis persists today as demand increases and cities continue to grow. Urban centres and large cities are attractive for people to live in because of their high-end facilities. In 2030, 28% of people worldwide will be concentrated in cities with at least 1 million inhabitants²³⁵, and the projections indicate that the world population will be around 9.7 billion people by 2050²³⁶. This population concentration increases the pressure imposed by land prices, shortening the useful life of buildings and making increasingly high levels of land use necessary, making housing unaffordable²³⁷. The current influx of immigrants and refugees makes the shortage of affordable housing even more pressing. The search for new affordable housing models in the world's growing cities has never been more urgent to address the challenges of urban segregation and make access and housing possible for everyone in a city²³⁸.

Nowadays, the focus in architecture and construction is gravitating towards more efficient and precise approaches, being environmentally conscious, making better workforce use and providing shorter construction cycles²³⁹. As an alternative to conventional construction methods, there is a greater reliance on the assembly of offsite manufactured and prefabricated components throughout the industry. Modular prefabrication constitutes one of the largest industries in prefabricated architecture and offers a better finish and the possibility to build 95% of a component before starting the structure on site²⁴⁰. The concept of flexibility became pertinent when it was first introduced into the architecture field in the early 1950s²⁴¹. In 1954, Walter Gropius pioneered the idea that architects must design buildings as receptacles for the flow of life, flexible enough to create a suitable background to absorb the dynamic characteristics of our modern life, and not as monuments²⁴². This idea challenges architecture, brings up the authorship question and requires knowledge of production and construction methods.

232 Banham 1970.

233 Ibid.

234 Hillebrandt and Seggewies 2019.

235 United Nations 2018.

236 United Nations 2019.

237 Hillebrandt and Seggewies 2019; Van Andel 2015.

238 Van Andel 2015.

239 Smith and Timberlake 2010.

240 Ibid.

241 Forty 2004.

242 Ibid.

Therefore, we must think of all the other issues that come with population growth, such as an increased demand for infrastructure, expansion of cities to green areas and increased use of materials. If architecture is successful in meeting these requirements, a positive impact on the quality of the built environment can be made²⁴³.

Various projects from history have implemented alternative solutions which approach the ongoing dilemma of social housing, such as increasing population density in cities through housing complexes, modularisation systems and fast and low-cost constructions with prefabricated methods and materials. As a result, this chapter aims to briefly overview modular, prefabricated and ecological projects in architecture towards a more reusable and recyclable approach to architecture. From Durant to the 21st century, the hypothesis was to analyse modularity and prefabrication's contribution to developing a consistent perception of contemporary housing reusable design, spatial organisation, dimensions and construction. Drawings and project documentation were collected from the literature review and organised into an Atlas of housing units' typologies divided into modular, prefabricated and ecological architecture, following the idea of evolution in the design and architecture production. Each subject will have an introduction and the projects mentioned in this text can be seen in more detail later. The building case studies were selected for their importance as prototypes and architectural quality which serve as an example for the standards to be followed as well as representing various building forms and problems. The idea to use analogous examples as references to obtain inspiration about some problems in the present is not new²⁴⁴. A reference to a problem or the study of similar solutions can be used to leverage thinking and reach a new conclusion²⁴⁵. We can learn from architectural projects through their design and propose new typologies combining solutions and improving them. Accordingly, the Atlas inspired the design concepts of three prototypes presented in Chapter 3 by using critical analysis to determine what could be incorporated into current practice.

243 Smith and Timberlake 2010.

244 Ferreira Silva et al. 2020.

245 Sherwood 1979.

2.1. The modularity in architecture design

Modularity is a valuable principle in different fields ranging from brain science and psychology to industrial engineering, artificial intelligence and robotics due to internal interdependence and independence between elements²⁴⁶. Modular methods are systems in which elements are prefabricated individually, which can be assembled as complete parts as a module and/or combined in different ways²⁴⁷. Modules can be described as components or products in a system structurally independent of each other, working with functional integration or as a module of another product²⁴⁸. For example, (a) connection arbitrarily by interfaces, (b) by combining a base module with alternative components, (c) a connection between two other components; and (d) a mix of different components in a permanent combination²⁴⁹, see Figure 2.1. Modular construction is a process in which a building is produced offsite in modules, under controlled conditions and assembled on site²⁵⁰. A standardised modular unit of construction is intended to facilitate assembly, as it can be more refined than other prefabrication processes but it is not restricted to scale²⁵¹. The modularity can be considered a follow-up, describing how components can separate and assemble²⁵².

The grid is also integrated into the modularity concept, an arrangement of one or more regularly spaced parallel lines used as a graphical basis or construction principles by architects and engineers to facilitate modular planning, reduce complexity and facilitate parallel work²⁵³. In architecture, it has traditionally been associated with spatial coordination aspects, i.e. according to the current location and size of the components, including their height, width and thickness²⁵⁴. In building construction, grids are a geometric system of organisation that allows the construction of components and prefabricated elements with standard dimensions²⁵⁵. Any construction system can have its grid logic²⁵⁶.

The use of parallel lines and square or rectangular grids to organise space began on the scale of urbanism and architecture in several ancient civilisations from the Americas to China. In Greece, city planning articulates the grid values to express social order and rationality²⁵⁷. In Rome, the planning grid of cities derived from military camps organised around two main streets, which spread throughout Europe with the

246 Baldwin and Clark 2000.

247 Correia 2017; Staib, Dörrhöfer, and Rosenthal 2008.

248 Baldwin and Clark 2000; Correia 2017.

249 Correia 2017.

250 Modular Building Institute 2020.

251 Smith and Timberlake 2010.

252 Correia 2017.

253 Ibid.; Harris 2006.

254 Correia 2017; Smith and Timberlake 2010.

255 Correia 2017.

256 Smith and Timberlake 2010.

257 Weston 2011a.

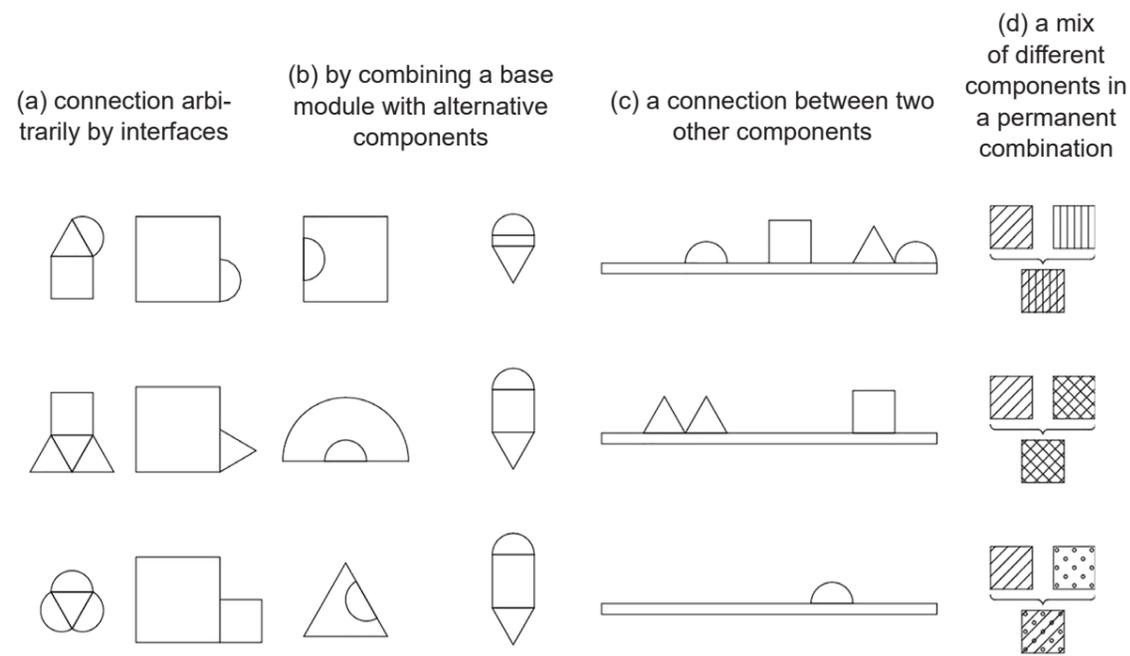


Figure 2.1. Types of modular architecture – adapted from Correia 2017

empire's expansion, imposing order on the occupied territory²⁵⁸. Repeated modules are found everywhere in Japanese architecture, from houses arranged according to the tatami mats' standard size, to the repetition of the roof tiles²⁵⁹. In China, standardised modules for buildings and wooden frames were published as government building regulations applicable throughout the empire, such as the manuals of Yingzao Ashi (1103) and Gongcheng Zuofa Zeli (1733)²⁶⁰. These manuals had the same ambition as current efforts to develop systems and components with an internationally coordinated dimension²⁶¹.

In European architecture, the transition from geometric systems to the rational demands of industrial construction became explicit in the work of Jean-Nicolas-Louis Durand, a method based on the intersection of axes and grids, coordinated by a squared paper to which modular elements of 'architecture' were combined²⁶², Figure 2.2. Durand was the first to endorse a grid of abstract dimensions in architecture to organise plans, sections and elevations of buildings, in the early 19th century²⁶³. For him, the architecture objective should be the most suitable and economical disposition, based on his *symétrie*, *régularité* and *simplicité* concept (symmetry, regularity and simplicity), used later on in the prefabrication process²⁶⁴. Durand's architecture, built on a modular grid, was meant to be both rational and universally applicable. It proved popular in Germany, where it was adopted by leading Neoclassicists such as Karl Friedrich Schinkel and Leo von Klenze²⁶⁵. A century later, the first attempt to provide encompassing dimensional guidelines for architects was made by Ernst Neufert, a former assistant of Walter Gropius at the Bauhaus²⁶⁶. The book Architects' Data by Ernst Neufert, first published in 1936, presents the framework and dimensions for the detailed planning of building projects and the dimensional assembly²⁶⁷.

As an example of the grid application in architecture, the Narkomfin residential complex was developed in 1928 by Moisei Ginzburg and Ignatius Milinis, in Moscow. The building was designed in a strategic grid to support the residential units' variations and the common areas, combining communal spaces and private life in one structure to solve the housing shortage²⁶⁸. Over time, the architects searching for an international style for the Machine Age were fascinated by the universality and rationality of the grid, widely used as both devices of abstract composition and as dimensional coordination of a building and its components²⁶⁹. Complementary to modularity, anthropometry is the science that studies the measurements of the human body and its movements

258 Weston 2011a.
 259 Weston 2011b.
 260 Ibid.
 261 Ibid.
 262 Ibid.
 263 Krufft 1994a; Smith and Timberlake 2010; Weston 2011a.
 264 Krufft 1994a; Smith and Timberlake 2010.
 265 Weston 2011a.
 266 Ibid.
 267 Neufert and Jones 1994; Weston 2011b.
 268 Sherwood 1979.
 269 Weston 2011a.

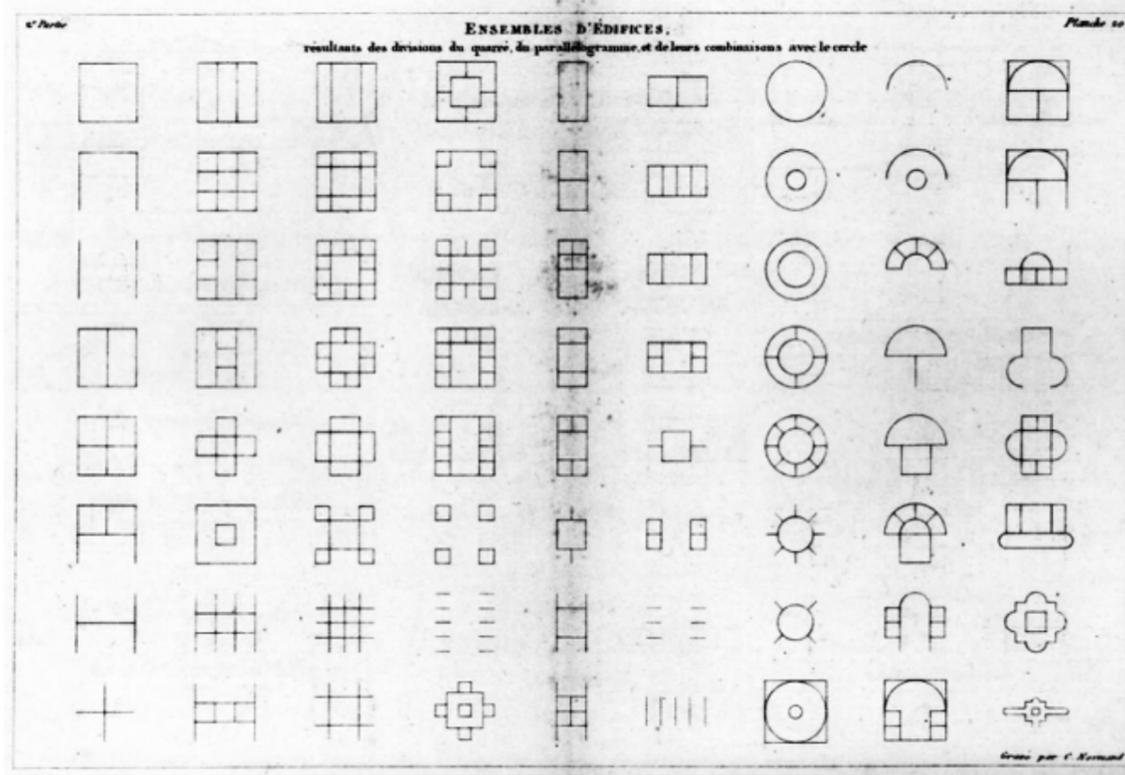


Figure 2.2. Jean-Nicolas-Louis Durand (1760-1834)

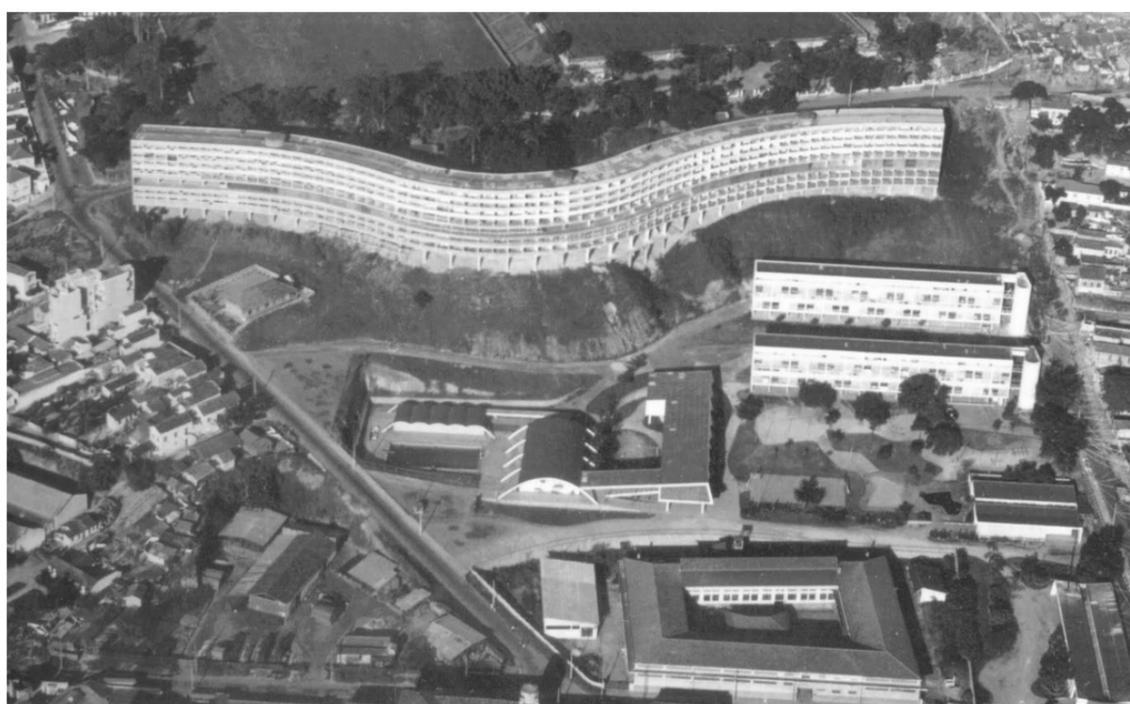


Figure 2.3. Pedregulho Residencial Complex, Affonso Eduardo Reidy in 1947

in space. Fundamental to architectural design, it has been applied over the centuries by architects, artists and scientists alike. Le Corbusier was one of the architects who developed a proportional system in design, *Le Modulor* concept, first published in 1948²⁷⁰. The concept combines human dimensions into a mathematical framework, relating its projects to a human scale that was universally applicable. The first proposal for *Le Modulor* was based on a man's height of 1.72 metres, and 2.16 metres when including the extension of the arms above the head. Later, a height of 1.83 metres was adopted, increasing the total dimension to 2.26 metres²⁷¹. In 1945, Le Corbusier developed *L'Unité d'Habitation* which would prove to be significant for architectural history post-WWII. It was characterised by the reconstruction of buildings and an unprecedented series of new dwellings urgently needed for the next several decades²⁷². The prototype was built as an experimental collective housing solution containing facilities necessary for 1,200 people, in which shapes, surfaces and lines are proportional and placed on top of each other from top to bottom²⁷³. The building's apparent concrete and architectural peculiarities are unmistakable, as are the amenities and apartments for the time, whose impact would be felt worldwide²⁷⁴. Le Corbusier also developed *Le Cabanon*, a prototype of the minimum unit according to the ergonomic and functional principles of *Le Modulor*²⁷⁵. The cabin is a small construction entirely made of wood with a single section roof, panels and furniture prefabricated in Corsica and built on site²⁷⁶. The prototype represents the culmination of the minimum cell concept in the centre of the research of twentieth-century modern architects²⁷⁷. Le Corbusier influenced several generations of architects, summarising a search for new tools and concepts to build cities, towns and villas²⁷⁸. Le Corbusier's modernist designs and concepts had much impact on construction in Brazil. For example, the *Prefeito Mendes de Moraes* residential complex, known as Pedregulho, was designed by architect Affonso Eduardo Reidy in 1947. The main residential construction built on pilotis, is linear based on repetition but follows the curved shape of the terrain²⁷⁹, Figure 2.3. Following the international style and rationalisation ideas, Mies van der Rohe's most crucial housing project with the fluid space concept was the Lake Shore Drive apartments, built in 1951 in Chicago²⁸⁰. The towers' floor plan was organised in a grid, expressed and simplified by the steel frame and had exposed columns placed at the intersections²⁸¹.

From the 1950s onwards, modularity in architecture was even more explicit through form, plans and structure. For example, between 1955 and 1961, Atelier 5's Halen

270 Neufert and Jones 1994; Corbusier 2015.
 271 Corbusier 2015; Neufert and Jones 1994.
 272 Sbriglio 2004.
 273 Corbusier 2015; Sbriglio 2004.
 274 Sbriglio 2004.
 275 Corbusier 2015.
 276 Ragot 2014.
 277 Ibid.
 278 Sbriglio 2004.
 279 Igor Fracalossi 2011.
 280 Alfirevic and Simonovic-Alfirevic 2016.
 281 Perez 2010.

Estate was built in the modern style, a housing complex situated in Bern, Switzerland. The modularity can be perceived through the repetition of housing units and their concrete structure²⁸². In the case of Harumi Apartment House built in 1956–1958, Tokyo, by Kunio Maekawa, the repetition can also be seen in the structure but with more freedom inside of the space, as Japanese tradition was to use wood framing and paper sliding doors to partition rooms²⁸³. In London, Alison and Peter Smithson designed the Robin Hood Garden, a social housing complex with the Brutalism style based on the modernism movement, and modular and prefabrication methods, built between 1968 and 1972²⁸⁴.

With the development of the modernist free plan, the grid allowed freedom in the organisation of space²⁸⁵. Some architects are still following this strategy in their projects, and this is the case of Shigeru Ban in the Nine Square Grid House project, 1997, in Kanagawa, Japan. The structure has a universal plan without internal walls, made of steel studs assembled on-site²⁸⁶. The GIFU Kitagata Apartments designed by Kazuyo Sejima in Japan, 1994-2000, reveal the freedom of organisation in the combination of housing units and free spaces, by binding them following a standard grid and connecting them through an intermediate floor space²⁸⁷. Similarly, Elemental's Quinta Monroy in Chile, built in 2001-2004, the architects developed a building typology in a grid sequence that allowed the owners to expand their house²⁸⁸.

In contrast to the freedom of organisational space, in the work of Oswald Mathias Ungers, the systematic grid of space is used to impose order in everything from the dimensions of rooms and furniture to the location of electrical sockets and light switches²⁸⁹. The engineering field follows the same idea since modular construction systems are being developed based on specific grids. In the 1870s, in France, the engineer Colonel Charles Renard proposed preferential numbers for use with the metric system where a 'basic module' of 100 mm was chosen, with multiples of 300 mm, 600 mm and 1,200 mm successively to be favoured as the dimensions increased, which were eventually adopted in 1952 by the International Organisation for Standardisation as ISO3²⁹⁰. In the US, modular grids are mainly used in panels and modular systems based on 0.6 metre intervals²⁹¹. In Europe, CREE System for building construction has been spreading, and it is based on a prefabricated wood-hybrid panels grid of 2.50 m, 2.70 m and 3 m²⁹². The dimensions of the building are multiples of the slab dimensions in each direction²⁹³. In the context of customisation, modularisation emerges as a requirement to achieve

282 Atelier 5 2020; Sherwood 1979.

283 Fukao 2000.

284 Banham 1970.

285 Weston 2011a.

286 Shigeru Ban Architects 1997.

287 Perera 2017.

288 Elemental 2008.

289 Weston 2011a.

290 Weston 2011b.

291 Smith and Timberlake 2010.

292 CREE GmbH 2020.

293 Ibid.

variability while rationalising production²⁹⁴. It is increasingly important in a globalised economy in which buildings are assembled from factory-produced components that allow little or no room for adjustment on site²⁹⁵.

Nevertheless, it can be concluded that modularity has inspired many architects, engineers and designers throughout architecture and construction. They sometimes tended towards a more poetic vision seeking to provide greater freedom, universal space and rationalisation within construction, like modernist architectural buildings. Other times, they were entirely motivated by the pure practicality and speed demanded by the construction industry as in most contemporary buildings and engineering components. It can be defined by the construction type or the factory's delivery methods. Consequently, the concepts of module and prefabrication are interrelated in the manufacturing process. Therefore, the concept of prefabricated architecture is best described and studied in Section 2.2. Finally, some of the architectural projects mentioned in the text are presented below separately to show how the concepts of grid and modularity were applied as case studies. They are presented in Section 2.1.1. These projects were essential to the evolution of architecture with their specific qualities and types. In addition, they bring solutions that can be adapted and applied today.

294 Correia 2017.

295 Weston 2011a.

2.1.1. Modular buildings

Narkomfin, Moisei Ginzburg and Ignatius Milinis, Moscow, Russia, 1928

Narkomfin is an example of a residential complex as a solution for the past housing shortage, combining communal spaces and private life in one structure, Figure 2.4. Because of the impossibility of giving conventional apartments to each family, a communal house was developed to provide collective amenities like a kitchen, canteen, day nursery, gymnasium, library and roof garden as a justifiable reduction in the size of the individual unit²⁹⁶. There are two types of duplex units: one-bedroom apartment of two rooms, and the other with two bedrooms, for a total of three rooms. The entrances of the units are in a single corridor on each third floor, bringing the idea of an interior street to the building. The building was built on pilotis - slab raised from the floor. The floors above ground are used for public facilities²⁹⁷. The building was designed in a strategic grid to support the residential units' and the sharing areas. Unfortunately, Narkomfin's community spaces fell into disrepair after Stalin, where the community and emancipatory ideals that the architecture meant to inspire were quickly repulsed by leftists²⁹⁸. Narkomfin combined ideas of public and collective spaces with duplex houses generating interior streets rationally using specific grids. Figure 2.5 shows the floor plans and grid of the building. These strategies were later modified and adapted by architects like Le Corbusier, and they continue to inspire architects to this day.



Figure 2.4. Narkomfin, Moisei Ginzburg and Ignatius Milinis, Russia, 1928 - Façade

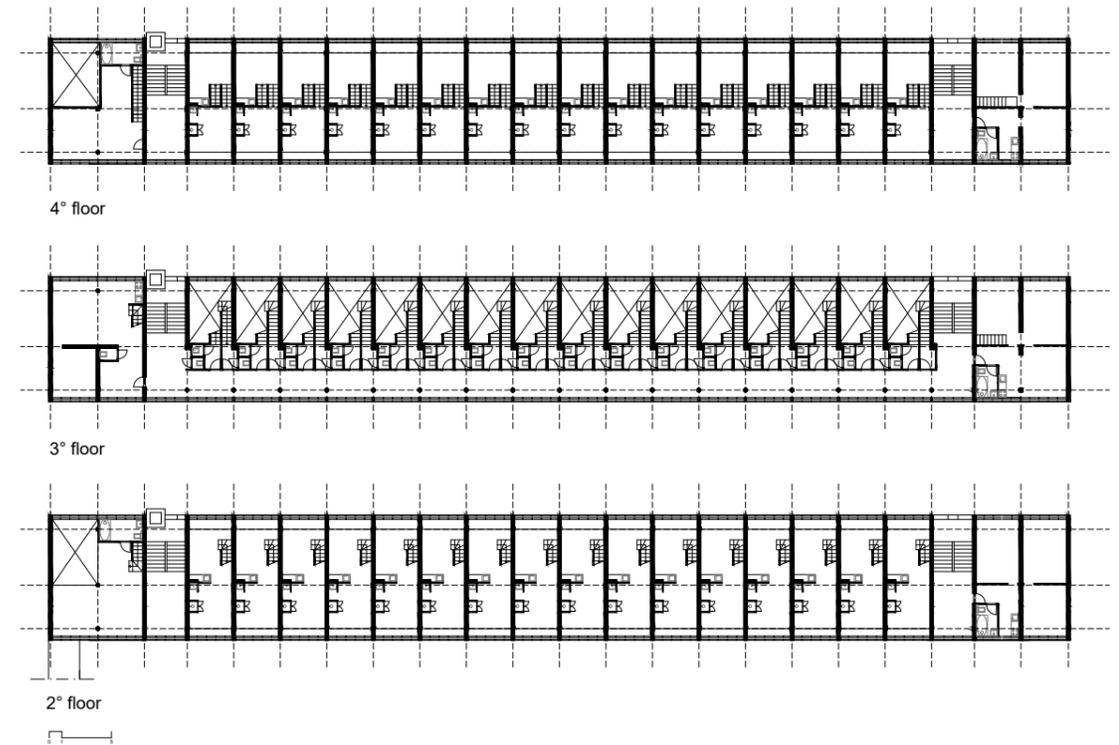


Figure 2.5. Narkomfin floor plans

296 Perényi 2013; Sherwood 1979.

297 Sherwood 1979.

298 Ibid.

STRUCTURE: Concrete

MODULE/ GRID(m)

Length: 8,00

Width:3,75

Height:2,60

INTERNAL DIMENSIONS (m)

Length: 9,45

Width: 3,45

Height:2,3

Total Area (m2): 32.6

BUILDINGS DIMENSIONS(m)

Length:82.35

Width: 10.10

Height:18.75

L'unité d'Habitation, Cité radieuse, Le Corbusier, Marseille, France, 1945–1952

The complex modernist housing embodies the community vision of Le Corbusier with the needs and realities of post-war France. The structure is reinforced concrete elevated from the ground floor by pilotis, with 337 housing units, an internal commercial street, a nursery and a recreation area with a pool on the terrace²⁹⁹, Figure 2.6 and Figure 2.7. The apartments have two floors consisting of a kitchen, living room, three bedrooms and a bathroom. Each apartment is composed of 5 modules inserted in a grid of 3.66 m wide, 4.2 m long and 2.26 m high, following the systematic application of *Le Modulor* measures internally³⁰⁰. Figure 2.8 shows the typical floor plans and grid of the building. The combination of blocks as a community offers a vertical city solution, an ordered structure for the fundamental acts of daily life in the machine age³⁰¹. Even if the ideas for the time were revolutionary, the building was falling into disarray. The apartments are rather narrow, the corridors long and dense, the pilotis was not utilised and the stores were not functioning at the time. Now, the building is basically used as architects' offices rather than as accommodation³⁰². Nevertheless, the *Unité d'Habitation* is probably the most copied building of the 20th century, influencing the form of subsequent housing, by varying it in almost every country, built on a large scale³⁰³. The structure over the years has become outdated despite having concepts that are still implemented today such as the community idea and the integration of public facilities in the complex. However, it is rigid in its framework and is not adaptable to the evolution of the daily way of life.



Figure 2.6. *L'unité d'Habitation*, Le Corbusier, France, 1945 – 1952 - Perspective view of the south and east facades



Figure 2.7. *L'unité d'Habitation*, Le Corbusier, France, 1945 – 1952 – The bottle-rack frame

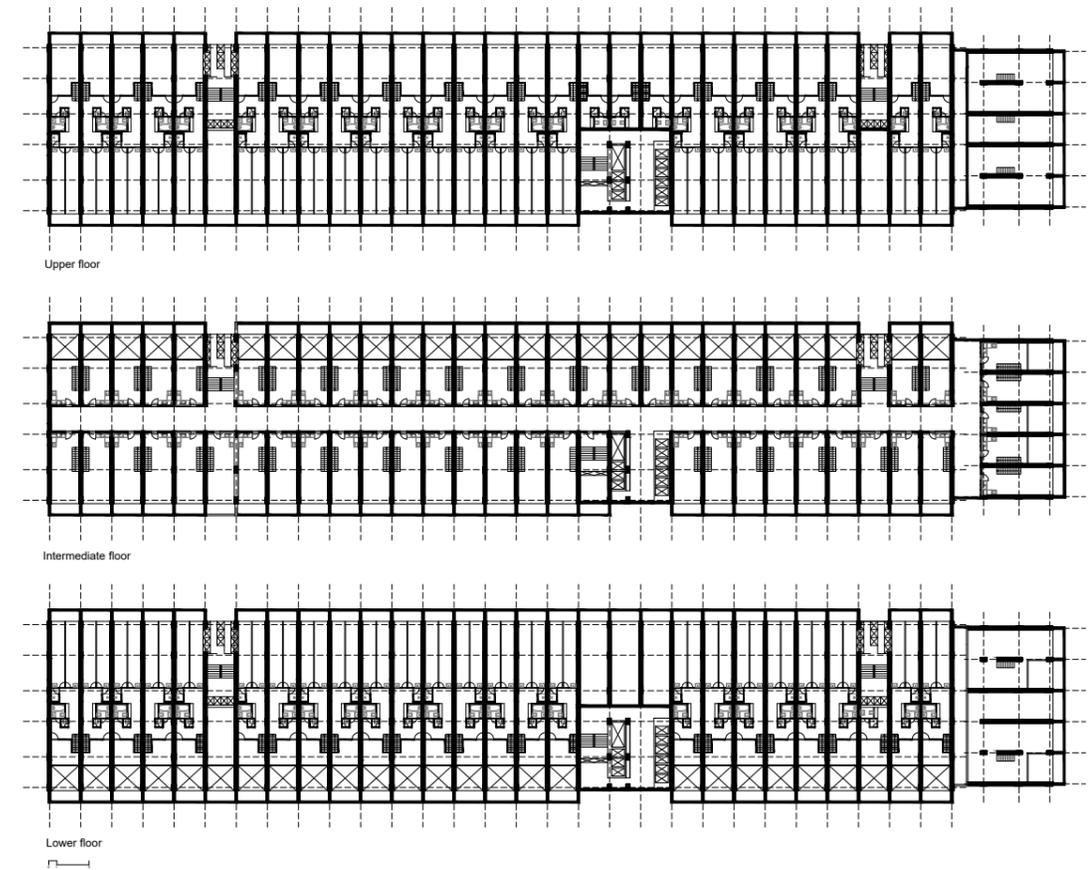


Figure 2.8. *L'unité d'Habitation* typical floor plans

299 Sbriglio 2004.
300 Corbusier 2015.
301 Sbriglio 2004.
302 Sherwood 1979.
303 Ibid.

STRUCTURE: reinforced concrete

MODULE/ GRID(m)
Length:4,2
Width:3,66
Height:2,26

INTERNAL DIMENSIONS (m)

Length: 23,6 Lower and upper floors /10 intermediate floor
Width:3,36
Height:2,26
Total Area (m2):

BUILDINGS DIMENSIONS(m)

Length:24,0
Width:140
Height:56,0

860-880 Lake Shore Drive, Mies van der Rohe, Chicago, 1948-1951

Lake Shore Drive apartments represent the concept of fluid space designed by Mies van der Rohe. The two high-rise towers are iconic in Chicago after the post-war generation³⁰⁴, Figure 2.9. All the rooms have been integrated, excluding the separate bathrooms as independent units and the bedrooms partially separated by the shelf with partitions³⁰⁵. The floor plan of the towers was organised in a 6.4 metre grid, expressed and simplified by the steel frame, and exposed columns placed at the intersections³⁰⁶. Figure 2.10 shows the typical floor plans and grid for each tower. It is scarcely modulated except by variations in detail³⁰⁷. The architecture is independent of the site. The towers took advantage of the concept of pilotis, and they seem to be flitting above the ground as just the core is connected with the ground floor generating free space under the building projection. The open space could have been optimised and utilised as a space for public demonstrations or even for the local market.



Figure 2.9. 860-880 Lake Shore Drive, Mies van der Rohe, Chicago, 1948-1951 – Façade

304 Perez 2010.
 305 Alfirevic and Simonovic-Alfirevic 2016.
 306 Perez 2010.
 307 Cohen 2018.

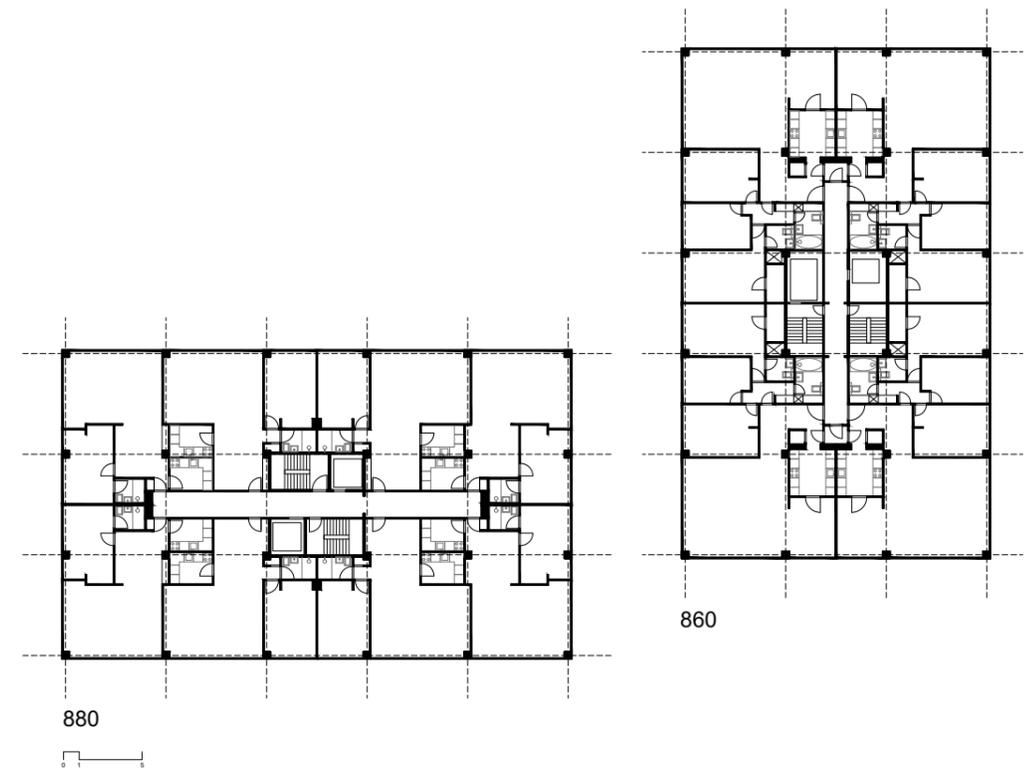


Figure 2.10. 860-880 Lake Shore Drive typical floor plans

STRUCTURE: steel and concrete	INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
MODULE/ GRID(m)	Length:9,7-880 / 16,1-860	Length:32,5
Length: 6,4	Width:6,3 – 880 / 9,7-860	Width:19,7
Width: 6,4	Height:2,7	Height:86,6
Height:3,1	Total Area (m2):62,0-880 / 156,2-860	

Le Cabanon, Le Corbusier, Roquebrune-Cap-Martin, France, 1951

The *Cabanon* is a minimum unit prototype based on a functionalist and ergonomic approach, according to Le Corbusier's Modulor. The cabin has a height and width of 3.66 m³⁰⁸. The cabin is a small construction made entirely of wood with a single section roof, panels and furniture prefabricated in Corsica and built on site³⁰⁹, Figure 2.11 and Figure 2.12. The interior has a working area, a sitting area, a toilet area and a sink, Figure 2.13. The furniture is minimised to a bed, a table and some storage. The prototype represents the culmination of the minimum cell concept in the heart of the research of the twentieth-century modern architects becoming an icon of modern architecture³¹⁰.



Figure 2.11. Le Cabanon, Le Courbusier, France, 1951 – Exterior



Figure 2.12. Le Cabanon, Le Courbusier, France, 1951 – Interior

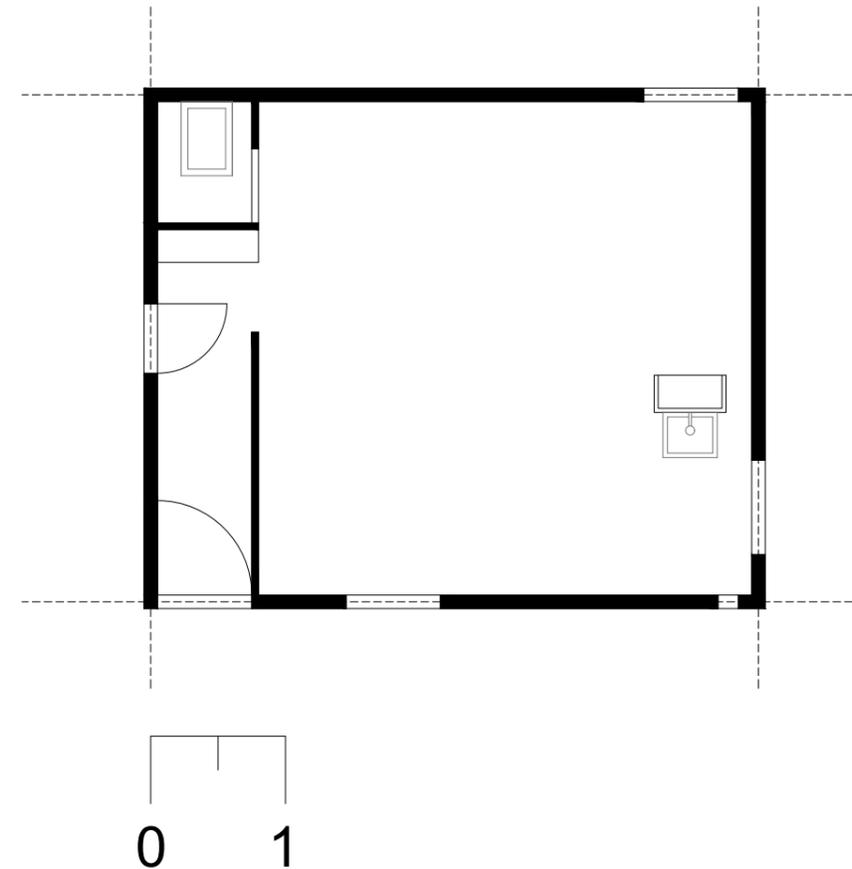


Figure 2.13. Le Cabanon floor plan

STRUCTURE:	INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
wood	Length: 3.66	Length: 4.6
	Width: 3.66	Width: 3.9
	Height: 2.26	Height: 4.33
	Total Area (m2): 16.10	

308 Corbusier 2015.

309 Ragot 2014; Corbusier 2015.

310 Ragot 2014.

The Halen Estate, Atelier 5, Berne, Switzerland, 1955-1961

The Halen Estate is a housing complex where the modularity can be perceived through the repetition of housing units and their concrete structure, Figure 2.14. There are 81 dwellings with two basic types of modules for housing units, with three floors for each unit. The housing units primarily consist of a kitchen, bathrooms, living room and three bedrooms. The internal layouts may vary and thus have more rooms, offices or multi-purpose space that could be added, incorporating the concept of flexible use³¹¹. Figure 2.15 shows the housing floor plans for Type 380 and 12. Apart from the modularity, Halen State brings strategies that combine functions that align cores or internal service walls. These strategies are also used in high-rise slabs, i.e. longitudinal stair arrangement, an outside kitchen or a bathtub above the kitchen³¹². The complex was designed as simply as possible while it simultaneously aimed to protect the private indoor and outdoor spaces. The entire complex has an almost urban character with its central square, streets and path connections³¹³. The flexibility of the project stopped at the level of interior layout. The housing units can no longer be extended or redesigned to integrate other facilities.



Figure 2.14. The Halen Estate, Atelier 5, Switzerland, 1955-1961 - Façade

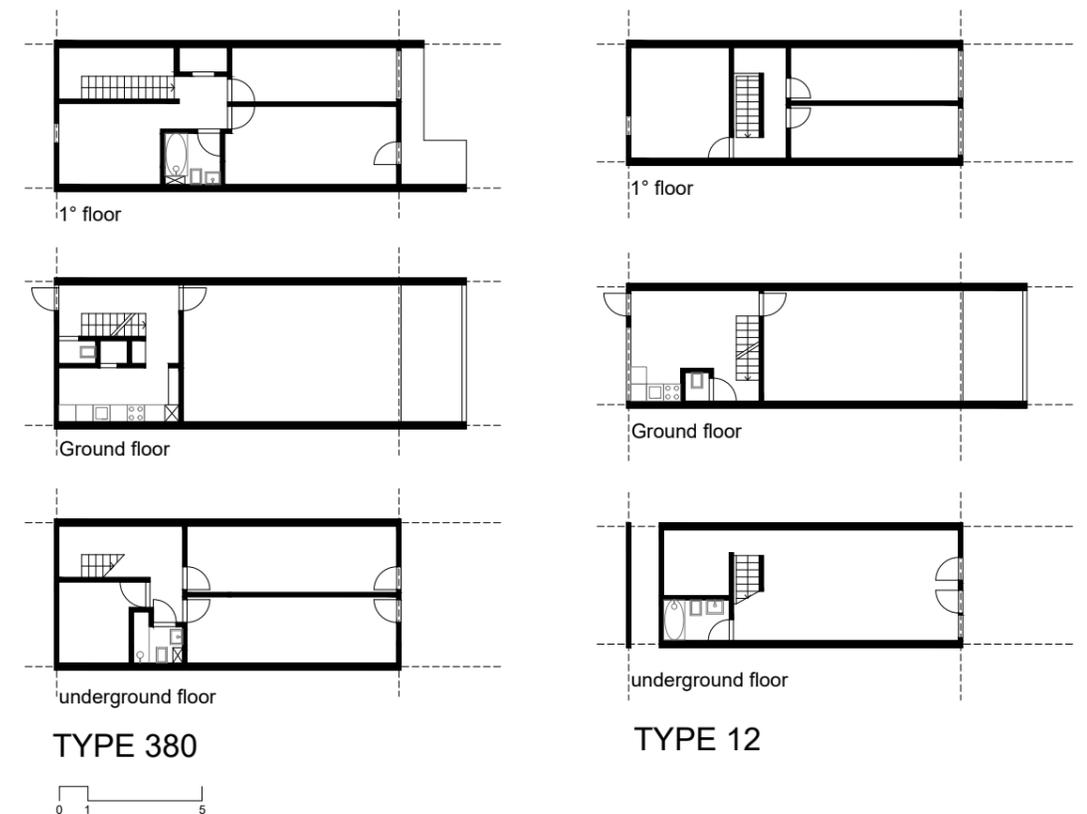


Figure 2.15. The Halen Estate housing plans

STRUCTURE: brick and concrete	INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
DIMENSIONS FOR TYPE 380	Length: 14.15	Length: 14.45
	Width: 4.8	Width: 5.3
MODULE/ GRID (m)	Height: 2.3	Height: 8.8
	Total Area (m ²): 181.76	

311 Atelier 5 2020.

312 Sherwood 1979.

313 Atelier 5 2020.

Harumi Apartment House, Kunio Maekawa, Tokyo, Japan, 1956–1958

The Harumi building has a structure of pillars and reinforced concrete beams³¹⁴, Figure 2.16. The interior of the apartments was designed using the conventional organisation of a traditional Japanese wooden house but placed in a reinforced concrete skeleton, Figure 2.17. The dwellings are on two levels with stairs that lead to the small unit below while the kitchen, stairs and bathroom are positioned along parallel walls³¹⁵. Figure 2.18 shows the typical floor plans for the building. The partitions between the rooms, such as living rooms and bedrooms, are sliding doors called *Fusuma*, which are composed of a wooden and paper frame³¹⁶. The rooms were to be remodelled but never were as the building was destroyed to make space for the construction of rental housing in 1997³¹⁷. In addition, the floor plans were inspired by the modern architecture of the Le Corbusier Housing Unit. The one-level and duplex apartments are contained throughout the building with access only on each third level from the circulation corridor³¹⁸. With the open apartment plans the organisation can be easily compared to a Western model with the gallery access apartment building³¹⁹.



Figure 2.16. Harumi Apartment House, Kunio Maekawa, Japan, 1956 – 1958 - Façade



Figure 2.17. Harumi Apartment House, Kunio Maekawa, Japan, 1956 – 1958 - Interior

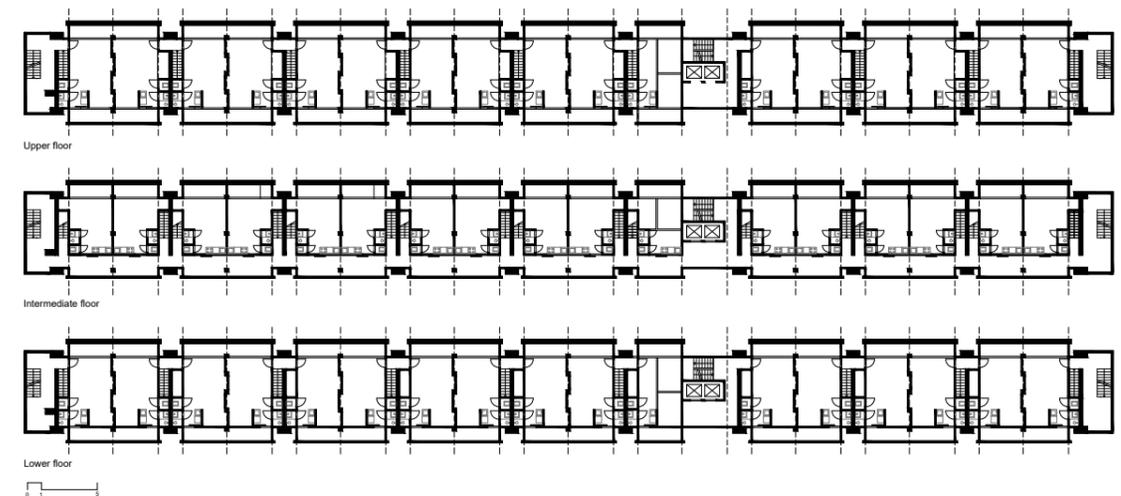


Figure 2.18. Harumi Apartment House typical floor plans

314 Perényi 2013.
 315 Sherwood 1979.
 316 Fukao 2000.
 317 Ibid.
 318 Perényi 2013; Sherwood 1979.
 319 Sherwood 1979.

STRUCTURE:	INTERNAL DIMENSIONS	BUILDINGS DIMENSIONS
concrete	(m)	(m)
MODULE/ GRID (m)	Length:7,0	Length:78,0
Length:5,0	Width:3,0	Width:7,4
Width:3,15	Height:	Height: 14 floors
Height:	Total Area (m2):21,0	

Robin Hood Garden, Alison and Peter Smithson, London, England, 1968-1972

The Robin Hood Garden is a social housing complex with the Brutalism style based on the modernism movement of architectural theories and prefabrication methods. It was built with prefabrication concrete panels and consists of two horizontal structures that include 214 apartments, Figure 2.19. One of the buildings has ten floors while the other has seven floors, and the prefabricated parts that form the faces of the buildings are 9 m high and 5.5 m wide, representing a complete section of the repetitive pattern³²⁰. Figure 2.20 shows the typical floor plans for the building. One of the social concepts implemented by the architects in the project was the “streets in the sky” as a new neighbourhood street for these housing units, including a large balcony every third level. The bedrooms and kitchens were placed inside the blocks, and living rooms and balconies were oriented towards the avenues. The apartments can have one to two floors in both buildings and combine from one to four modules³²¹. In 2017, the western block began to be demolished due to poor conservation conditions, but the eastern block still stands and will be demolished later. For the same reason as the *Unité d’Habitation*, the Robin Hood Garden was outdated as it lacked the necessities required of contemporary users and could not adapt.



Figure 2.19. Robin Hood Gardens, Alison and Peter Smithson, London, 1972 – Façade

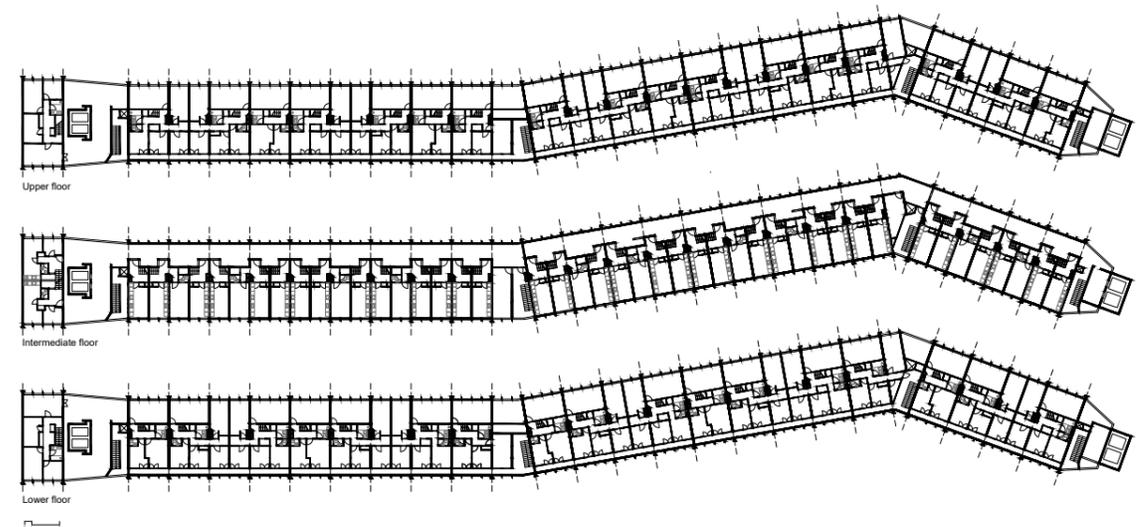


Figure 2.20. Robin Hood Gardens floor plans

STRUCTURE:	INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
concrete	Length: 7.2 (Intermediate floor) / 10.55 (Upper and lower floors)	Length: 160
	Width: 2.70	Width: 11
	Height: 2.55	Height: 20.45
	Width: 2.7 (Intermediate floor) / 8.55 (Upper and lower floors)	
	Height: 2.7 (Intermediate floor) / 2.7 (Upper and lower floors)	
	Total Area (m ²): 19.44 (Intermediate floor) / 89.675 (Upper and lower floors)	

320 Banham 1970.

321 Banham 1970.

Nine-Square Grid House, Shigeru Ban, Kanagawa, Japan, 1997 mycelium plates

The design is a combination of a universal open floor with retractable wall systems³²², Figure 2.21. The open interior can be divided by two or three horizontal predefined directions³²³. The furniture was made of steel for installation with studs in place. The space can be arranged with a kitchen, a bathroom, a living room, a dining room and bedrooms. Full-height sliding doors can partition the square floor space of 10.4 metres into nine square areas, Figure 2.22. These sliding doors allow for a variety of spatial arrangements, adjustable to accommodate seasonal or functional needs³²⁴. The utterly open plan concept is the peak point of this project. The lack of walls in the bathroom areas yield even more arrangement combinations. The question is if the modules can be easily disassembled as proposed for reassembly later on and the furniture can be adapted throughout the plans for other uses.



Figure 2.21. Nine-Square Grid House, Shigeru Ban, Japan, 1997 - Interior

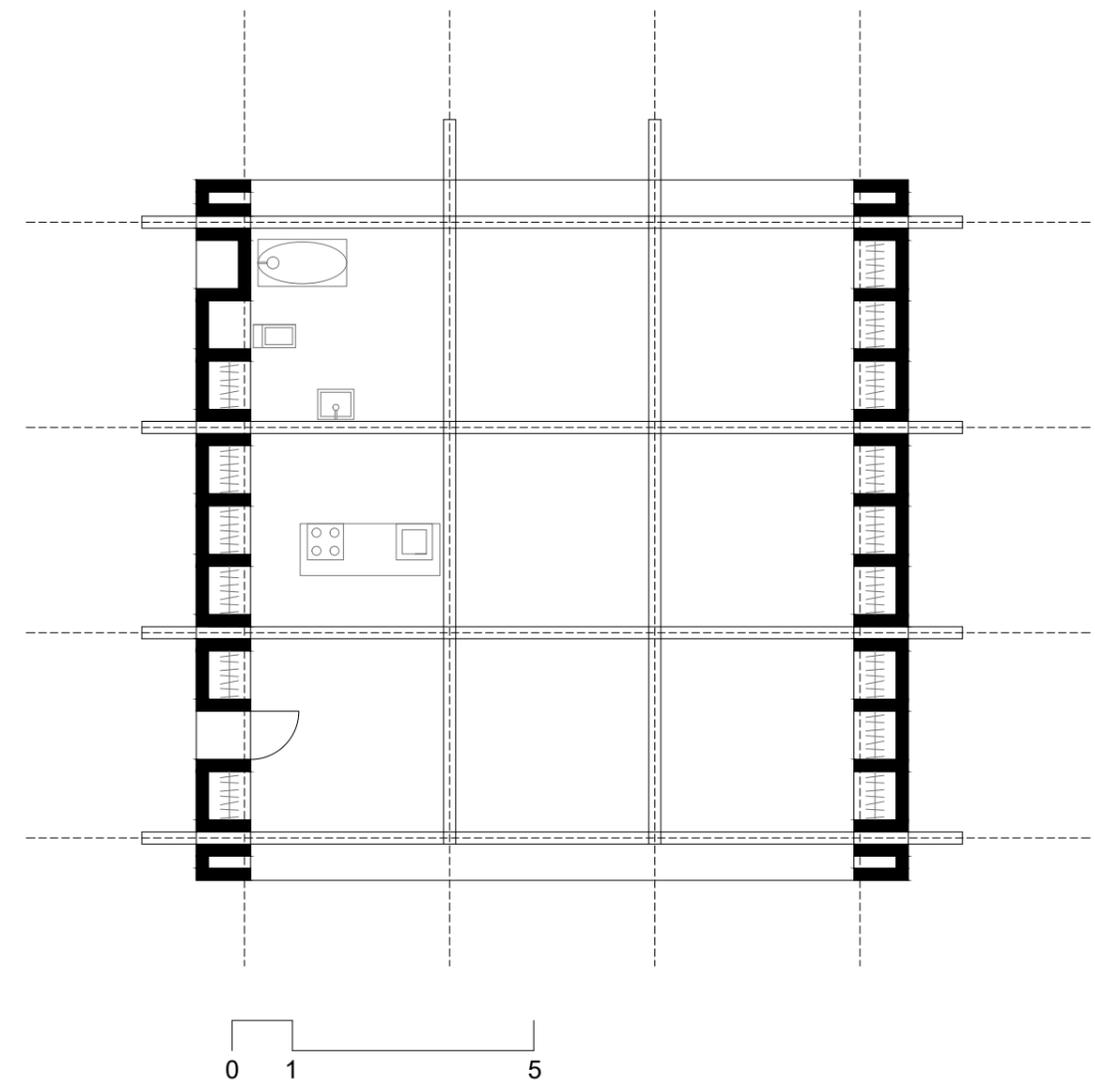


Figure 2.22. Nine-Square Grid House plan

322 Shigeru Ban Architects 1997.

323 Alfirevic and Simonovic Alfirevic 2019.

324 Shigeru Ban Architects 1997.

STRUCTURE: steel

MODULE/ GRID (m)

Length:10,4

Width:10,4

Height: 2,4

INTERNAL DIMENSIONS (m)

Length:10,0

Width:10,0

Height:2,4

Total Area (m2):100,0

BUILDINGS DIMENSIONS(m)

Length:11,8

Width:11,6

Height:3,0

Gifu Kitagata Apartments, Kazuyo Sejima, Ryue Nishizawa, and Koichiro Tokimori, Gifu, Japan, 1994-2000

The Gifu apartments are a public house of several housing units, displayed following a standard module and connecting them through an internal gallery³²⁵, Figure 2.23. The ground floor comprises a field of pilotis and open-air parking, allowing direct access to the site from any direction, Figure 2.24. Above the 107 residential units are the remaining nine floors. About one-third of the units are maisonettes, roughly half of which have two-storey spaces. Reducing the depth of the apartments allowed the building to be thinner. Every unit has its own terrace aligned to the unit that creates holes in the block and visually reduces the impression of massiveness. Each unit consists of a linear distribution on the terrace, an eat-in-kitchen and bedrooms, all linked by a narrow sunroom on the south façade. Figure 2.25 shows the typical floor plan for the building. The silhouettes of people moving inside will thus be visible across the screen³²⁶. The arrangement of the apartments and the building elevation is complex but rhythmical. The flexibility of the building still offers the different sizes and house configurations, although the structure itself is concrete and rigid.



Figure 2.23. Gifu Kitagata Apartments, Kazuyo Sejima et al., Japan, 1994-2000- Façade

325 Perera 2017.
326 Sejima 1996.

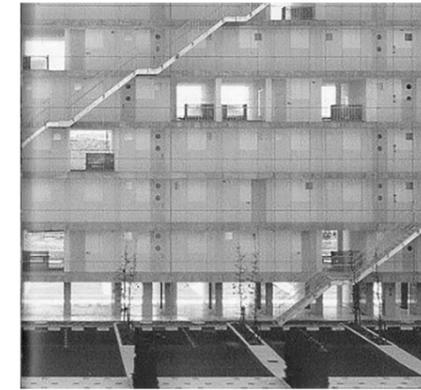


Figure 2.24. Gifu Kitagata Apartments, Kazuyo Sejima et al., Japan, 1994-2000- Pilotis

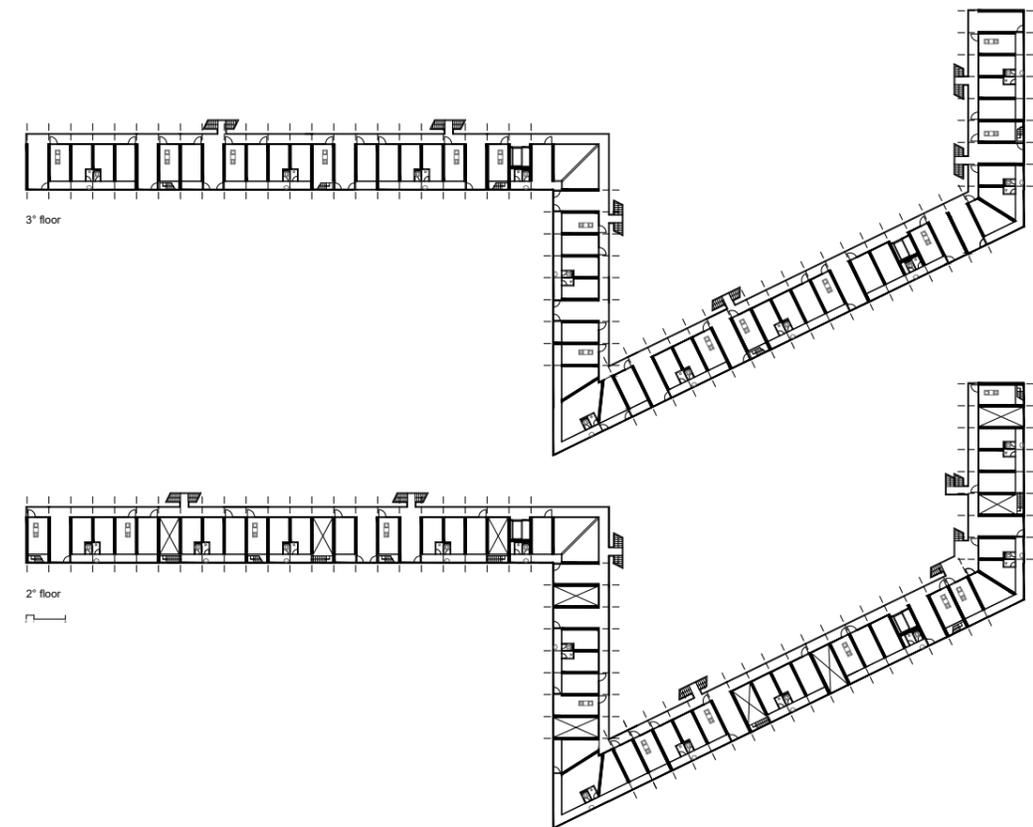


Figure 2.25. Gifu Kitagata Apartments typical floor plans

STRUCTURE:	APARTMENTS INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
reinforced concrete structure and steel additions	Length:2.5 Width:5.7 Height:2.3	Length:130.0 Width:7.2 Height:25
MODULE/ GRID (m)	Total Area (m2): 14.25 each module	
Length:5.9 Width:2.8 Height:2.5		

Quinta Monroy, Alejandro Aravena, ELEMENTAL, Iquique, Chile, 2001-2004

The project is a 93 incremental house complex. It challenged accommodating as many families as possible with a limited and reduced budget for affordable houses. As a result, the architects developed adjoining houses that allowed the owners to expand their areas out of small building parts at the beginning instead of selling them, Figure 2.26. Therefore, the house's standard has changed, where the main walls of the divisions between the different houses, stairs, kitchens and bathrooms had to be designed for a final area of 72 square metres³²⁷. Figure 2.27 shows the typical floor plan for the housing units. The project found a way to increase the units' area to bring more than one family to live in the same plot areas. Besides allowing expansion, the project also employs raw and exposed material to facilitate the later implementations. On the other hand, the use of this unfinished strategy means that most families who were no longer able to have a house finished before probably will not be able to finish it later in a proper way.



Figure 2.26. Quinta Monroy, Alejandro Aravena, Chile, 2001-2004 – Façade

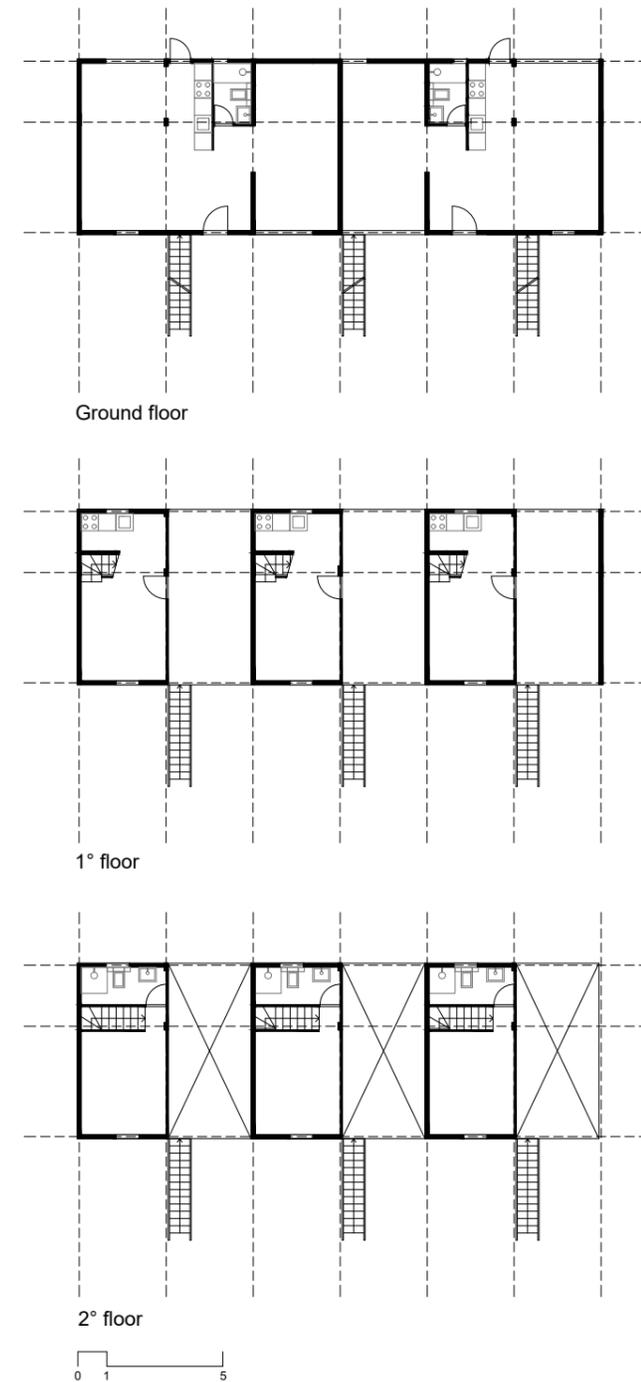


Figure 2.27. Quinta Monroy typical floor plans

STRUCTURE:	INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS (m)
precast and site-cast concrete	Length:5,8	Length:18,14
	Width:2,85	Width:6,0
	Height:2,2	Height:7,46
	Total Area (m2):16,5 one unit	

327 Elemental 2008.

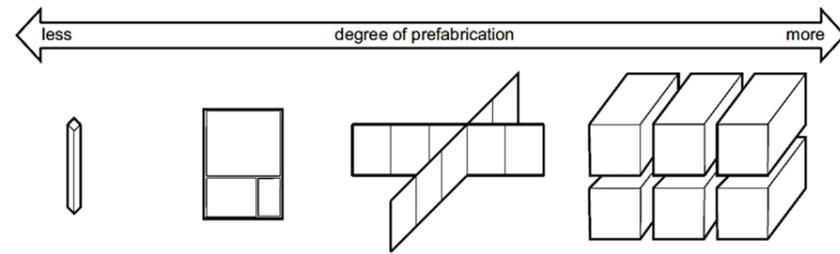


Figure 2.28: Prefabrication classification. From left to right: materials, components, panels, and modules

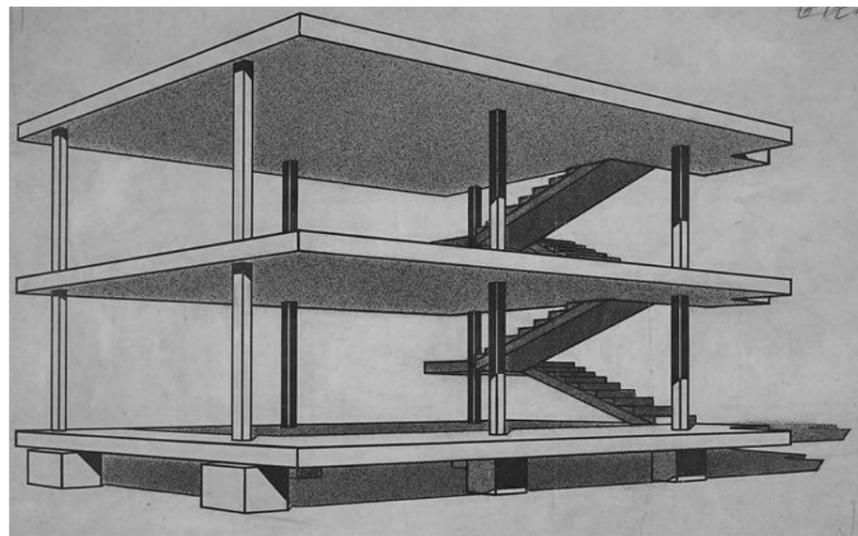


Figure 2.29. Maison Dom-ino, not located, Le Corbusier design

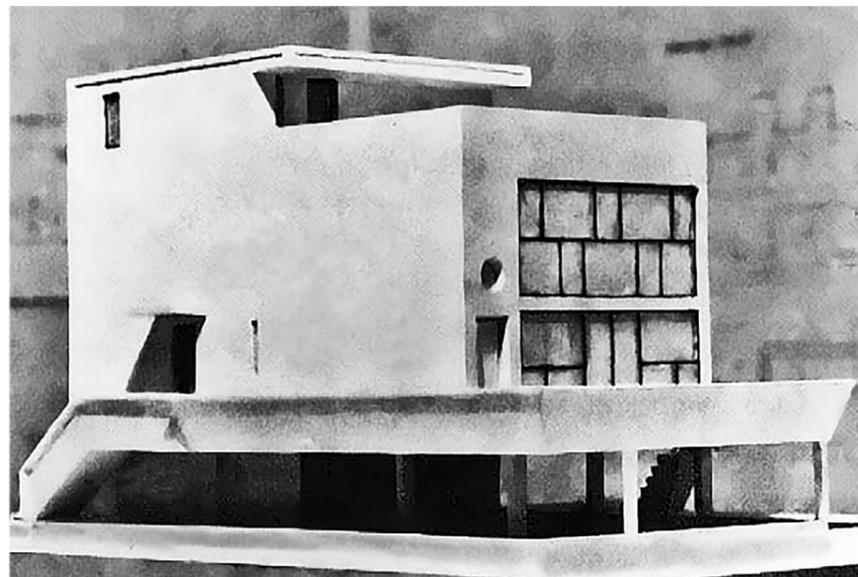


Figure 2.30. Citrohan House, 1920–1930, Le Corbusier

2.2. The prefabrication in architectural design

Prefabricated architecture is no longer outdated, and the most relevant points in history often mirror today's circumstances. In order to build faster and in mass quantity, or even in isolated places, society has used prefabrication - a manufacturing process offsite - moving from traditional local construction to factories, to facilitate the construction and then assemble on site³²⁸. The prefabrication of elements can be classified as materials, components, panels and modules, see Figure 2.28. In general, the higher degree of prefabrication, customisation and compatibility in the design and execution phases in projects, the more significant its benefits and faster assembly on site³²⁹. Thus, architects, engineers and contractors need to understand prefabrication's history, theory and practice to effectively develop and implement these methods in architecture creation³³⁰. For this reason, this section contains a chronological overview with facts and projects that have influenced the evolution and application of prefabrication.

As a starting point, Durand's architectural conception of *symétrie, régularité and simplicité* (symmetry, regularity and simplicity) influenced the prefabrication in the first half of the 19th century, as on modularity³³¹. His functionalism was total, claiming that the architecture should be the most suitable and the most economical disposition since he fully understood the architect's role in industrial production³³². Thus, the application of the prefabrication can be traced back to the United Kingdom's colonisation, which required a rapid building initiative in the settlements³³³. In 1830, Henry John Manning designed the Portable Colonial Cottage, a timber and panel infill prefabricated system, for emigrants to Australia³³⁴. In the mid-19th century, William Fairbairn built four cruise ships from riveted plates to form units that could be assembled, disassembled and reassembled. Later, this technology was translated into the construction of prefabricated iron plate houses. The advances in manufacturing methods and the ideas of "better, faster, cheaper" from the Industrial Revolution paved the way for new theories and approaches to prefabrication technology in architectural production³³⁵. The Joseph Paxton Crystal Palace is one of the earliest prefabricated buildings built in London to house the 1851 Great Exhibition. The structure was standardised components in a largely repetitive system. After the exhibition, it was dismantled and relocated elsewhere. It signifies a change in the architects' interpretation that aesthetic beauty is as simple as the practical form of production³³⁶.

At the turn of the 20th century, wooden houses with pre-cut light structures became common. The principles of mass production, standardisation, interchangeability and

328 Hearn 2018; Smith and Timberlake 2010.

329 Smith and Timberlake 2010.

330 Ibid.

331 Ibid.

332 Krufft 1994a; Smith and Timberlake 2010.

333 Smith and Timberlake 2010.

334 Hearn 2018; Smith and Timberlake 2010.

335 Smith and Timberlake 2010.

336 Ibid.

movement were transferred to the housing industry and can be traced back to Henry Ford³³⁷. Several companies began offering prefabricated houses in different scales and qualities; for example, Aladdin Homes was one of them, founded in 1906 by W.J. and O.E. Sovereign. The houses were delivered through mass production and pre-cutting in a factory. This process removed on-site waste from the structure, improved accuracy, increased manufacturing speed and simplified assembly while providing affordability and variety within a standardised product for the consumer³³⁸.

In 1914, the idea that the city and architecture are transitory and temporary appeared in the pioneer Antonio Sant Elias's Manifesto of Futurist Architecture, pronouncing that each generation must build its own city because the houses will not endure as long as the population³³⁹. Futuristic projects focused on rationalised, mechanical and industrialised cities and high-rise buildings, integrating different uses such as offices, houses, shops and public spaces in the same building. From the 1920s onwards, an international architecture emerged which looked the same everywhere, irrespective of climatic, political or economic conditions³⁴⁰. Besides this experience of the time, a rapid passage leads to the renunciation of the old principle of Durability for the first time³⁴¹.

Sequentially, during the Modernist movement, prefabrication gained more space through the search for innovative approaches to design and production. The *Maison Dom-Ino* from Le Corbusier, Figure 2.29, conceived in 1914 and only applicable in 1929, was a construction system design that foresaw the problems of post-war reconstruction³⁴². The structural system was conceived independently from the house plans, offering floors and stairs. It was to be manufactured from mass-produced standard elements such as windows and doors to be fixed to each other, allowing a great variety in the grouping of the houses³⁴³. 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 based on rationalisation through standardisation³⁴⁴. As part of this attempt to design a machine for living, Le Corbusier developed the Citrohan House prototype, Figure 2.30. Although none of Le Corbusier's buildings were constructed employing prefabricated methods, his ideas about using the manufacturing industry were standard practice for architects of the time³⁴⁵. In 1932, Frank Lloyd Wright was the first to use the term "assembled house", which consisted of modular units as spatial building blocks defining the various rooms³⁴⁶. The modules were a parts kit in concept and could be added and removed from the building and could extend to become living organisms³⁴⁷. Wright's methods never varied much from the construction on site and

337 Smith and Timberlake 2010.

338 Ibid.

339 Krufft 1994a.

340 Ibid.

341 Ferreira Silva et al. 2020.

342 Fondation Le Corbusier 2020.

343 Ibid.

344 Ibid.; Smith and Timberlake 2010.

345 Smith and Timberlake 2010.

346 Davies 2005.

347 Ibid.; Smith and Timberlake 2010.

his houses were expensive due to the high demand for quality in the handmade details, such as the Usonian houses with rationalisation plan built in the late 1930s³⁴⁸.

Technocratic ideas facilitated and influenced architectural attitudes towards frenetic development, espoused by CIAM's Athens Charter of 1933, the manifesto of modern urbanism that advocated rational and efficient state-driven development under the guidance of expert planners³⁴⁹. Walter Gropius harnesses off site manufacturing technology to reduce the cost of housing since he was concerned about industrialisation and social equality in architecture. In 1942, in collaboration with Konrad Wachsmann, Gropius produced the "Prepackaged House" with prefabricated wood structure and panels³⁵⁰. The prefabrication was also adapted by Mies van der Rohe, who contributed to societal acceptance of steel and glass tower. The Seagram Building in New York City is a good example of this³⁵¹. Although Seagram elements were standardised, the assembly process was customised, making factory process cost savings insignificant³⁵².

Following some ideas of Modernism, Richard Buckminster Fuller saw architecture as an applied technology, expressed in terms of energy, mathematics and rationality³⁵³. In 1928, he patented the Dymaxion house, efficiently designed to achieve maximum benefit with minimum energy in order to control climate conditions, which was developed further into the Wichita House prototype in 1945–1946³⁵⁴ (see Figure 2.31 and Figure 2.32). The prototype was fabricated in aluminium and fastened with rivets in a hexagonal plan followed by a fixed structural pattern. All the services were grouped at the centre core. However, Fuller stopped the production, claiming it was not ready for larger deliveries³⁵⁵.

The connection between architecture and the mass production of houses changed over the second half of the 20th century. Architects began to put their faith in influence and example more than direct intervention with the desire to change the world³⁵⁶. The most famous is the prefabricated Charles and Ray Eames House, situated in California, designed for the Case Study House Program of 1945³⁵⁷, Figure 2.33. The steel structure and other house elements were standardly designed, ordered and supplied by an industrial manufacturer to produce the cheapest space possible, with the maximum industrialisation level. Ray claimed that the new project reused steel from a previous project, reinforcing the idea of the house as a collection of mass-produced components that could one day be disassembled and rearranged³⁵⁸. In the end, this process of systematic design and construction was not affordable, not efficient and,

348 Davies 2005; Smith and Timberlake 2010.

349 Pyla 2002.

350 Berthier 2015; Smith and Timberlake 2010.

351 Guy and Ciarimboli 2005a; Smith and Timberlake 2010.

352 Smith and Timberlake 2010.

353 Krufft 1994a.

354 Ibid.; Smith and Timberlake 2010.

355 Smith and Timberlake 2010.

356 Davies 2005.

357 Ibid.

358 Ibid.

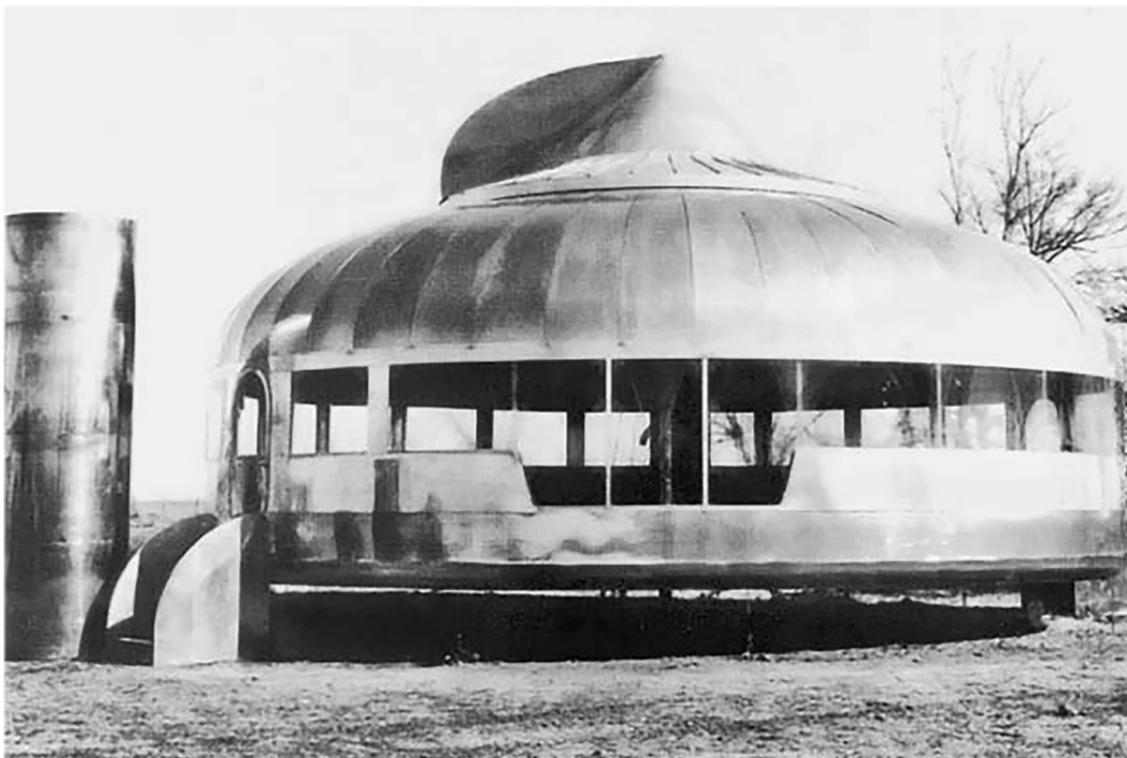


Figure 2.31. Richard Buckminster Fuller, Dymaxion House project

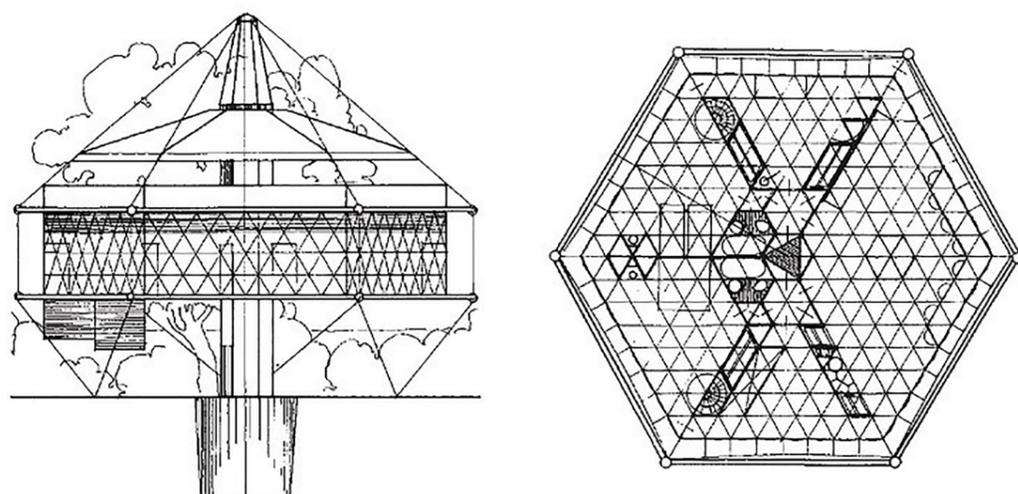


Figure 2.32. Richard Buckminster Fuller, Wichita House, 1945–1946

therefore, not repeated. Nevertheless, it represents the maximisation of the industry available at the time³⁵⁹.

The prefabrication was also affected by WWII as soldiers began to return. Based on Frederic Taylor's method of management, the technocratic approach was more attractive after the war when it was necessary to objectify, map and analyse the needs, resources and social relations for the reconstruction and relocation of cities³⁶⁰. In the US, the housing market rose in causing the federal government to pass the Veteran Emergency Housing Act (VEHA). The VEHA Act mandated the production of 850,000 prefabricated houses in less than two years³⁶¹. William Levitt benefited from the VEHA by enabling him to produce homes in the factory, systematise the on-site process and add the separation of construction planning and execution³⁶². Similar to Levitt, Jean Prouvé produced French post-war housing which included temporary prefabricated 3x3 metre huts to house soldiers³⁶³. In Western Europe, the Marshall Plan was implemented for rapid growth after World War II. Prouvé and Pierre Jeanneret developed packed and dismountable family houses made entirely of wood called Pavillons, which were 8x8 and 8x12 metres wide. These lightweight designs were quickly erectable prefabricated shelters used as a temporary housing solution. Prouvé worked to minimise waste and maximise benefits beyond designed structures that provided a frame for infill panels, systems manufactured outside the factory, and modules for cranes³⁶⁴. Like other architects, he also had Le Corbusier's projects and his Modulor as a reference³⁶⁵. The difference is that Prouvé managed to place the manufacturing industry and mass production for houses in practice. The United Kingdom's post-war housing programme mirrored that of the US. The difference was that the prefabricated houses were transitory, focusing on speed instead of quality and the support to maintain factories and create employment. Four main types of temporary bungalows manufactured in the UK were the Arcon (steel frame), the Uni-Seco (see Figure 2.34), the Tarran (both timber-framed), and the AIROH (Aircraft Industry Research Organisation on Housing) houses. The homes had a minimum floor space size of 59 m², employed a prefabricated kitchen and bathroom systems and the panels had a maximum of 2.3 m wide to allow transportation by road³⁶⁶. After WWII, the Mobile house gained attention. In 1954, many companies that began as recreational mobile trailer manufacturers shifted into producing permanent portable housing in the US. This caused a trailer size increase of from 2.45 metres to 3.00 metres-wide. They were built entirely as a module on a chassis in a factory and then trucked to the site³⁶⁷.

Yona Friedman was also concerned about the uncontrolled growth and rigidity of the contemporary city, in which housing could not be easily modified for a growing family or

359 Ibid.; Smith and Timberlake 2010.

360 Pyla 2002.

361 Smith and Timberlake 2010.

362 Ibid.

363 Berthier 2015; Davies 2005; Smith and Timberlake 2010.

364 Berthier 2015; Smith and Timberlake 2010.

365 Corbusier 2015.

366 Smith and Timberlake 2010.

367 Ibid.



Figure 2.33. Charles and Ray Eames House



Figure 2.34. Uni-Seco is being built inside

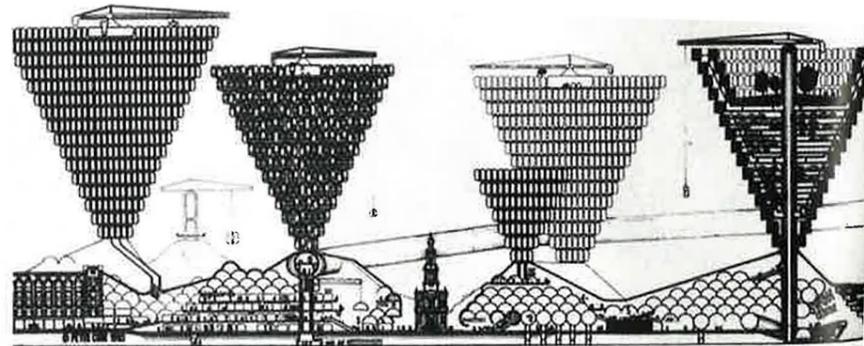


Figure 2.35. Peter Cook, Housing for Charing Cross Road, 1963

different ownership, and the relationship between an architect and a client³⁶⁸. Thus, he proposed a plan in 1957 for mobile architecture, the Ville Spatial, a huge superstructure above existing cities in which all the unit components - walls, ceilings, water and power supply - could be altered or adjusted easily to accommodate new demands. Finally, the client would have the role of supervising dwelling construction. He believed that increasing the client's power in the design process could revitalise architecture. For Friedman, a mobile project means an architectural element that could be easily modified according to consecutive inhabitants' needs and not necessarily move through space³⁶⁹. Yona Friedman's ideas were influential for European professionals in the 1960s, such as Archigram, Superstudio and Japanese Metabolism.

In the middle of the 20th century, prefabrication was exploited in high-tech architectural movements and as a Module. During the 1950s, the idea of mass-produced capsuled housing can be seen in Lonel 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 Disneyland³⁷⁰. These houses started the movement based on the space age and influenced projects like Matti Suuronen's Futuro House, 1968-1978, an early investigation of plastic's role in prefabricated housing³⁷¹. In the 1960s, Archigram's manifestos provoked debates and theories about how architecture and urbanism will move forward through propaganda and marketing imagery inspired by technology. From 1962 to 1964, the plug-in cities were set up by applying a large-scale network structure containing access, pathways and essential services. The plug-in city integrated the metal cable housing concept, a megastructure of concrete that placed removable housing elements with the ability to be updated as technology advanced and adapted to the resident as their needs changed. The Peter Cook's Housing for Charing Cross Road in 1963 and the Warren Chalk's Plug-In Capsule Homes in 1964 were good examples of the plug-in houses³⁷² (see Figure 2.35). Archigram did not build prototypes or develop technical specifications for these ideas. Although other architects further developed the group's ideas in architectural concepts and construction proposals, most of the prototypes were unique, costly and highly customised³⁷³. Among these experiences is the Zip-up House designed by Richard and Su Rodgers in 1968-1971, which would be expandable and portable tubular modules constructed from insulated aluminium panel walls with curved corners and glazed edges, see Figure 2.36. The walls, roof and floor components were to be fabricated separately offsite and attached on site to create a structural ring which was then added to complete the subdivisions³⁷⁴.

The 1960s also brought the Japanese Metabolists' manifesto, published by Kisho Kurokawa and others³⁷⁵. The central idea was the individual capsule, which was movable, prefabricated, and able to plug into a structural service core. Located in Tokyo,

368 de Wit 2009.

369 Ibid.

370 Cook 1999.

371 Bergdoll, Christensen, and Borries 2008.

372 Cook 1999.

373 Smith and Timberlake 2010.

374 Ibid.; Smith and Timberlake 2010.

375 Kruff 1994a; Smith and Timberlake 2010; Tamari 2014.

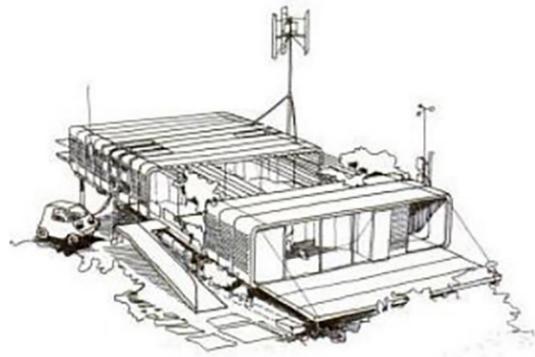


Figure 2.36. Zip-up House, Richard and Su Rodgers, 1968-1971: Sketch model



Figure 2.37. Hilton Palacios del Rio, Riverwalk, 1968

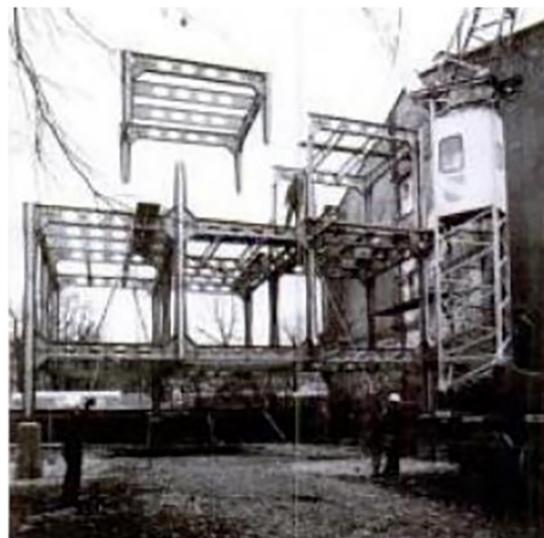


Figure 2.38. Metastadt-Bausystem, Richard Dietrich, 1969-1972: Experimental structure

the Nakagin Capsule Tower by Kurokawa is the most famous example of Japanese Metabolism. The project consists of 144 individual, movable and prefabricated capsules attached in two interconnected concrete towers³⁷⁶. Unfortunately, the modules have never been exchanged, and the building has deteriorated³⁷⁷. Kurokawa even claimed that his technology “meta-architecture”, with its notion of natural organic life cycles, introduced an ecological system into architecture³⁷⁸.

Influenced by Metabolisme and Archigram, Moshe Safdie at the 1967 World Expo in Montreal designed his first built project, the Habitat 67 housing complex³⁷⁹. It consisted of 158 houses constructed from 354 modular reinforced precast concrete units manufactured offsite. The units could be combined providing different sizes for residents. The blocks were too heavy to be easily installed or relocated, had too many variations, required specific tools, towering cranes and intensive labour³⁸⁰. Following the same concepts, the Hilton on the Riverwalk was built from prefabricated modules by Zachary Construction Corporation in 1968 as the tallest modular building in the US³⁸¹, see Figure 2.37. The 496 module units were fitted inside with a pre-installed external window. The building was designed to allow for changes to the modules over time, but the concrete modules were too heavy and depended on one another for structural stability, making this impossible³⁸².

The latest modernists used the building’s inner workings as an aesthetic. Louis J. Kahn contributed to the prefabricated architecture revealing materials and systems (precast columns, vierendeel girders, and beams) and its construction method for aesthetics and design³⁸³. In 1969, Richard Dietrich started the implementation of his *Metastadt-Bausystem* (Meta city building system) with Bernard Steigerwald and others (see Figure 2.38). His approach drew attention to the gradual city centres’ redensification with a global structural system, mixing urban uses such as residential, work, commercial, cultural and entertainment spaces. The steel structural system with its joints could be adapted to a specific spatial requirement. The superstructure and the ground floor could be changed and expanded at any time, or the structure could be disassembled. An experimental prototype of *Metastadt-Bausystem* was erected on the grounds of Technische Hochschule in 1971. The project combined city planning, architecture and structural engineering³⁸⁴.

Going in the same direction of a structural system, the Centre Georges Pompidou, designed by Renzo Piano and Richard Rogers between 1971 and 1977, brought superstructure and internal mechanical core and utility systems wholly exposed to the viewer, see Figure 2.39. In addition, this design provides open, flexible floor plans

376 Kruft 1994a; Smith and Timberlake 2010.

377 Smith and Timberlake 2010.

378 Ibid.; Tamari 2014.

379 Smith and Timberlake 2010.

380 Ibid.

381 Ibid.

382 Smith and Timberlake 2010.

383 Ibid.

384 Bergdoll, Christensen, and Borries 2008.

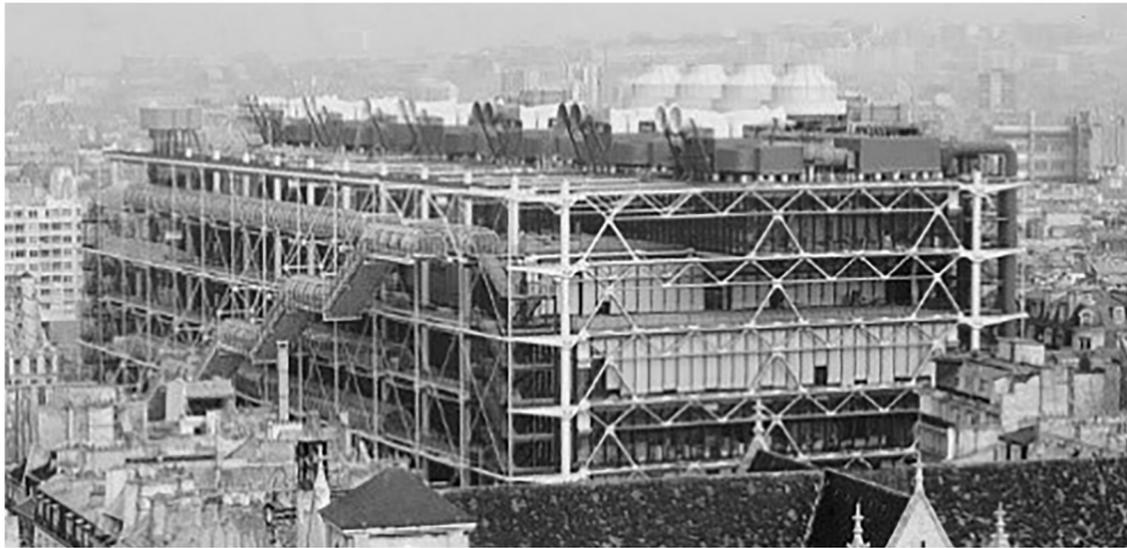


Figure 2.39: Centre Georges Pompidou, 1971–1977, Renzo Piano and Richard Rogers



Figure 2.40: Dortheavej residence, 2018, Big

within the envelope of the building structure, redefining the function of prefabrication in the architecture³⁸⁵. The Yacht House also followed the structural system concept. Richard Horden designed it in 1983 with naval technology for construction consisting of a lightweight frame and infill panel system. The house was expanded into a grid, mixing design with technology³⁸⁶.

The prefabrication period was an era of architectural ideas. The prefabricated architectural constructions were designed to put them on the scene of mass production and stand out over conventional architecture, as did the architects who designed them even if they had not yet reached a high degree of prefabrication during the construction phase. Due to a lack of cooperation between manufacturers and designers the systems became too customised and as a result made them inappropriate beyond being a prototype³⁸⁷.

Nevertheless, the unique and primary creation of form and design are potent aspects. Recently, housing manufacturing methods have been used to establish a different level or degree of quality. This evolution can be seen in projects from companies and architects such as Michael Maltzan Architecture in Stars Apartments, incorporating prefabrication to shape social interaction spaces within the city, BIG in Dortheavej residence which is based in a prefabricated structure and housing modules repetition, Figure 2.40, and Michelle Kaufmann and Joe Tanney in Resolution: 4 Architecture, who used the modular boxes to imbue a higher level of sustainability, control of quality and craftsmanship. In contrast, the main tenants of these houses focused on advantages such as the reduction of overheads, on-site labour and initial cost³⁸⁸. Prefabricated modules and panels are the main methods used today to provide internal design or factory-based housings. Flexibility, speed and easy installation have made these construction units an essential item on the market³⁸⁹.

Prefabrication and offsite assembly of modules held promise for the foreseeable future as an alternative to conventional building and architectural design practices and to reduce waste generated during construction. However, prefabricated architecture is not new, and the aspects of history in which it was most relevant often reflect today's circumstances³⁹⁰. Five of the architectural projects relevant to the scenario of housing existing building construction in prefabrication were deeply analysed and presented in Section 2.2.1.

385 Guy and Ciarimboli 2005a; Smith and Timberlake 2010.

386 Bergdoll, Christensen, and Borries 2008; Smith and Timberlake 2010.

387 Smith and Timberlake 2010.

388 Smith and Timberlake 2010.

389 Ibid.

390 Ferreira Silva et al. 2020.

2.2.1. Prefabricated buildings

Pavillon 8x8 Housing packed, Jean Prouvé, 1947

Jean Prouvé patented in 1939 a dismantlable metal frame construction as a module. After the second war, the need for housing for soldiers in France had risen drastically and temporary pavilions were proposed as a solution³⁹¹. The Figure 2.41, Figure 2.42 and Figure 2.43 show the Pavillon 8x8, a movable module 8 metres wide. This technical data determines a minimum surface area of 64 m² per module, which is considered adequate living space for a user. It consisted of prefabricated timber panels assembled in situ on a masonry base that was adjusted according to the particular soil conditions. The structural system was steel-framed³⁹². The concept of a prepacked dismantlable house is strong, and the project's realisation showed that it is feasible. The design of the house is simple and replicable in different dimensions, apart from the possibility of being timber or steel framed as well as having an adaptable interior area suitable for the user.



Figure 2.41. Pavillon 8x8 Housing packed, Jean Prouvé, 1947 - Assembling the prototype Pavillon 1944

391 Berthier 2015; Davies 2005; Smith and Timberlake 2010.

392 Berthier 2015.

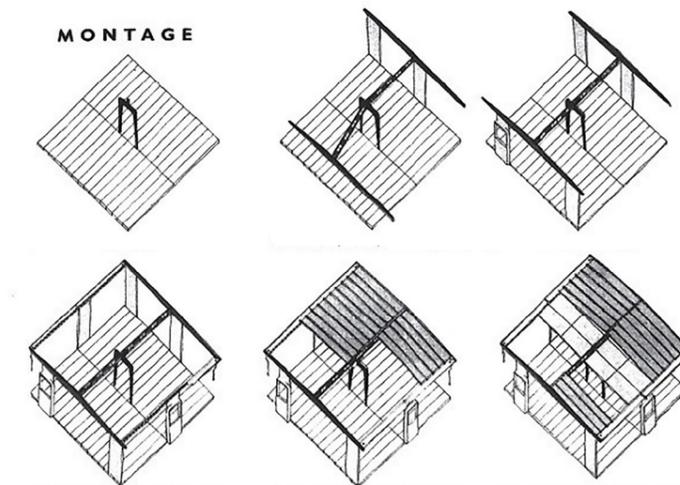


Figure 2.42. Pavillon 8x8 Housing packed, Jean Prouvé, 1947 - Prefabricated house type assembly diagram

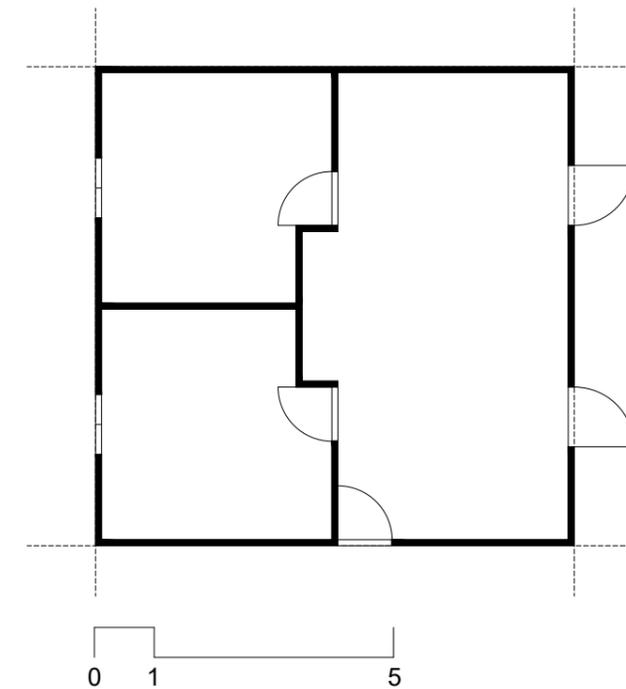


Figure 2.43. Pavillon 8x8 Housing packed plan

STRUCTURE: Steel
Frame

MODULE/ GRID (m)
Length: 8,0
Width:8,0
Height:3,0

INTERNAL DIMENSIONS
(m)
Length: 7,8
Width:7,8
Height:3,0
Total Area (m²): 64,0

BUILDINGS DIMEN-
SIONS(m)
Length: 8,0
Width:8,0
Height:3,6

Habitat 67, Moshie Safdie, Montreal, 1967

The Habitat 67 project was designed for the Montreal World Expo in 1967. The modular unit serves as the base for the 12 storey housing complex, constructed from 354 modular units arranged in 158 houses, pedestrian streets and suspended terraces, Figure 2.44. The modules were prefabricated reinforced concrete manufactured offsite. The concrete units were stacked on top of one another, which creates space for gardens and open-air decks³⁹³. Figure 2.45 shows 3 different housing arrangement with the concrete blocks, single modular unit, duplex and with four modules. The modules were not simple to move or install due to their weight and required special equipment. Large cranes and manual labour were used to connect the modules on site. This plug-and-play concept went over budget as a result of the selected fabrication material and difficulty posed by the erection of the modules³⁹⁴. However, the rationalisation expressed by the models and their interconnection to arrange the dwellings in different sizes together with the urban densification provided architects to rethink the architectural function in the city.

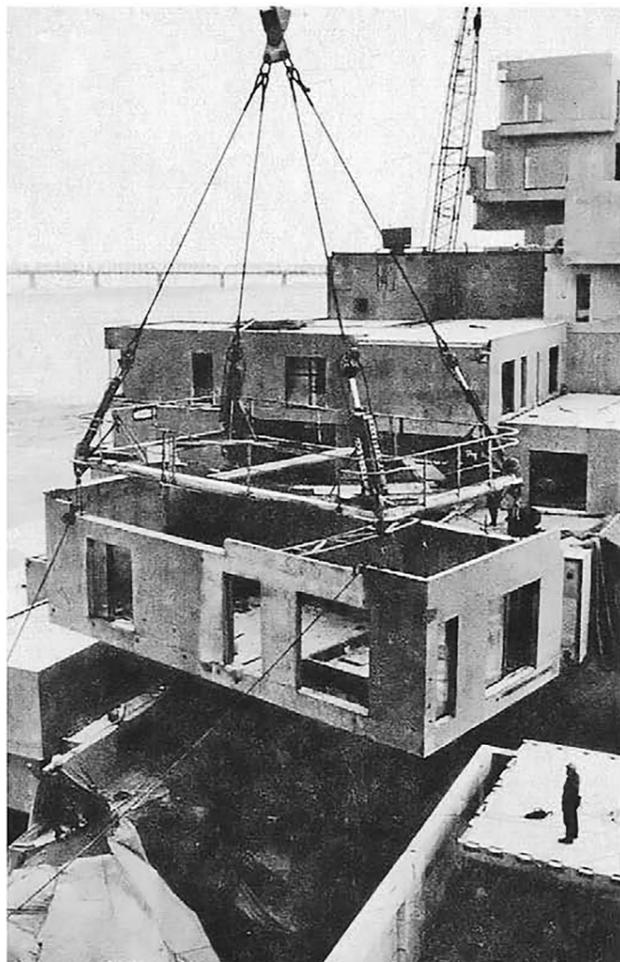


Figure 2.44. Habitat 67, Moshe Safdie, Montreal, 1967 – Construction phase



Figure 2.45. Habitat 67 module dwelling floor plans

STRUCTURE: reinforced precast concrete

DIMENSIONS FOR MODULAR UNIT
MODULE/ GRID (m)
Length: 11,7
Width: 5,3
Height: 2,6

APARTMENTS INTERNAL DIMENSIONS
Length: 11,5
Width: 5
Height: 2,27
Total Area (m2) 57,5

BUILDINGS DIMENSIONS(m)
Length: 306.8
Width: 62.4
Height: 42

393 Smith and Timberlake 2010.

394 Ibid.

Nakagin Capsule Tower, Kisho Kurokawa, Tokyo, 1968-1972

The Nakagin Capsule Tower represents the ideas of the Metabolism movement. The tower was initially designed as an affordable hotel for businesspeople who could not go back home at the end of the day. The building has two central cores with 144 moveable, prefabricated and plug-in and -out individual capsules, Figure 2.46 and Figure 2.47. The residential units were completely fabricated offsite³⁹⁵. The modules are the same, with a concise layout for essential needs, a built-in bed and a drop-in bathroom unit, without the possibility of adding more space³⁹⁶, Figure 2.48. The building has evolved into a multi-use complex comprising hotel space, residences and office spaces³⁹⁷. Kurokawa believed that the modules could be easily extracted or connected when the tenants moved out or when the interior of the modules had to be updated³⁹⁸. However, the building has deteriorated and has never been changed or extracted from its core purpose³⁹⁹. Even so, the idea that the small module accommodation could be removed for maintenance or replacement was innovative. In addition, the design celebrates flexibility by its ability to accommodate small spaces and reinventing itself to the city's needs.



Figure 2.46. Nakagin Capsule Tower, Kisho Kurokawa, Tokyo, 1970–1972 - Facade

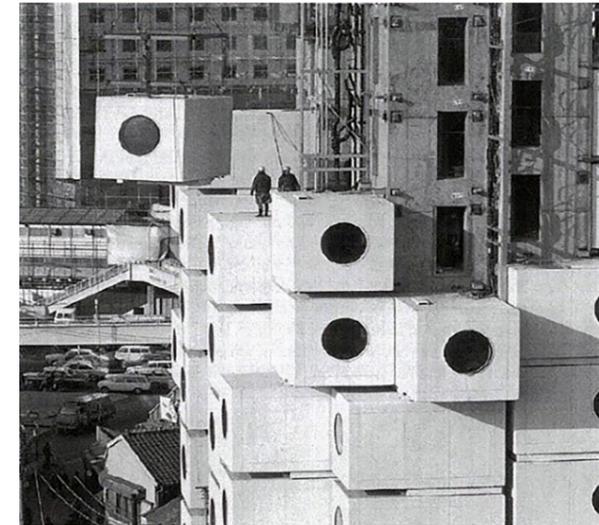


Figure 2.47. Nakagin Capsule Tower, Kisho Kurokawa, Tokyo, 1970–1972 - Construction phase modules integration

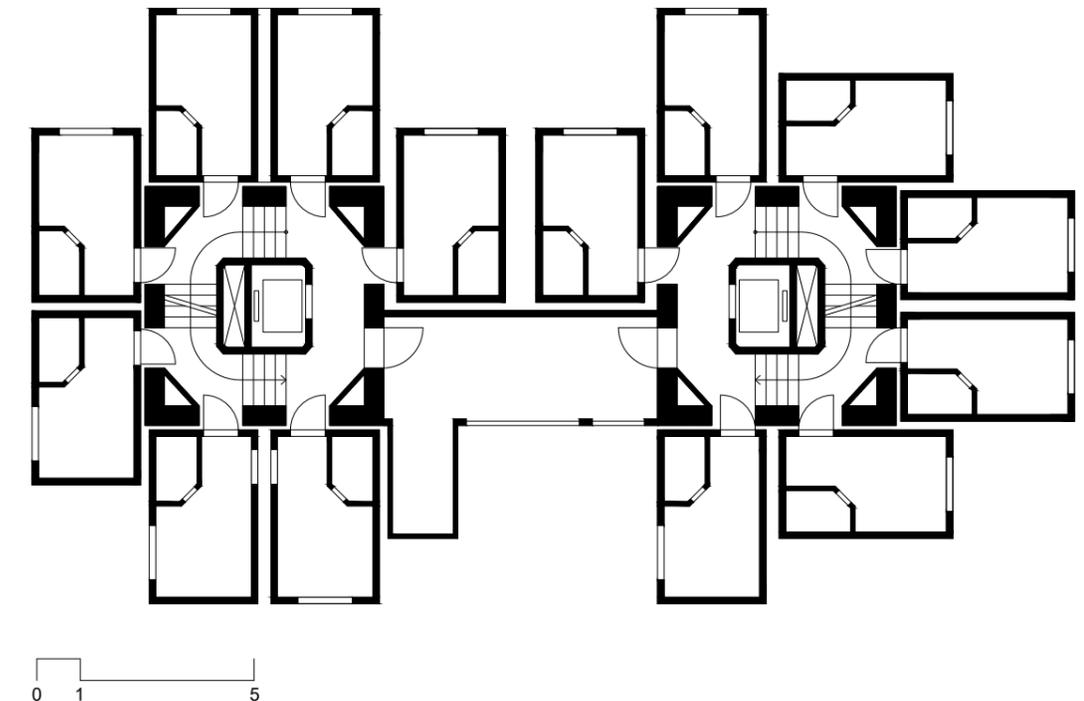


Figure 2.48. Nakagin Capsule Tower typical floor plan

395 Bergdoll, Christensen, and Borries 2008; Kruff 1994a; Smith and Timberlake 2010.
 396 Smith and Timberlake 2010.
 397 Bergdoll, Christensen, and Borries 2008.
 398 Smith and Timberlake 2010.
 399 Bergdoll, Christensen, and Borries 2008; Smith and Timberlake 2010.

STRUCTURE:	APARTMENTS INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
reinforced concrete core	Length: 4,0	Length: 24,0
	Width: 2,5	Width: 14,0
	Height: 2,5	Height: 54,0
MODULE/ GRID (m)	Total Area (m2) 10,0	
Length: 4,0		
Width: 2,5		
Height: 2,5		

Yacht House, Richard Horden/Horden Cherry/Lee Architects, Hampshire, UK – 1983-1992

The Yacht House was a part of the High-Tech movement in the UK. The project illustrates the connections between design and technology. It was built for a family who wanted to expand their property. The original house was a single-storey design to allow a space frame grid of cubic units, Figure 2.49. The structure was in steel tension to hold the frame together and supported by a concrete foundation⁴⁰⁰, Figure 2.50. This membrane acts like a strong wind frame, increasing the structure and function as the armature into which the floor, roof and interior wall modules lock. The owners assembled the house by themselves⁴⁰¹. The structure of the building is arranged by columns in a grid of 3.7 m, composed of square 5 x 5 bays, giving a footprint of 342 square metres, Figure 2.51. The entrance is located over the axis and central part of the building. The roof and covering modules can be moved to reorder the layout and additional bays if the owner desires⁴⁰². Made from an assembly of recognisable yacht components, it was designed for a new purpose, lending buildings a sense of lightness and dynamism and retaining domestic design requirements⁴⁰³.



Figure 2.49. Yacht House, Richard Horden et al, UK, 1983-1992 - Exterior view

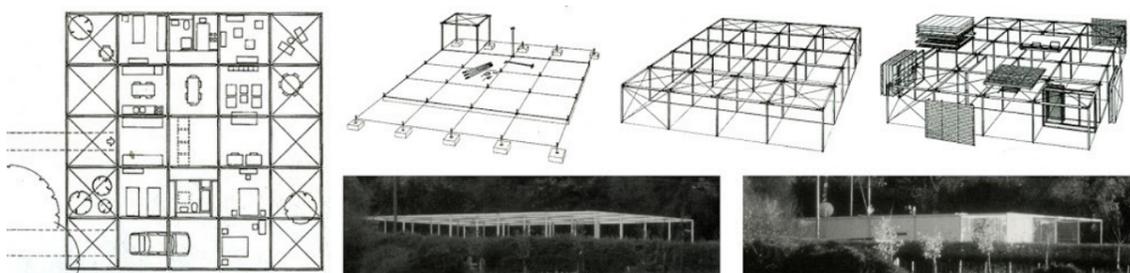


Figure 2.50. Yacht House, Richard Horden et al, UK, 1983-1992 - Assembly process

400 Bergdoll, Christensen, and Borries 2008.
 401 Ibid.
 402 HCL Architects 1992.
 403 Kronenburg 2008.

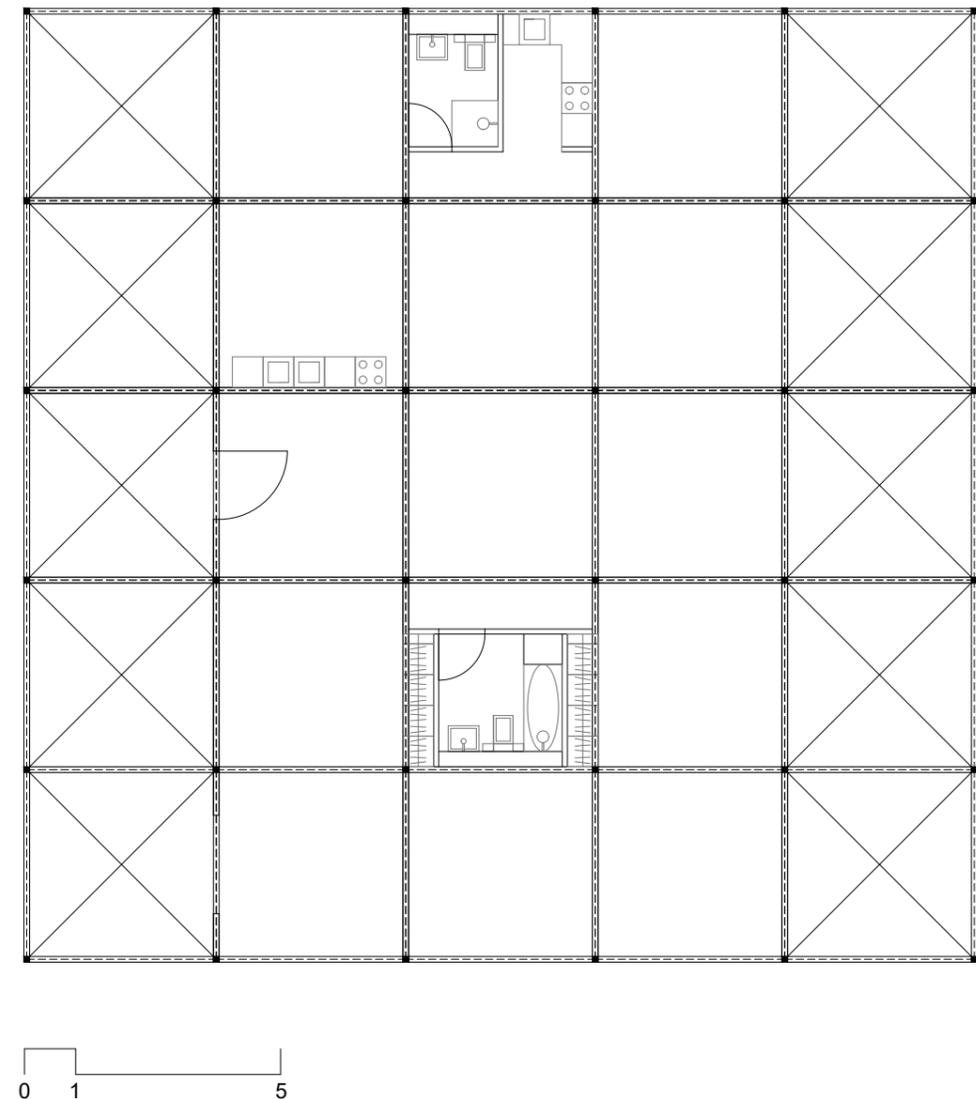


Figure 2.51. Yacht House floor plan

STRUCTURE: aluminium and stainless steel spars

MODULE/ GRID (m)
 Length: 3,7
 Width:3,7
 Height: 3,0

INTERNAL DIMENSIONS (m)
 Length: 18,5
 Width:18,5
 Height:3,0
 Total Area (m2): 342,0

BUILDINGS DIMENSIONS(m)
 Length: 18,5
 Width: 18,5
 Height:3,0

Stars apartments, Michael Maltzan Architecture, Los Angeles, California, US, 2014

The Star Apartments are a part of the Skid Row Housing Trust project for the formerly homeless. The apartments increased density and transformed an existing one-storey commercial building into a mixed-use complex while adding shared community spaces and 102 apartments on the levels above, Figure 2.52. The buildings are arranged around three principal zones stacked one on top of another comprising a street-level public health zone, a second level for wellness and community activities (community kitchen, meeting room, art room, library, recreational spaces such as running/walking track, exercise room and a pickleball court), and four residential levels. The studios have a kitchen, bathroom and bedroom, Figure 2.53. With a limited budget and schedule, the use of prefabricated modules raised in place of the existing podium provided higher precision and accelerated construction time⁴⁰⁴. The building stands out by utilising the existing building as support to the new residential units as well as with the integration of an expansive and communal wellbeing area on the second floor, integrating the internal physical and social space with the city.



Figure 2.52. Stars apartments, Michael Maltzan Architecture, US, 2014 - Perspective



Figure 2.53. Stars apartments typical residential floor plan

STRUCTURE: concrete and wood

MODULE/ GRID (m)
Length:9,0
Width:3,5
Height:

APARTMENTS INTERNAL DIMENSIONS (m)
Length:8,8
Width:3,3
Height:
Total Area (m2):

BUILDINGS DIMENSIONS(m)
Length:51,0
Width: 48,5
Height: 7 levels

2.3. The ecology in architectural design

In addition to the ecological concepts and trends presented in the introduction, architects have been developing architectural projects to integrate them. Ecology deals with organisms and their environment, including interactions between other organisms, populations and the physical environment⁴⁰⁵. Architecture is one of the mediators of the relationship between nature and humans⁴⁰⁶. Therefore, ecological architecture has the role of producing a building integrated into the environment, adapted to the climate, has natural resources and reducing the waste of energy and materials. For this reason, the connection between recyclability and ecology nowadays is clear. Recycling and reusing practices have existed as long as humans have been in the world. Stones or parts from buildings no longer needed or abandoned were used to build new houses or facilities⁴⁰⁷. Over time and with human evolution, trash production has become enormous, and its requalification and recycle has been forgotten or made impossible. Today, recyclability and reusability are necessary to reduce dependence on landfills and incinerators, preserve natural resources by reducing the purchase of raw materials, and protect the environment and human health by removing harmful substances from the waste stream⁴⁰⁸. Similar to modular and prefabrication research, this section presents facts and projects to understand how the ecological concepts were implemented in the construction to approach recyclable and reusable architecture.

Through the first half of the twentieth century, the driving factor of recycling was its monetary value. In 1885, New York City discovered a solution fit for its time, a policy for waste management to bury it or burn it. To accomplish this, an incinerator was built on Governor's Island to burn the remaining materials without reuse or recycling. Other cities soon followed suit. However, through ingenuity, people saw an opportunity to create value out of this waste which motivated private efforts to recycle or reuse⁴⁰⁹. During the Great Depression of the 1930s, many people were unemployed and could not buy essential items or afford to waste anything⁴¹⁰. Therefore, when it made economic sense or met a financial need, people took cans to a recycling centre or picked through garbage for items to sell. Anything left over was burned or tossed into trash yards⁴¹¹.

The initial influences of ecology concepts in architecture can be seen in the post-war reconstruction of the Netherlands by J.H. Van den Broek and Jaap B. Bakema⁴¹². His discourses reflected a holistic view of the world - space, form, structure, man - recommending architecture with a starting point in the landscape and basic concepts such as Space, Nature and Energy⁴¹³. However, in the 1950s, garbage or the reuse

405 Demos 2017; Pimm and Smith 2019.

406 Schröpfer 2012.

407 Hillebrandt and Seggewies 2019.

408 EPA 1988.

409 Byers 2018.

410 Ibid.

411 Ibid.

412 van Es 2016.

413 Krufft 1994a; van Es 2016.

of waste had little value and did not grasp the public's interest. Where waste was encouraged, items were used once and thrown away. At that time, the garbage was still compacted every day and covered with soil. These actions helped control odour and flies, but the rotting garbage under the layers of earth released toxic gases. These issues did not reach the public until the environmental movements on the 1960s and 1970s⁴¹⁴.

The first Earth Day in 1970, together with similar events in several countries, garnered international concern about pollution issues primarily related to waste⁴¹⁵. The land, water and air were devastated because people were not dealing responsibly with their waste. As a result, the various movements sought to find ways to eliminate or reduce waste⁴¹⁶. In addition to the waste problem, the concern with the possibility of material depletion started in 1970. The US oil production peaked and forced a dramatic rise in the price of energy, products and services across the entire global supply chain⁴¹⁷. By 1972, environmental awareness had reached a global level⁴¹⁸. The United Nations Conference on the Human Environment was held in Stockholm, leading to the creation of environmental agencies including the UN Environment Program⁴¹⁹. The Club of Rome, an association of science and political leaders, emphasised the growing pressure on natural resources in their report *The Limits to Growth*⁴²⁰. In 1997, the Kyoto Protocol international agreement was signed to stabilise greenhouse gas atmospheric concentrations to prevent dangerous interference in the climate system⁴²¹. Consequently, projects started to focus on obtaining the maximum performance with minimal resources, and new architectural solutions emerged.

The architect Emilio Ambasz stood out by combining building and nature. To investigate this relationship of built, natural and socio-cultural environment, he created the *Universita's Project*, a cooperation between MoMA and the Institute of Architecture and Urban Studies (IAUS). The project explored a new type of institution focused on evaluating and designing the environment created by man. Gyorgy Kepes is one of the designers present in the project at MoMA, drawing attention to the artist's role as an advocate for environmental balance that consists of educating the public, bringing new experiences to cities, forms or visual patterns that serve for ecological awareness⁴²². In addition, Kepes investigated the relationship between biological and social evolution, where individual consciousness is expanded to a social and environmental consciousness for the common good⁴²³.

414 Byers 2018.

415 Ibid.

416 Ibid.

417 Rifkin 2011.

418 Ibid.

419 Colini and Eckardt 2011.

420 Donella H. Meadows et al. 1972; Colini and Eckardt 2011.

421 UNFCCC 2008.

422 Colini and Eckardt 2011.

423 Ibid.

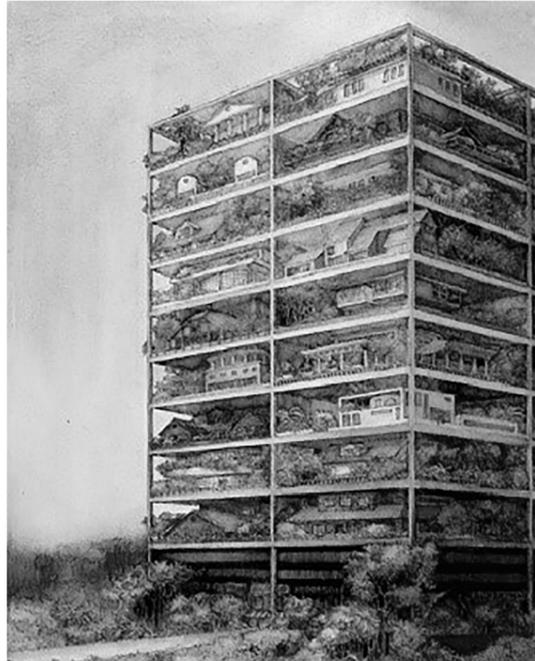


Figure 2.54. SITE, High-rise of homes, 1981



Figure 2.55. NEXT21, Yositika UTIDA, Shu-Koh-Sha Architectural and Urban Design Studio, 1993



Figure 2.56. Tamedia Office Building, Shigeru Ban Architects, Zurich, Switzerland, 2013

An up and coming application of ecology in architecture that is still in the design phase is the High-rise of Homes, a theoretical project developed by SITE in the US from 1981 (see Figure 2.54). 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 personalised architectural identity⁴²⁴. Inspired by SITE, Frei Otto saw architecture as a way to improve humans' 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 architecture⁴²⁵. Through research, he developed a new form of natural, adaptable, flexible and lightweight construction to build with minimum consumption of material, energy and economic means⁴²⁶. In 1990, Otto applied these principles in the Ökohäuser (Ecological houses) in Berlin, a vertical structure composed of three residential houses with a concrete skeleton positioned on solid columns. The inhabitants customised the open and raw structure with the architect's support and guidance. Initially, new families were supposed to demolish the oldest and start over again, but this has never been the case⁴²⁷. The project opens the discussion about flexibility, individual housing in a community and ecology despite the lack of is guarantee it will be affordable and that the families will keep the concepts⁴²⁸. Another project that has the same characteristics is NEXT21 from Yositika UTIDA, Shu-Koh-Sha Architectural and Urban Design Studio, developed in 1993 in Japan, Figure 2.55. The project is an experimental multi-family housing, in which the structure consists of one basement floor and six floors above articulated as a frame, infill and cladding. Thirteen different architects designed the apartments. The structural system offers the possibility of different living arrangements and independent components such as mechanical and electrical equipment⁴²⁹. Even though the structure is independent, the internal layout of the apartments never had significant alterations.

In the late 2000s, the Tiny Homes movement started in North America as a result of the housing market crash. These tiny homes were usually 37 m² or smaller, meaning the homeowners could 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"⁴³⁰.

Technology was more emphasised and integrated with ecological and prefabrication concepts by architects. For example, Werner Sobek designed the R128 single-family house in 1998–2000. The exposed bolted steel frame, bathroom modules and modular glazing panels were prefabricated offsite⁴³¹ and can be dismantled, allowing its materials

424 SITE 1981.

425 Meissner and Möller 2015

426 Ibid; Nerdinger 2005.

427 Offbeats 2017.

428 Ferreira Silva et al. 2020.

429 Schmidt III and Eguchi 2014; Minami 2017.

430 Mok 2018.

431 Guy and Ciarimboli 2005a.

to be either reused or recycled. It was designed to produce no emissions and is self-sufficient in heating energy demand⁴³². Sobek also developed the UMAR research project which focuses on the reusability and recyclability of materials for a modular housing unit⁴³³. Another example is the works of Michael Jantzen that merge art, architecture, technology and sustainable design into the project. His famous prototype is M-vironments/M-house, from 2000. The system consists of hinged rectangular panels attached to an open room grid of seven embedded cubes that can be assembled and disassembled to accommodate some needs⁴³⁴.

Another interesting project for today's needs is R50 Cohousing, designed by the Heide and Von Beckerath office built in Berlin from 2010 to 2013. 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 unfinished surfaces, open design and standard grid for fixtures allows resident participation in interior layouts⁴³⁵.

The choice of materials for architecture is also part of the ecological strategies. For example, timber is a renewable material that is considered the most crucial biotic building material⁴³⁶. Herzog & de Meuron designed the 029 Apartment Building in modular wood for a competition to expand an existing building in Basel, Switzerland. In 2013, Shigeru Ban proposed the Tamedia Office Building in Zurich with the main structure completed in wood with a glazed façade, see Figure 2.56. The rigid frame of beams and columns have no joints and steel struts. In addition, it has 3.2x10.98 m and 3.2x3.2 m spans, which the smaller ones have the stairs as an intermediate area between the exterior and interior⁴³⁷. The use of wood is employed as well on the project Kajstaden Tall Timber Building, by C.F. Møller, Martinsons & Slättö Förvaltning, Sweden constructed in 2016–2019, an example of the use of timber in residential construction.

Apart from Shigeru Ban and Werner Sobek, other architects nowadays develop environmentally-conscious projects. This design can be seen in the works of Lacaton & Vassal, where the building is reused for a different purpose with minimal interventions or is refurbished to adapt to users' needs to avoid demolition, e.g. Palais de Tokyo in Paris and Tour Bois-le-Prêtre in Paris respectively⁴³⁸. Arno Brandhuber, in the refurbishment case of Antivilla, Figure 2.57, proposed strategies to keep as much of the existing building as possible to avoid building demolition and to consume less energy, such as the use of curtains to reduce the floor area and diminish the use of heating⁴³⁹. Another

432 Werner Sobek AG 2014.

433 Heinlein and Sobek 2019a.

434 Jantzen 2000.

435 Heide & von Beckerath 2013.

436 Hillebrandt 2019.

437 Shigeru Ban Architects 2013.

438 Petzet and Heilmeyer 2012.

439 Brandhuber 2015.; Petzet and Heilmeyer 2012.

architect is Eduard François, who was more focused on bringing nature to the interior of the construction, using plants and other natural materials such as Tower Flower project. Lendager Group proposed projects that use locally sourced and recycled materials while adhering to technical and legislative requirements, such as reusing materials from abandoned homes to build and use in new ones⁴⁴⁰. In the first phase, a Rotor Deconstruction cooperative is working to collect reusable materials from the construction before demolition. Finally, Chris Precht proposes high-rise buildings as vertical farms and modular homes in timber structures.

There is no simple solution to deal with ecological architecture and garbage problems; a combination of them must be considered. To improve some solutions, the environmental movement's international slogan "Reduce/Reuse/Recycle" (3Rs) incorporates the waste hierarchy, classifying it in order of priority and evaluating methods according to energy consumption and loss⁴⁴¹. "Reduce" aimed to avoid and minimise waste, "Reuse" aimed to use something more than once before throwing it away and "Recycle" is a way of processing material from end-of-life so it can be used for a new purpose⁴⁴². Further recovery refers to both reuse and recycling⁴⁴³. In architecture, the 3Rs create a hierarchy of strategies. First, with fewer interventions by extending, adapting and continuing what is already there using less energy. Second, from demounting built extensions and converting waste into valuable material. Finally, giving a new place or function to the building or elements that differs from the first building's purpose⁴⁴⁴. Adaptive reuse is an alternative to demolition and is applied to saving material resources, avoiding urban expansion and preserving the appearance of urban landscapes⁴⁴⁵. To exemplify ecological architecture strategies and to understand the relation between them, some projects mentioned here in above were analysed further and are presented in Section 2.3.1.



Figure 2.57. Antivilla, Arno Brandhuber, Berlin, 2010-2015 – Façade

440 Lendager Group 2017.

441 Byers 2018; Petzet and Heilmeyer 2012.

442 Byers 2018; Lambert and Gupta 2004, vol. 19; Petzet and Heilmeyer 2012; EPA 1988.

443 Lambert and Gupta 2004, vol. 19.

444 Freschi and Maas 2017; Petzet and Heilmeyer 2012.

445 Freschi and Maas 2017.

2.3.1. Ecological buildings

Ökohäuser, Frei Otto, Berlin, Germany, 1987-1990

In the early 1980s, Frei Otto developed a vertical structure called Ökohäuser, composed of three residential buildings with a concrete skeleton positioned on solid columns, Figure 2.58, Figure 2.59 and Figure 2.60. The inhabitants themselves customised the open structure with Frei Otto's support and the guidance of the architects selected by each family⁴⁴⁶. They had to follow ecological requirements, such as installing large windows, setting up green roofs and conserving the existing green surroundings. The idea was that a prominent concrete structure had to be built as cheaply as possible to keep it affordable. Initially, new families were supposed to demolish the oldest and start over again, but this has never been the case⁴⁴⁷. The project opens the discussion about flexibility, individual housing in a community and ecology. In contrast, there is no guarantee that it will be affordable or that the families will actually keep the concepts⁴⁴⁸. The project intended future change but this never happened and they did not think of a way that they could demolish the building without generating waste.

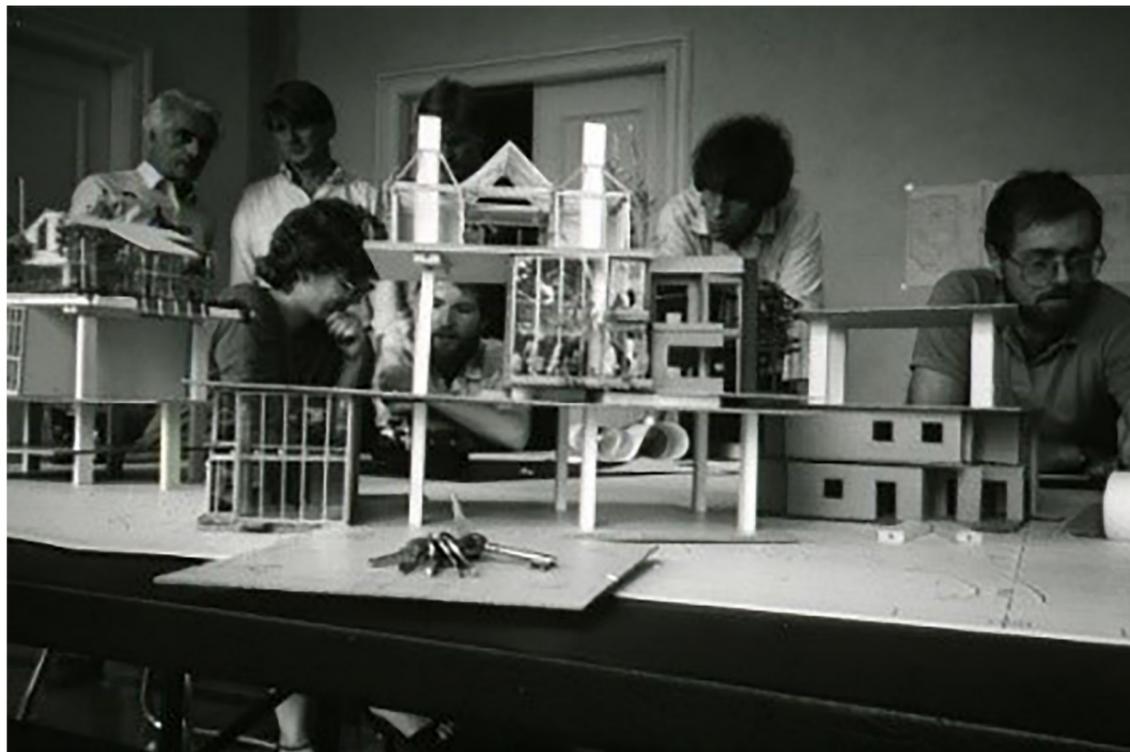


Figure 2.58. Ökohäuser, Frei Otto, Germany, 1990 – Prototype

446 Meissner and Möller 2015

447 Offbeats 2017.

448 Ferreira Silva et al. 2020.



Figure 2.59. Ökohäuser, Frei Otto, Germany, 1990 – Façade

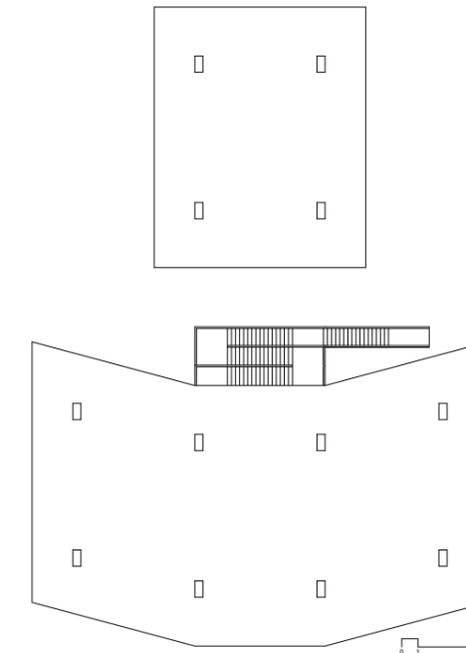


Figure 2.60. Ökohäuser, Frei Otto standard floor plans

STRUCTURE: Concrete	INTERNAL DIMENSIONS(m)	BUILDINGS DIMENSIONS (m)
MODULE/ GRID (m)	Length 14,45	Length: 28,0
Length 7,5	Width 6,5	Width: 16,0
Width 9,0	Height 2,6	Height: 18,0
Height 6,0	Total Area (m ²): 198	

029 Apartment Building, Herzog & de Meuron, Basel, Switzerland, 1987-1988

The 029 Apartment project was developed for a competition to expand an existing building in Basel, Switzerland. The building was mainly constructed in modular wood marked by slender supports, Figure 2.61 and Figure 2.62. The apartment block continues the neighbourhood's courtyard development, expanding the existing wing's façade. The rooms follow the linear configuration, and the staircase is centralised as seen on Figure 2.63. The bottom two floors are covered with oak panels that create a sort of wooden interspace between the inside (living room) and the outside (garden)⁴⁴⁹. The apartments presented the spaces separated by the partitions, organised by a living room, kitchen, bedrooms and bathroom. The project brings the idea of expansion and rationalisation provided by the modular wood structure prefabricated offsite.



Figure 2.61. 029 Apartment Building, Herzog & de Meuron, Basel, Switzerland, 1987-1988- Façade

449 Herzog & de Meuron 2019.



Figure 2.62. 029 Apartment Building floor plans



Figure 2.63. 029 Apartment Building floor plans

STRUCTURE: timber-framed	APARTMENTS INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
MODULE/ GRID (m) Building	Length:6,7 smallest	Length:34,1
Length:5,4	Width:6,0	Width:8,8
Width:2,9	Height:	Height:
Height:	Total Area (m2):40,2	

R128, Werner Sobek, Stuttgart, Germany, 1998-2000

Werner Sobek designed the R128 four-storey single-family house to be recyclable, zero-emission and self-sufficiently heated by means of solar cells⁴⁵⁰, Figure 2.64. The assembly employing offsite pre-fabrication and modular systems can be dismantled, allowing its materials to be either reused or recycled⁴⁵¹. The house forms a cubic shape and the structure is an exposed bolted steel frame with a triple glazed panel is modular to reduce weight and optimise the efficiency of construction and connections. Figure 2.65 shows the floors plans for the house. The mechanical systems and the plumbing are positioned in vertical and horizontal bases or channels. The bathrooms are prefabricated modules inserted into the building⁴⁵². The offsite prefabrication and the super exposition of materials, technology and operating systems of the house can facilitate effective disassembly and reuse of the materials. These characteristics could be implemented in high rise buildings.



Figure 2.64. R128, Werner Sobek, Germany, 1998–2000 – Façade

450 Mandoul et al. 2012; Werner Sobek Group 2019.

451 Ibid.

452 Guy and Ciarimboli 2005b.

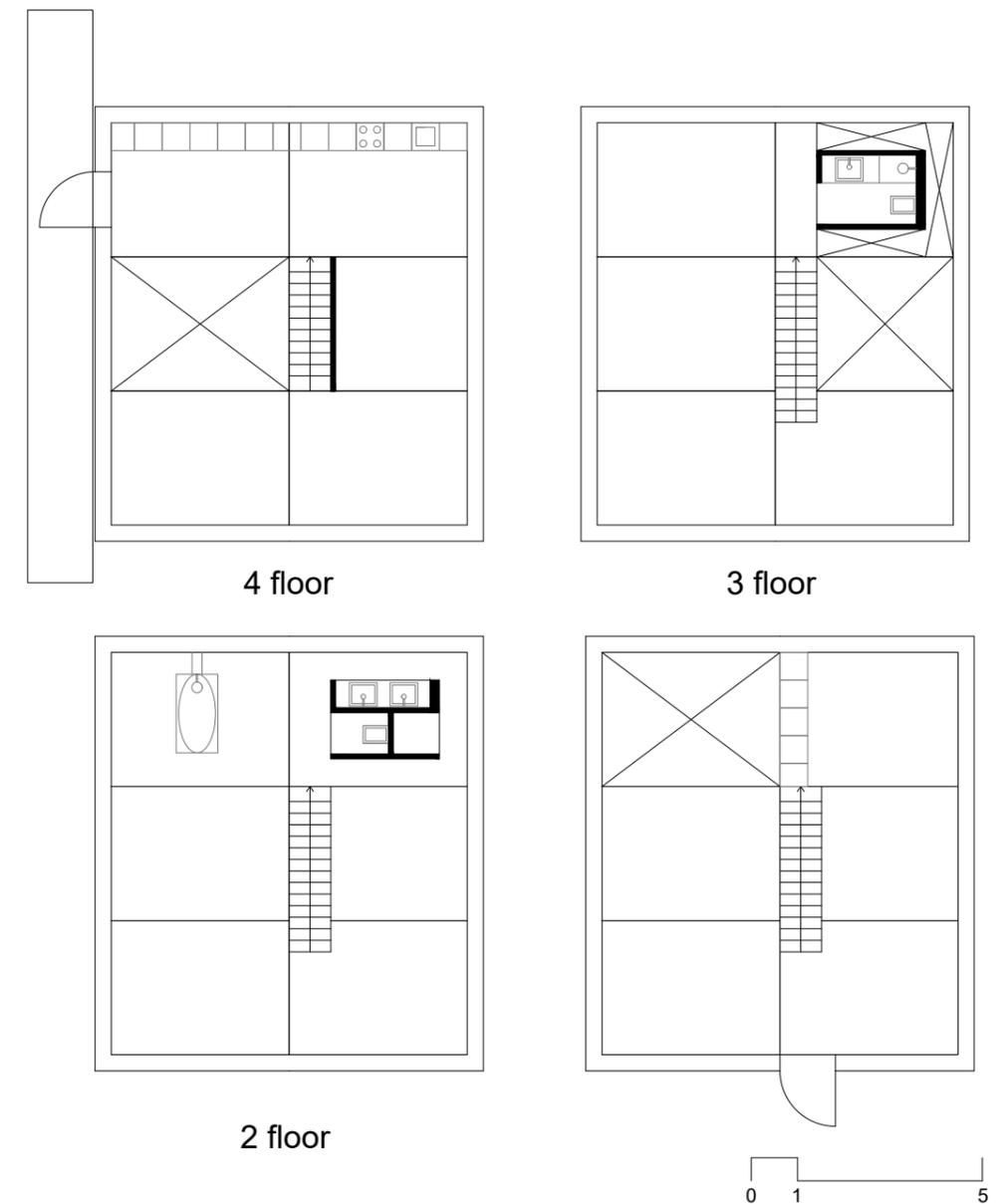


Figure 2.65. R128 Werner Sobek housing plans

STRUCTURE: steel structure and glass facade	APARTMENTS INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
MODULE/ GRID (m): Length:3,85 Width:2,9 Height:2,8	Length:8,7 Width:7,7 Height:2,7 Total Area (m2): 67,0 one level	Length:9,4 Width:8,4 Height:11,2

M-vironments/M-house, Michael Jantzen, 2000

M-vironments prototype is an example of customisability and flexibility of a housing system⁴⁵³. The M-house functions as a single private vacation retreat, with modular structure and components connected within a grid of seven spaced frames that can be arranged variously to accommodate changing needs, Figure 2.66 and Figure 2.67. For example, the components can increase or decrease in number and size as well as be used for exhibition structures, pavilions, children's playgrounds, commercial spaces, office modules and commercial applications due to the different sizes, shapes, materials and types of panels. The nature of the seven interlocked steel framed cubes and rectangular panels articulate the horizontal and vertical design of M-house concept and allow for various uses of the structure such as working, sleeping, sitting or eating, and protection from wind, rain and sun⁴⁵⁴.



Figure 2.66. M-vironments / M-house, Michael Jantzen, 2000 – Façade

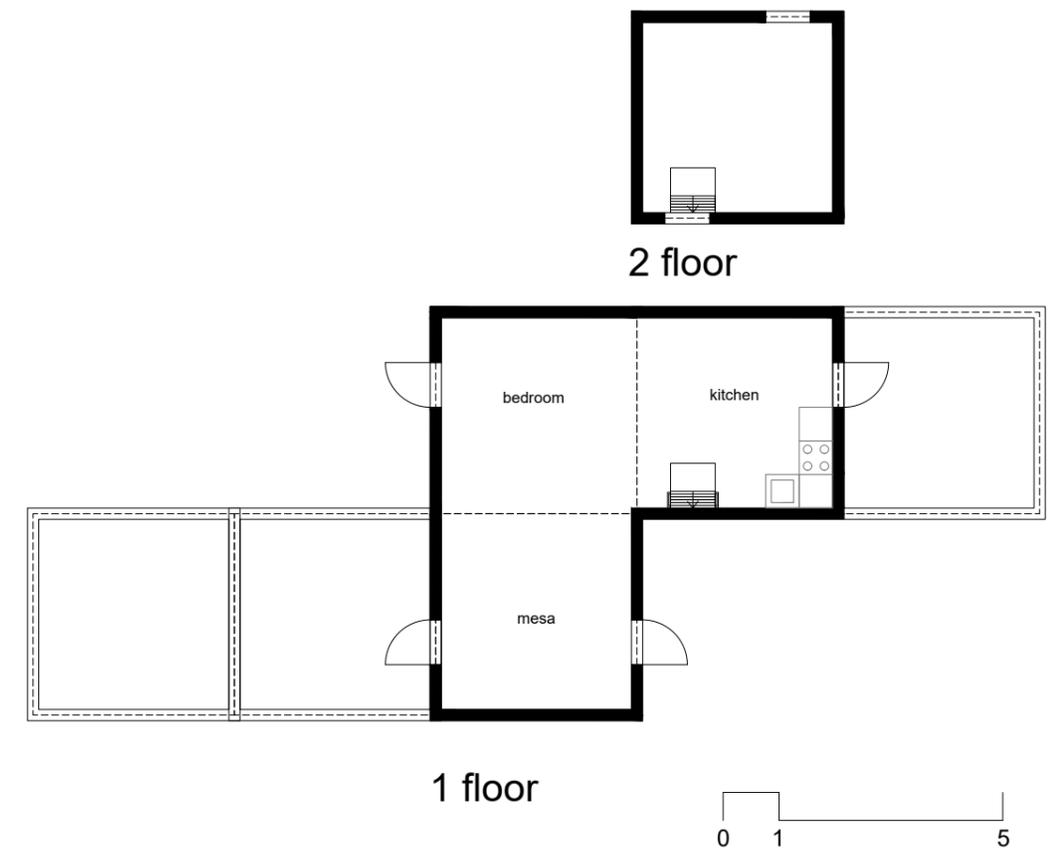


Figure 2.67. M-vironments / M-house floor plans

453 Bergdoll, Christensen, and Borries 2008.

454 Bergdoll, Christensen, and Borries 2008; Jantzen 2000.

STRUCTURE:steel

MODULE/ GRID (m)

Length:3,6

Width:3,6

Height:3,6

INTERNAL DIMENSIONS (m)

Length:3,4

Width:3,4

Height:3,4

Total Area (m2):11,56 one module

BUILDINGS DIMENSIONS(m)

Length:18,2

Width:7,4

Height:7,4

R50 cohousing, Ifau und Jesko Fezer Heide and Von Beckerath, Berlin, Germany, 2010 – 2013

The R50 cohousing has 19 individual apartments, one studio and shared spaces spread into six stories, an attic and a basement, Figure 2.68. The reinforced concrete skeleton is based on the sizes of the apartments and suspended steel construction for all-around balconies that connect the apartments on each floor. The typical floor plan for the apartments can be seen in Figure 2.69. The modular wood facade with an opening glazed door was specially developed for this building combined with the reduced and partly exposed infrastructure and two service cores. The open design, unfinished internal surfaces and a standard grid for fixtures and fittings were developed to allow individual layouts. This design allows residents to participate in the design of shared spaces. The common areas include laundry, an urban garden, a workshop room, a terrace with a summer kitchen and a winter garden on the roof⁴⁵⁵. The residential building integrates the individual and communal life and offers the possibility for adaptation according to the needs of each habitant throughout its lifetime. The structure is exposed and combines concrete, wood and steel to generate an aspect of light construction.



Figure 2.68. R50 cohousing, Heide and Von Beckerath, Germany, 2010–2013 - Façade

455 Heide & von Beckerath 2013.

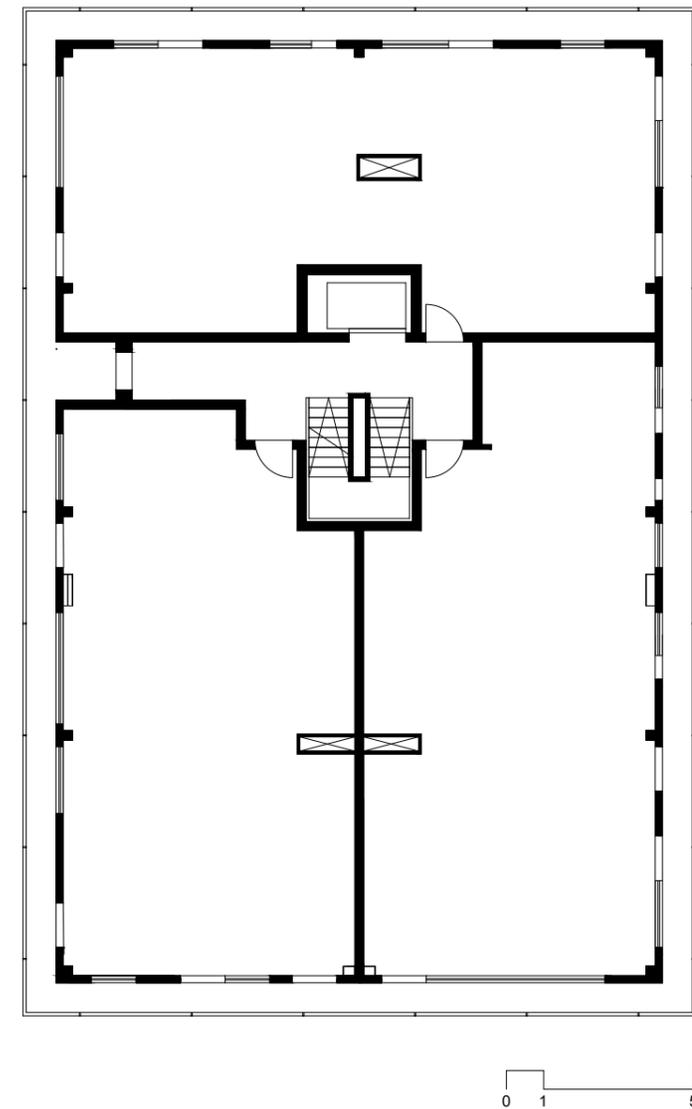


Figure 2.69. R50 cohousing typical floor plan

STRUCTURE: Reinforced concrete, modular timber façade	APARTMENTS INTERNAL DIMENSIONS (m) Length: 15,85 Width: 7,6 Height: 2,6 Total Area (m2) 120,46	BUILDINGS DIMENSIONS(m) Length: 26,8 Width: 18,0 Height: 23,2
MODULE/ GRID (m) Length: 6,15 Width: 7,8 Height: 3,0		

NEST-Unit Urban Mining & Recycling (UMAR), Werner Sobek, Dirk E. Hebel and Felix Heisel, Dübendorf, Switzerland, 2015 - 2017

The UMAR Experimental Unit design is based on the proposal that all resources in the building should be reusable, recyclable or compostable, placing life-cycle thinking at the forefront of the design. It is simultaneously used as a materials laboratory and as temporary material storage. The reinforced concrete structure supports prefabricated modules with the capability of removing or separating materials and products, Figure 2.70. The plan of the module can be seen in Figure 2.71. The facade includes untreated wood, aluminium and copper, which can be separated and reused after the module is disassembled. Some of the technologies employed are recycled bricks, repurposed insulation materials, rented floor coverings and a solar thermal multifunctional installation⁴⁵⁶. The materials are not returned to the material cycle but remain withdrawn from it⁴⁵⁷. The project focused on the removable modules integrating recycling materials into the architectural design process. Although the concrete structure used to support the modules is massive, there was no mention of its recyclability.



Figure 2.70. NEST-Unit Urban Mining & Recycling (UMAR), Werner Sobek, Dirk E. Hebel, and Felix Heisel, Dübendorf, Switzerland, 2015-2017- Façade

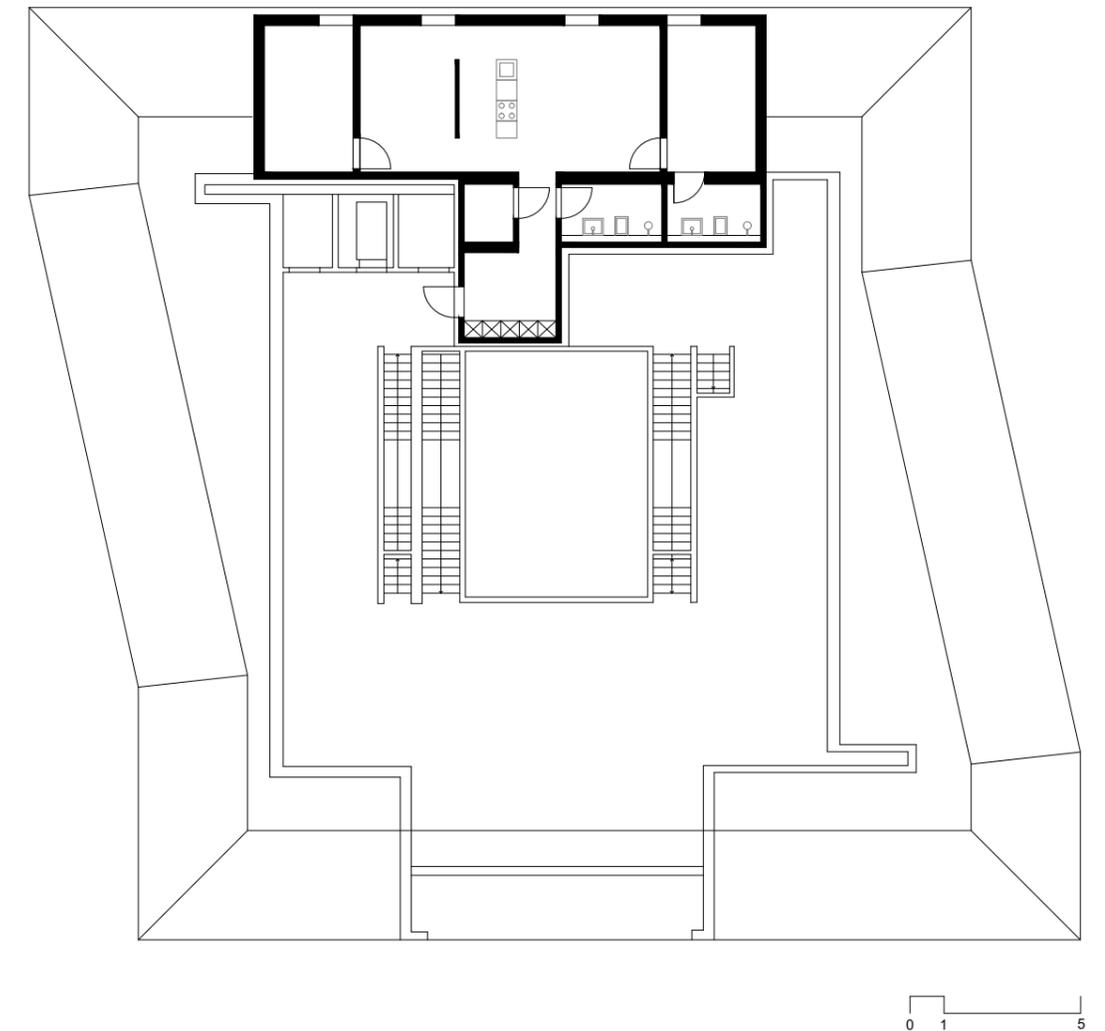


Figure 2.71. NEST-Unit Urban Mining & Recycling (UMAR), module floor plan

STRUCTURE: Reinforced concrete and Wood façade	APARTMENTS INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
MODULE/ GRID (m)	Length:14,40	Length:30,8
Length:4,8	Width:4,3	Width:27,3
Width:3,75	Height:2,5	Height:20,0
Height: 3,53	Total Area (m2): 98,4	

456 Heinlein and Sobek 2019b.

457 Geipel 2018.

Kajstaden Tall Timber Building, C.F. Møller, Martinsons & Slättö Förvaltning, Sweden 2016 – 2019

The most vital characteristic of Kajstaden's building is the timber structure made of nine floors, Figure 2.72. The ground floor and an upper floor have a higher ceiling height. The building offers four different apartment options that range from one room to five rooms. Figure 2.73 shows floor plan with two types of apartments. The torchwood used in the structure and walls provides the hermeticity and energy efficiency of the apartments, reducing the quantity of material in the walls. The material's low weight means a more efficient, safer and quieter working environment during construction and less deliveries. The building can be disassembled so that the materials can be recycled by using mechanical bolted joints. Carbon dioxide emissions are reduced by using solid wood instead of concrete⁴⁵⁸. However, the apartments cannot be expanded even though the building is entirely made of timber and arranged in a grid that has a system facilitating the assembly.



Figure 2.72. Kajstaden Tall Timber Building, C.F. Møller, Martinsons & Slättö Förvaltning, Sweden 2016 – 2019 – Façade

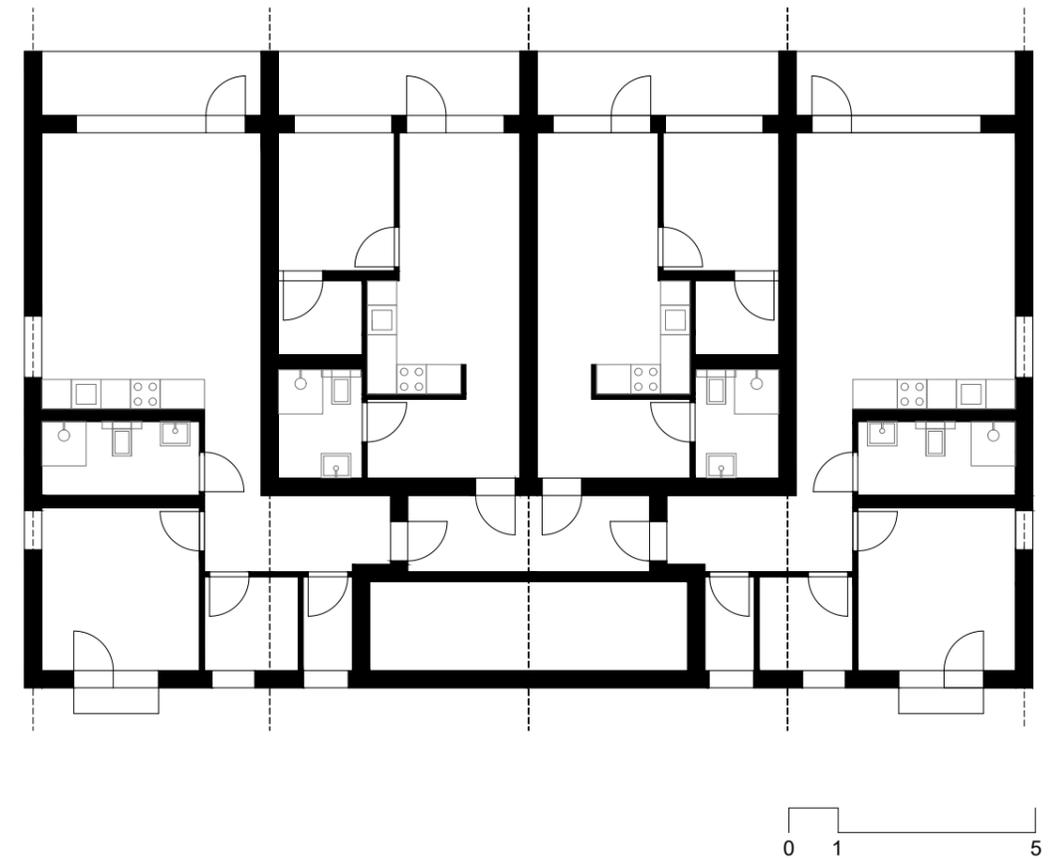


Figure 2.73. Kajstaden Tall Timber Building's typical floor plan

STRUCTURE:timber	INTERNAL DIMENSIONS (m)	BUILDINGS DIMENSIONS(m)
MODULE/ GRID (m)	Length:12,2	Length:20,45
Length:12,9	Width:4,45	Width: 12,9
Width:4,8	Height:2,4	Height:31,0
Height:2,9	Total Area (m2):54,3	

2.4. Critical reflection and the relation between modularity, prefabrication and ecology

Different designs have emerged globally and the solutions presented in the Atlas are the starting point to open up the discussion and expectations of what a building designed for the future should look like. There is a paradigmatic shift in our understanding of architecture and humanity's place within the environment, rather than outside of it, where buildings can no longer be considered a discrete object⁴⁵⁹. Architecture throughout time has made fundamental deviations from its traditional, visual and stable position, becoming a dynamic and interdependent structure that responds to the needs of change and increasing controls of humans⁴⁶⁰. The issues confronted in modular and prefabricated buildings are becoming less difficult to manage, and the concept of ecology and recyclability is more often employed. The idea to use analogous examples as references to obtain inspiration about some problems in the present is not new. In architecture, invention often involves ideas inspired from an existing building with a similar program, functional specification or site condition, becoming a model or prototype⁴⁶¹. Architects sought techniques to increase the quality of design and production over time and saw modularity and prefabrication as a way to introduce and improve sustainability and control⁴⁶². Each architectural project mentioned in this chapter offers insight into how modularity, prefabrication and ecology should or should not be leveraged to provide recyclable architecture. The process is evolutionary and not revolutionary. This research presents the evolution in design linearly, although the architectural moments concerning modularity, prefabrication and ecology are intertwined throughout the chapter. Solutions to problems are developed through trial and error to comprehend what works and what previous solutions may be implemented today.

Modularity is a characteristic present in several buildings throughout the years, whether or not they are permanent or temporary, prefabricated or focused on recycling, bring many advantages for construction, such as speed, higher quality prefabrication and assembly facility. Initially, it was applied in permanent buildings developed in traditional on-site construction to bring rationalisation and organisation to the structure, like the buildings presented in the section on modular buildings, e.g. Narkofin, Unité d'Habitation, Harumi, Quinta Monroy and others. The apartments were connected to a linear corridor towards a central core for access. Their living units' organisation is very similar in all countries and persists to this day. Even for different cultural demands, such as a tatami lifestyle in Harumi by Maekawa, Tokyo, it has resulted in an organisation that can be compared to a western model, such as Narkofin in Russia, Robin Hood Halen in England, Unité de Habitation in France and The Halen Estate in Switzerland. These high-rises have typical two-level units. The entrance is at the corridor level every other level, with rooms above and stairs leading to the unit below⁴⁶³. Not only the

459 Schröpfer 2012.

460 Kepes 2017.

461 Sherwood 1979.

462 Smith and Timberlake 2010.

463 Sherwood 1979.

housing units' disposition is similar to these buildings, but the access by a central core can also be seen in almost every high-rise building presented in this Atlas and our daily life. The "street in the air" concept is also highlighted in the Robin Hood Halen and Unité de Habitation. This concept evolved in 1919 by Brinkman at Spangen Quarter in Rotterdam and was employed in post-war English housing such as Park Hill. The corridor remains open as gallery access and utilises the street in the air concept, where the climate permits⁴⁶⁴. In addition, some projects that embraced social needs often associated multi-family homes with shared facilities, such as health care, kindergarten and laundry, like Narkofin and Unité de Habitation.

Le Corbusier's buildings were mainly cast-in-place concrete on site, focusing more on form and material than mass production. The rationalisation translated into modularity can also be highlighted in the projects of Wright and Mies van der Rohe, even if the prefabrication methods required vast amounts of manual work on site. Repetition and standardisation are the inherent qualities of the mass production of a consumer-oriented society. However, parts could be changeable or interchangeable depending on the individual needs and preferences as well as whether it is economically feasible⁴⁶⁵. Now, the design production process must be implemented as part of the overall process⁴⁶⁶. Therefore, prefabrication became more evident in architecture during the 1960s. The temporality, mobile and new materials as well as assembly and disassembly techniques were integrated with modular architecture. The temporary buildings were generally considered portable modules usually built with a chassis, including construction trailers, portable classrooms, communication capsules and exhibition rooms. In contrast, even though manufactured and mobile homes are an affordable option⁴⁶⁷, they did not increase people's quality of life by not adapting to their needs, thus becoming marginalised. Furthermore, the low quality and lack of durability of the houses would require continuous storage of supplies to sustain the operation of the building during its life cycle compared to traditional houses⁴⁶⁸. For example, the temporary building concept can be seen in the projects like Kisho Kurokawa's Nakagin Capsule Tower, Fuller's Dymaxion house, the Prepackaged House of Gropius and Wachsmann, Prouvé's Pavilions, Moshe Safdie's Habitat 67, and Sorbek's R128 house, which used bolted, folded and prefabricated structures and modules for possible dismantling. They were easily assembled and could be disassembled, although the connections allowing for disassembly of the structure were only applied on a small scale for houses, and the prefabricated modules could not expand.

Besides the concern with the structure, Fuller, Cook, Reyner Banham and Friedman believed that modern architecture was too formulated and limited by the demands of mass production, which has produced buildings and cities unable to respond to ever-changing social needs⁴⁶⁹. Until today, modern architecture as well as several modular, prefabricated and ecological architectural experiments throughout history only covered

464 Sherwood 1979.

465 Cook 1999.

466 Smith and Timberlake 2010.

467 Ibid.

468 Ibid.

469 de Wit 2009.

basic needs and did not satisfy the demand for adaptation, which has become more necessary as society continues to rapidly evolve⁴⁷⁰. In addition, aesthetic constraints and fixed ideas, styles and materials were often too complex to adapt and change to suit individual living patterns since aesthetic preferences changed over time⁴⁷¹. A shift in this perspective and its use needs to change. Each generation should be able to adapt and build their own buildings, aligning with the idea of the Futurist Manifesto temporary building.

The traditional family model strongly influences the housing currently under construction, and the number of households meeting these criteria is steadily decreasing. Moreover, the current housing market and lifestyles require a more integrated relationship between the living and working, the individual and society, urban and natural, and the growing need for communal, hybrid and transferable activities⁴⁷². The attempt to make public spaces as significant as inside spaces suggests a new housing form that might recall public housing. Presently, collective housing in the metropolis means a massive volume on a site⁴⁷³. However, the physical design principle of adaptation demanded by sustainable development concepts can increase land quality and flexibility-in-use⁴⁷⁴ and should be considered at the beginning of the design phase⁴⁷⁵. As a reference, the residential projects selected and presented in this chapter were organised in chronological order to understand the evolution of technologies and approaches over time, see Figure 2.74. The applied strategies and solutions that should be considered to be tested and brought to present and integrated into the design of future recyclable architecture were extracted from the case studies and presented in the Table 2.2. In total, 33 architectural strategies were verified, and for each existing strategy in the building, one square has been filled in. The architectural strategies are divided into:

- the level of modularity (rationalisation in grid or repletion; and module);
- the characteristics of the whole structure (exposed structure, central core, pilotis, outside stairs, internal street, terrace, rooftop, open floor, and unfinished space);
- which elements were prefabricated (structure, panels and modules);
- use combination (shared/communal + private, public + private, or multi-use);
- housing aspects (combined room activities, duplex configuration, have reduced space, the building offer different sizes of apartments, walls are retractable/sliding, and possibility for housing expansion);
- how can it be dismantlable (steel studs, bolted, superposition/stacked, plug-in, and hinged/joints);
- energy efficiency (solar panels);
- if the building used recycled materials;
- and if the construction densifies the site.

470 Cook 1999.

471 Smith and Timberlake 2010.

472 Ferreira Silva et al. 2020.

473 Sejima 1996.

474 Gijsbers, Lichtenberg, and Erkelens 2009; Šijaković and Perić 2014.

475 Kumar Dhar, Sk. Maruf Hossain, and Rubayet Rahaman 2013.

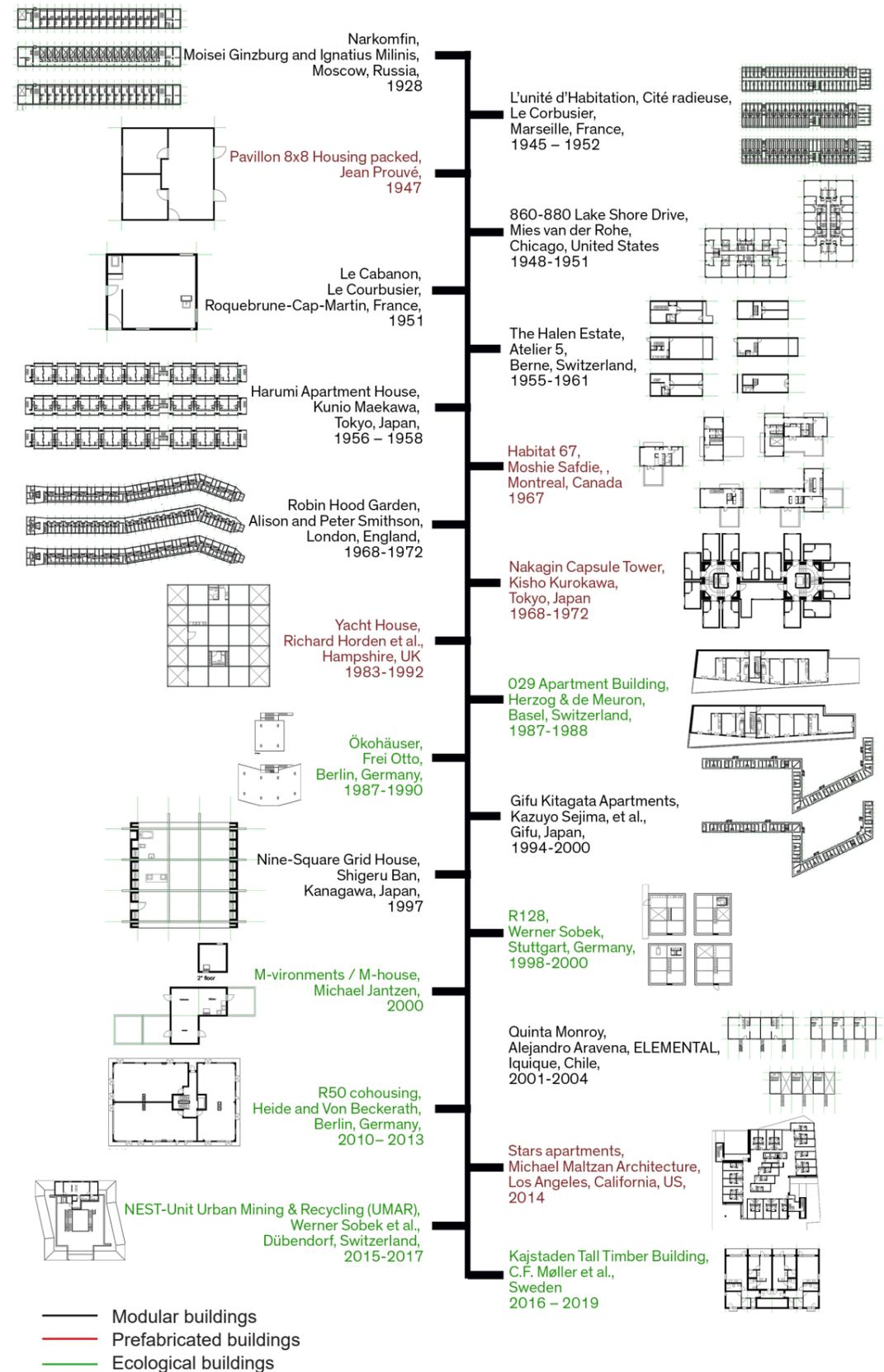


Figure 2.74. Chronological order of cases study projects

The existing building strategies and concepts can be combined to design high-rise buildings and integrate mixed uses such as commercial, residential, shared and public spaces. For example, the combination of high-tech movement of large, open, and exposed infrastructures allowing different layouts and the metabolism manifesto of organic design and interconnected fabric of prefabricated modular units - plugged-in and -out housing capsules - can be translated to the present day by allowing the development of a new housing typology in which models of suburban houses can integrate urban skyscrapers. Furthermore, the plug-in concept can be improved by combining the Mobile Homes and the Tiny House ideas in which one housing unit can be transported and installed in a different structure.

Regarding the interior design, the layout of modular and prefabricated housing units was quite similar to tall buildings or massive housing complexes, with separated rooms for each activity, i.e. kitchen, living room, bedroom and bathroom. The anthropometry used by modern architects like Le Corbusier and developed further by Neufert is applied intensively today as a primary guide that can provide comfort with the minimum internal dimensions required in a home. In architecture, the kitchen was commonly integrated into the dining and living rooms in the 1960s. A living space that allows overlapping functions (a fluid space) can be considered a flexible space, created to integrate and improve the comfort of space beyond an optimised space to live and work in⁴⁷⁶. Figure 2.76 shows the case study dwellings. The minimal dimension presented in this Atlas for housing units are 2 m in length, 2.2 m in width and 2.2 in height, while the maximum dimensions for the buildings are 306.8 m in length, 140m in width and 86.6 m in height. Finally, the average grid sizes are 7.1 m in length, 4.2 m in width and 2.9 m in height, as shown in Table 2.1. The dimensions of the apartments and building can be seen in Annex A. Furthermore, the translation of modularity concepts for apartment design can begin with basic units, see Figure 2.75: Single-oriented unit, double-oriented unit, 90°, and the open-ended double-oriented unit⁴⁷⁷. These three types of units can have typical variations that depend on the positioning of elements such as kitchen, bath, staircase, entrance and the depths required for natural light. In addition, the minimum dimensions of the units vary from country to country as regulations and construction practices are different, and the layout of the central elements, natural light and ventilation requirements change from one place to another. The dimensions and layout of the apartments can be translated and used as a reference to design a future housing module.

Over time, building technologies and design were improved to be assembled, manipulated, added and maintained during their life cycle through modularisation, prefabrication and ecological concepts. However, not necessarily to be recycled or reused, much less disassembled and relocated⁴⁷⁸. Generally, architects and builders focus on building refurbishment or reducing the amount of material and visualise their creations as permanent, resulting in not making provisions for their future disassembly⁴⁷⁹. Instead, the structures and components were assembled, covered and

476 Alfirevic and Simonovic-Alfirevic 2016.

477 Ibid.

478 Kibert 2003.

479 Chini 2005.

glued to other materials, making them inseparable. This made it challenging to reuse, and unsuitable for disassembling at the end of life. Prefabrication in construction was also problematic due to the sheer cost of updating technologies, replacing components and the dependency on big infrastructures for intervention⁴⁸⁰. Equally important would be the fact that it is the lack of integrated processes in the early stage of design in a building venture that is responsible for many of these failures⁴⁸¹. On the other hand, from a technical point of view, the offsite manufacturing process can offer greater accuracy, shorter construction times, increased safety and working conditions, better value, promote recycling, reuse industrial supplies and offer disassembly. It also reduces time, cost and material waste from the design and construction phases as well as reduce the amount of negative impact on the environment⁴⁸². Industrialised flexible and dismountable building systems also provide greater possibilities for adapting and changing the building layout over time and operating upgrades/relocation/recycling⁴⁸³.

In addition, technology has allowed for many companies to lower costs through precision modelling, robotic manufacturing and lightweight materials, improving efficiency and digital building information⁴⁸⁴, which can help improve the design and manufacturing processes⁴⁸⁵. 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 environment⁴⁸⁶. The deconstruction of conventional demolition brings environmental benefits such as reducing waste and creating new landfill spaces while minimising carbon emissions and energy usage in the reprocessing of new construction materials as well as the potential reuse of building components and recycling of materials⁴⁸⁷. The conversion of waste into valuable materials is one example of a positive attitude that needs to be adopted towards the existing stock⁴⁸⁸. Besides the question about the assembly and disassembly process, most buildings are still constructed using concrete since it is a part of architectural culture and will last for years, generating a significant CO₂ emission and making recycling rather expensive⁴⁸⁹. Infrastructure and existing buildings should be seen as valuable cultural, social, and architectural resources for shaping our future.

Today's challenge would be to update and combine these strategies while integrating the Otto and SITE ecological concepts by combining nature and the built environment, reducing the use of materials and waste production. Thus, rationalisation and modularity should be brought to the present, improving the prefabrication process for construction without generating additional costs and manual labour since industrialised buildings with the potential for modular repetition has become a standard method and will expand

480 Ferreira Silva et al. 2020.

481 Smith and Timberlake 2010.

482 Arif and Egbu 2010; Jaillon, Poon, and Chiang 2009; Smith and Timberlake 2010.

483 Jaillon and Poon 2014.

484 Jaffe 2018.

485 Ferreira Silva et al. 2020.

486 Ibid.

487 Jaillon and Poon 2014; Kibert 2003.

488 Petzet and Heilmeyer 2012.

489 Ferreira Silva et al. 2020.

to all architecture. Furthermore, cities require more ecological, sustainable, smart and recyclable building concept integration. Although recycling is a requirement that is still not met in the actual residential model, the sustainability of the built environment is often limited to the building's lifecycle, neglecting the grey energy and CO₂ emissions produced during the construction and demolition phases. 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 via collaboration⁴⁹⁰. Designing for less waste is a step towards a cleaner environment and preserving natural resources for future generations. Today, the goal is a society that produces zero waste, where any waste that is produced can become the raw material for another project⁴⁹¹. Architects can impact the building environment, most significantly the housing sector, with prefabrication and proposing reusability of space and materials, simultaneously addressing social and ecological issues. Therefore, new building typologies should be created for the future, which can be refurbished, redesigned, upgraded or disassembled without generating waste and serve as stock for the new building.

In conclusion, recyclable architecture has many historical, environmental, social and economic benefits, making it an essential component of sustainable development⁴⁹². Reusable and recyclable architecture can be achieved with different strategies. First, using modularity in structures and systems to provide open plans, easy expansions and modifications or simply provide order for construction. Secondly, using prefabricated components or developing complete modules that may be added and removed on demand. The third strategy is implementing a temporary construction concept, where the architecture can be moved and dismantled, allowing adaptation to future changes, new demands and uses, and the reuse and recycling of their materials. Finally, adding the concept of sustainability and ecology while thinking about humans' interaction with their natural environment without interfering is the future for the coming generations. As these generations implement the strategy of reusing and recycling materials, the seemingly endless cycle of producing unnecessary waste will end, ultimately reducing the overall production of waste for years to come. Therefore, the characteristic of flexible space or the concept of unfinished space can motivate different possibilities to use space and create new layouts to achieve the ideal living space. Many architects and designers offer building solutions for sustainability, but the architect design process involves more than just having a building in the end. Instead, the building should be designed to forecast future needs and reduce natural resources. It is complex and demand integration the design of reusable and recyclable architecture can be complex and demand integration and collaboration of different fields. The global problems, ecological concepts and architectural strategies presented in Chapters 1 and 2 were combined and tested to develop new generic typologies and models for reuse and recyclable architecture. The prototypes designed are presented in Chapter 3 with detailed explanations of their development. Thus, our goal is to imagine and create architectural typologies with technologies and social aspects that appear desirable

490 Smith and Timberlake 2010.

491 Byers 2018.

492 Šijaković and Perić 2014.

for the future in terms of human values, where inhabitants and users can adapt to the space for themselves and their way of living, respecting nature as much as possible. Accepting that the future will have a different way of living is a state of mind that must be considered in everyday life in a temporary, reusable, recyclable and circular world.

Table 2.1. Housing dimensions analyses

	Grid or Module size (m)			Housing/Apartment internal dimensions (m)				Building external dimensions (m)		
	Length	Width	Height	Length	Width	Height	Total area	Length	Width	Height
Average	7.0	4.2	2.9	9.4	5.6	2.5	90.4	50.6	21.4	26.5
Minimum	3.4	2.5	2.3	2.0	2.2	2.2	8.1	4.6	3.9	3.0
Maximum	14.5	9.0	6.0	23.6	18.5	3.4	342.3	306.8	140.0	86.6

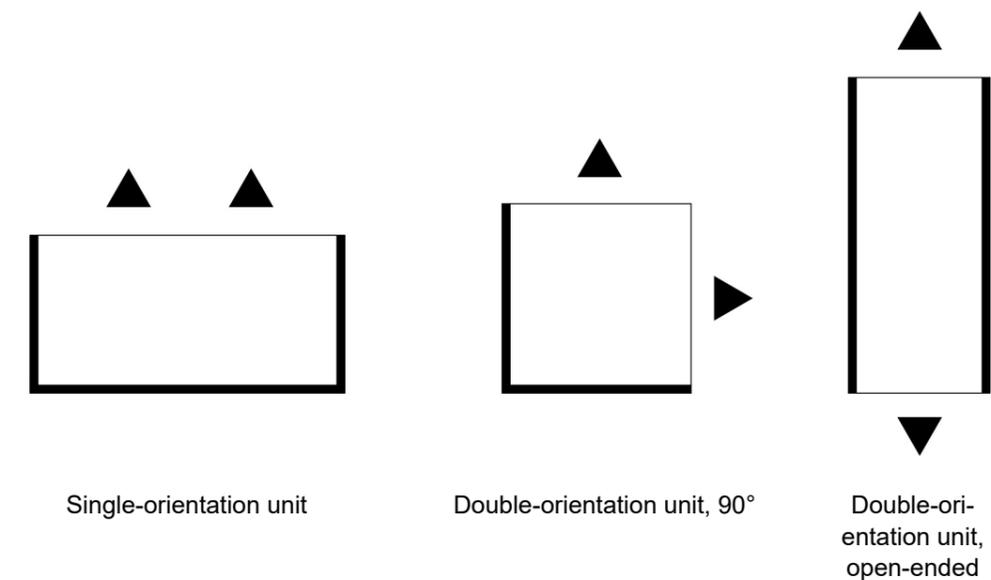


Figure 2.75: Basic apartments or units

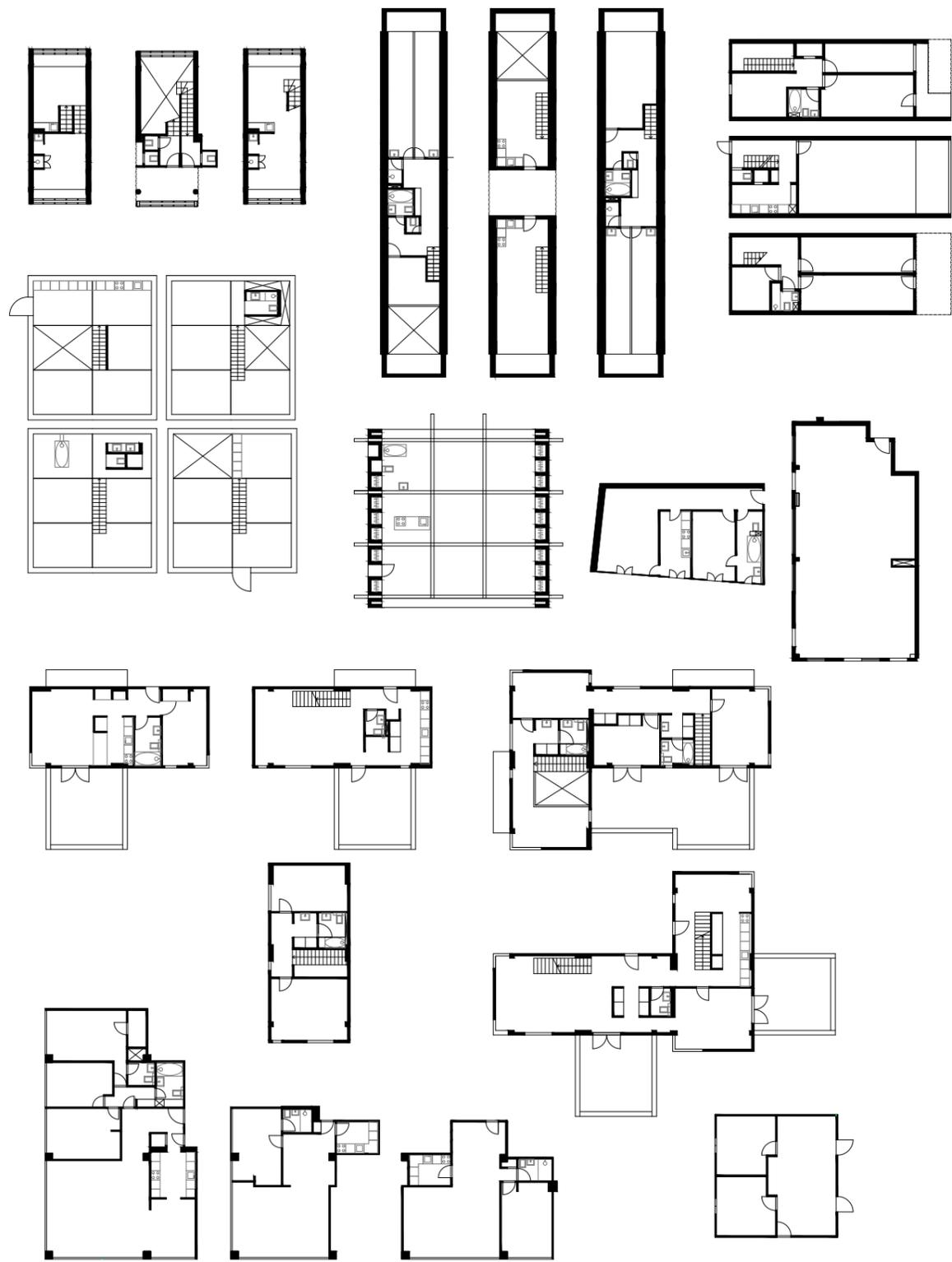


Figure 2.76. Housing units from Atlas

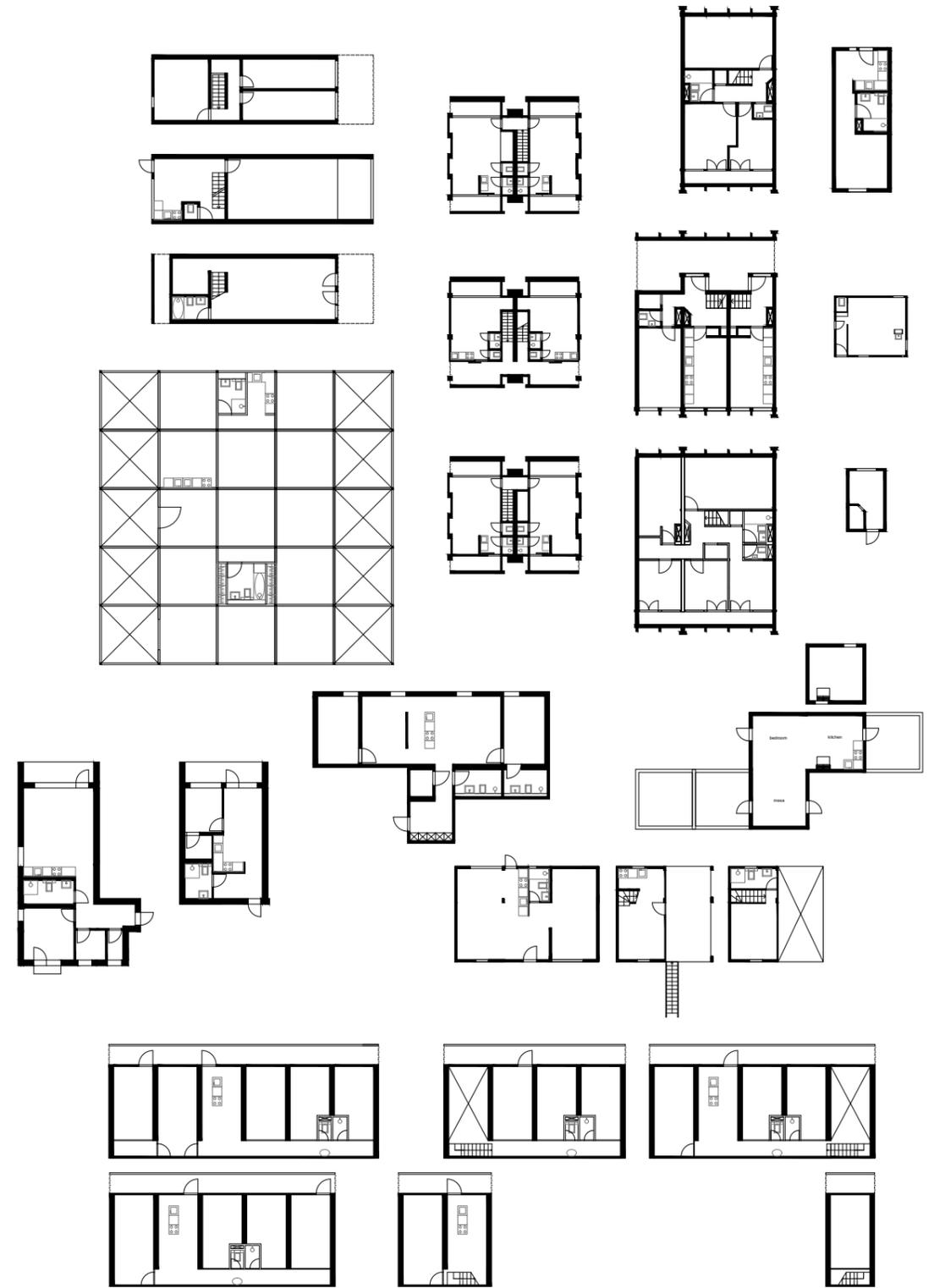


Table 2.2. Architectural strategies for recyclable architecture

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	19	18	20	21	22	23	24	25	26	27	28	29	31	32	33			
		Modularity			Structure									Prefabricated			Usability			Housing aspects					Disassemble					Energy efficiency	Used recycled materials	Densify				
		Rationalization		Module	Exposed structure	Central core	Pilotis	Outside stairs	Internal Street	Terrace	Rooftop usage	Open floor	Unfinished space	Structure	Panels	Modules	Shared/comunal + private	Public + private	Multi-use	Combine room activities	Duplex	Reduced	Offer different size	Retractable/Sliding walls	Possible expansion	Steel Studs	Bolted	Super-position / stacked	Plug-in	Hinged /joints	Solar panels	Used recycled materials	Densify			
		Grid	Repetition																																	
Modular buildings	Atlas Case studies																																			
	1 Narkomfin, Moisei Ginzburg and Ignatius Milinis, Russia, 1928																																			
	2 L'unité d'Habitation, Le Corbusier, France, 1945 – 1952																																			
	3 860-880 Lake Shore Drive, Mies van der Rohe, US, 1948-1951																																			
	4 Le Cabanon, Le Corbusier, France, 1951																																			
	5 The Halen Estate, Atelier 5, Berne, Switzerland, 1955-1961																																			
	6 Harumi Apartment House, Kunio Maekawa, Japan, 1956 – 1958																																			
	7 Robin Hood Garden, Alison and Peter Smithson, England, 1968-1972																																			
	8 Nine-Square Grid House, Shigeru Ban, Kanagawa, Japan, 1997																																			
	9 Gifu Kitagata Apartments, Kazuyo Sejima, Ryue Nishizawa, and Koichiro Tokimori, Japan, 1994-2000																																			
10 Quinta Monroy, Alejandro Aravena, ELEMENTAL, Chile, 2001-2004																																				
Prefabricated buildings	11 Pavillon 8x8 Housing packed, Jean Prouvé, 1947																																			
	12 Habitat 67, Moshe Safdie, Canada, 1967																																			
	13 Nakagin Capsule Tower, Kisho Kurokawa, Japan 1968-1972																																			
	14 Yacht House, Richard and Cherry Horden, Lee Architects, UK – 1983-1992																																			
	15 Stars apartments, Michael Maltzan Architecture, US, 2014																																			
Ecological buildings	16 Okohäuser, Frei Otto, Germany, 1987-1990																																			
	17 029 Apartment Building, Herzog & de Meuron, Switzerland, 1987-1988																																			
	18 R128, Werner Sobek, Germany, 1998-2000																																			
	19 M-virionments / M-house, Michael Jantzen, 2000																																			
	20 R50 cohousing, Ifau und Jesko Fezer Heide and Von Beckerath, Germany, 2010–2013																																			
	21 NEST-Unit Urban Mining & Recycling (UMAR), Werner Sobek, Dirk E. Hebel and Felix Heisel, Switzerland, 2015-2017																																			
22 Kajstaden Tall Timber Building, C.F. Møller, Martinsons & Slättö, Sweden, 2016 – 2019																																				

CHAPTER 3. PROTOCOL - NEW ARCHITECTURAL TYPOLOGIES

It is necessary to design buildings that increase their suitability for recycling and future use. Furthermore, people's habits and intake of commodities are changing at every social level, which eventually will impact their way of living⁴⁹³. The social questions that pertain to the use of natural resources, land use and human needs can determine a building's form. Thus, new designs should be capable of addressing ecological challenges as well as social changes. Architecture must serve the needs of the public, allocating more shared and accessible space in the cities while offering highly developed technological buildings to improve the life quality. In this regard, this research aims to produce alternative generic models that allow functional flexibility through time. Flexibility has advanced in many branches from architectural and planning systems to design complexes, infrastructures, urban plans and regional studies worldwide⁴⁹⁴. Considering the diverse needs of the current society and envisioning the future society, three different architectural typologies were developed in this research. This chapter provides an empirical overview of these new architectural typologies. Each typology considered the adaptability, reusability, demountability and recyclability of construction, taking into account the environmental consequences of their design and materials from the first design stage.

The research by design methodology was implemented in order to design the building prototypes with references presented in Chapter 2 - Atlas. The architectural strategies, ideas, designs, uses and techniques related to modularity, prefabrication and recyclability presented in the existing buildings served as a starting point in the typologies' design principles. Their dimensions were transcribed and served as the basis of design for new reusable and adaptable residential buildings. As a result, three different recyclable architectural typologies were proposed that provided flexibility, multi-purpose use and disassembly and reassembly components. A structural, functional, spatial and aesthetic layout was developed for every architectural typology. During ECON4SD regular workshop meetings, drawing plans and 3D models were tested, analysed and the feasibility of construction was demonstrated and discussed. The prototypes were named according to their strongest characteristics. The Prototype 1 - Slab typology designed as shelf structure where wooden housing modules could be plugged in and out; the Prototype 2 - Tower typology allowed for an easy layout change and used different floors; and the Prototype 3 - Block typology characterised by the entire disassembled building components to form a new structure. These typologies combine modularity, prefabrication, flexibility and disassembly that address the increasing demands for multi-use, reusable and resource-efficient construction avenues. The main building designs principles are the possibility to be reusable as much as possible and them disassembled and recycled at the end of their life. The practice of large-scale structures for flexible use in various modular and prefabricated construction methods allows for a highly practical space with a minimal footprint and individual accommodation types with communal activities. Furthermore, the surfaces

493 Cook 1999.

494 Pyla 2002.

of the architectural typologies developed in this research were analysed to show how much of the structures were reusable and recyclable. The following Section 3.1 presents the design principles that guided the development of this research and Sections 3.2, 3.3 and 3.4 presents each developed prototypes' details. Section 3.5 highlight the process and exchange between the ECON4SD project and the Section 3.6 is the synthesis of the results, with benefits and barriers to designing reusable and recyclable architectural typologies.

3.1. The typologies principles

The intended purpose of high-rise residential block construction was to increase the city centre's density while offering open public and shared spaces. In the mid-2010s, especially in Europe, migration contributed to temporary and permanent relocation, becoming a pervasive challenge most notably for young and elderly single people seeking adequate and affordable housing⁴⁹⁵. For this reason, the target residents of the prototypes are the new generations to include young workers, people living alone and young couples with possibly one child, Figure 3.1. However, the housing units and apartments were designed to adapt to all kinds of use and be affordable for all social classes, giving the population equal choice on how they want to live.

The first step in designing recyclable buildings is to consider their lifecycle. At the end of their service life, the construction elements should be transformed into other building resources, closing loops in industrial ecosystems and minimising waste. Exposed and massive structures, both internal and external, that utilised grid systems, modular units and prefabricated components were optimised to be disassembled and reconfigured throughout its lifecycle, consequently reducing the residual end waste. Therefore, the entire building structure, or parts such as beams, slabs and pillars, among other elements, can be reused to relocate the building, build a new structure or recycle to create new materials. Mega, modular and prefabricated structures also increase the possibility for building expansion and allow larger spans that provide more flexible and different uses, functions and layouts according to the user's needs. For example, e.g. the same floor can transform into a house or an office, depending on society's necessity.

Secondly, public space is essential for exchanging experiences, productivity, debate, collective fun and human well-being⁴⁹⁶. All the prototypes have public space and communal areas that improve residents' lives, with more facilities within the same location and satisfying the group activity needs. The shared space was designed as a housing extension and was designed to benefit users' lives while integrating people with different habits and providing various activities. It allows residents to live, work and rest within the same space⁴⁹⁷. The shared zones were placed on the ground floor, rooftop and along the circulation on different floor levels. The activities can be selected initially and then adapted through time according to the resident's or neighbourhood's needs — swimming pools, saunas, sports facilities, urban gardens, kindergartens, libraries, markets etc. Some buildings function as independent modules or they can also be combined with other modules to provide more than one activity type. Another combined strategy used to promote public space is to have the smallest footprint reducing the area that provides access to the building. It gives more public accessibility to the ground floor while offering accessibility to host shops, gathering spaces and urban gardens. A central core, including the elevators, stairs and technical shafts, is one of the solutions adopted to reduce the ground floor structure.

495 Nelson 2018a.

496 Herreros 2017; Urbonas, Freeman, and Lui 2017.

497 Krufft 1994b.



Figure 3.1. Occupant's profile

Table 3.1. All possible scenarios for recyclable architecture

STRUCTURE	FUNCTIONS	USERS	HOUSING UNITS	GROUND FLOOR	ROOFTOP
In steel	Multi-use	People Living alone	Same for 100 years	Open	Open
In timber	Single-use			Close	Close
In concrete	Single/multi-Use/	Young workers	Same for 50 years	Public	Public
Mixing of the tree materials	For 100 Years	Couples	Same for 50 years	Private	Private
Use new material	Single/multi-Use/	Families with a child	Same for 25 years	Shared	Shared
Use recycled material	For 50 Years	Big Offices	Expanded	Communal	Communal
	Change use after 25 Years	Independent Workers	Diminish		
Same for 100 years		Car users	Movable	Shops	Swimming
Same for 50 years	Public	Companies	Permanent	Markets	Pool
Same for 25 years	Private	Public Organizations		Offices	Sauna
Expanded by adding more components	Shared		Module	Urban farming	Library
Part disassembled and partly remained	Communal		Apartment	Urban garden	Analog
Completed, disassembled, and reassembled in another location	Collaborative		One floor	Sports	Lounge
	Mixed		Duplex		Collaborative Coworkspace
Dismantled to be reused in another construction	Residential				Urban Garden
Dismantled to be recycled	Commercial				Sports
	Parking				Kitchen
	Housing				
	Office				
	Kindergarten				
	Sport Gym Room				
	Analog Lounge				
	Coworkspace				
	Kitchen				
Open slabs	Library				
Close slabs	Urban farming				
Divided slabs	Urban garden				
Stairs in structure					
Stairs out of structure					

Finally, the buildings offer places where the residents can have moments to be on their own and moments to meet others. As a private space, housing units were designed to reduce the space necessary to live due to the increased demand for residential units, including cooking, eating, sleeping, taking care of hygiene and working, already proclaimed by Le Corbusier in "*Vers Une Architecture*." This study takes advantage of smaller living spaces to make them more affordable, examining the benefits and challenges of implementation. The dwellings can adapt to contemporary families' needs, while the buildings can receive more than one residential layout. For example, the dwellings can reduce and increase their size for one resident, a couple and a couple with kids.

According to these principles, the design process started with the main qualities to reach recyclable architecture. The typologies were designed with components that can be disassembled, reassembled in another place or reused after the first life cycle. The interior spaces are as open as possible to provide affordable housing and able to change according to people's needs. Table 3.1 illustrates all the possible scenarios for the architectural typologies. Some of the solutions were combined to predetermine the main typologies aspects. The possible scenarios considered the three primary structural materials - timber, concrete and steel - and how the structure, layout, function and users can change throughout time.

3.2. Prototype 1 – Slab typology

The Slab prototype's main objective is to increase density by providing more housing with public and shared living spaces. A recyclable reinforced concrete structure was proposed, wholly exposed in shelf-form, allowing the connection of wooden housing units. The building design allows different dwellers' arrangements by plug-in/out modular housing units that can accommodate different families and residents. Apart from the housing units, the building has a reduced footprint, providing public space on the ground floor, and shared spaces on the rooftop, as shown in Figure 3.2. This Section presents the models' evolution through the design process to the final Slab typology.

The first proposal for Prototype 1 was a model, Figure 3.3, designed with two vertical cores on each side for access, with the smallest footprint possible. The reduced footprint and the excellent open space create public zones on the ground floor that can be used as gathering spaces, shops, offices and covered gardens. The two cores support the slabs with prefabricated wooden residential units. The building is orientated to the West and East so that apartments on either end can have direct solar insolation. A corridor in the middle of the slabs connects the two cores.

The most significant modification is from the first model to the second one. Due to the lengthy span, the second model, Figure 3.4, was reduced to the distance of five housing units in each slab. The prefabricated wooden portable house modules were designed to be expandable. They were positioned between the ceilings and extended over two floors, enabling more possibilities to arrange and grow the housing units according to the occupants' needs. One vertical core remained to access the elevator, internal stairs, and shafts while the second core was replaced with a thick wall to support the slabs. Some facilities were integrated into the core as small laundry units with bicycle parking on the ground floor. The top of the building becomes a shared space for the inhabitants. The building's shared spaces were designed to compensate the house units' reduced size, thus giving more space for the inhabitants.

The third model, Figure 3.5, kept the same characteristics as the second one. The difference is that the building becomes oriented to one side allowing the dwellings to receive natural light on two facades as long as the other facade is an open corridor. This passage is a large terrace, a kind of "street in the air" with a new sense of space, light and freedom facing the house's doors to balance the condensed housing units. The stairs were integrated with the open corridor façade, an alternative skyway that reduced the vertical core area.

Finally, in the last physical prototype, Figure 3.6, all the previous concepts were explored further. The prototype is an 11-storey building with a primary reinforced concrete structure and connected wooden housing units. The shelf structure provides a stable slab with a structure extending over two floors for standardised, prefabricated, modular and portable housing modules. A central wall was placed every three housing units to support and reduce the thickness and materials used in the structure and slabs while at the same time giving some possibilities for the housing arrangements. The modules are positioned in the building's main façade. In the beginning, the structure

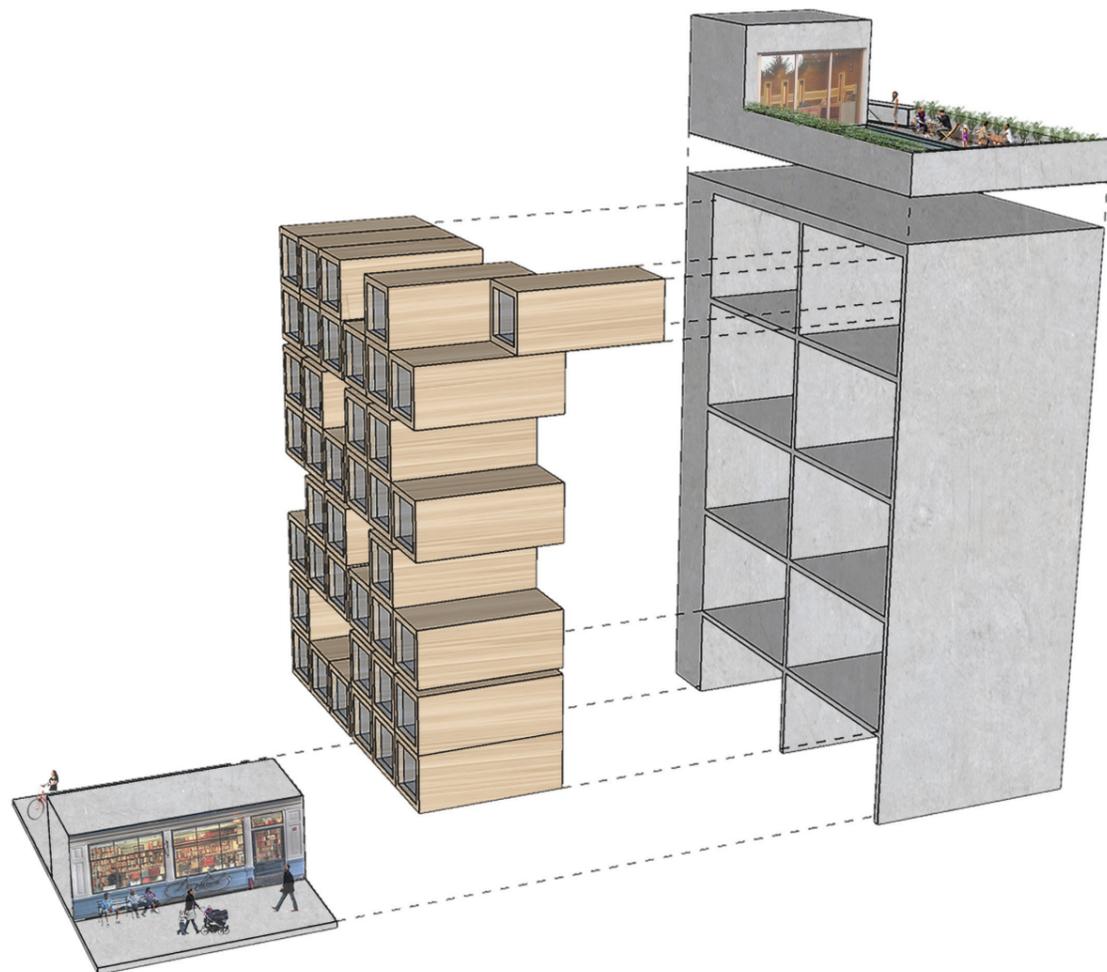


Figure 3.2. Prototype 1—Slab typology: Diagram

is filled with a few modules, and over the years, it will be filled according to their need, Figure 3.7 and Figure 3.8. They can be added or removed into the building and slid through rails by mobile crane at any time, as shown in the Slab section in Figure 3.9 with the first housing units' placement, and Figure 3.10 the evolution over time. The vertical core is positioned on one side of the building to access the elevator and shafts, Figure 3.11, and from the first floor integrates small laundry units for the residents, Figure 3.12 and Figure 3.13.

The balcony and corridors were completely open without walls facilitating the building extension and the housing complex connections, Figure 3.6 B and Figure 3.12. The optimisation of the housing surface is associated with a range of communal activities on the top floor, which adds a significant floor surface per inhabitant. According to the occupants' needs, theme-oriented activities were proposed for shared spaces as shown in Figure 3.14 and Figure 3.15: a recreational area, swimming pool with sauna, collaborative workspace, urban garden, sports and a communal kitchen. The basement offers an appropriate envelope to be occupied according to the building's location by shops mainly in urban situations, and offices or workspaces in suburban cases (Figure 3.8, Figure 3.10 and Figure 3.11). The public and shared spaces can be chosen initially and then change through time, satisfying residents or neighbourhood needs to improve users' lives.

The optimal housing unit with 27 m² offers a living space designed to use less space and to sleep, live, cook, eat and bathe for either a single person or a couple, Figure 3.16. The connection between the structure and the modules are made by rails and mobile crane. For example, a module weight is around 5 tons and a mobile crane that reach 48 m height can lift around 12 tons. Thanks to this system, the modules can be individually plugged in and out. The shelf structure provides building services including HVAC through a connection point which was developed by WG5 from ECON4SD project⁴⁹⁸, Figure 3.17. The wood walls and structure can be easily disassembled and shipped by any standard truck, Figure 3.18. In addition to that, the module Type 1 (T1) can adapt, expand, and shrink as needed for new ways of life from one to four arrangements, as shown in Figure 3.19 and Figure 3.20. The module expands as a duplex (T2) with two modules offering ample living space with a separate room. The three modules (T3) expansion can have two rooms – one for a couple and one for a child, or an extra room – and two bathrooms, one bigger than the other. The last configuration is four modules (T4), with more space for the occupants following the three modules' scenario, including one more room and bathroom.

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Figure 3.3. Prototype 1 – Slab typology: First model



Figure 3.5. Prototype 1 – Slab typology: Third model, A - Frontal Façade; B - Back Façade



Figure 3.4. Prototype 1 – Slab typology: Second model, frontal and back façades are similar

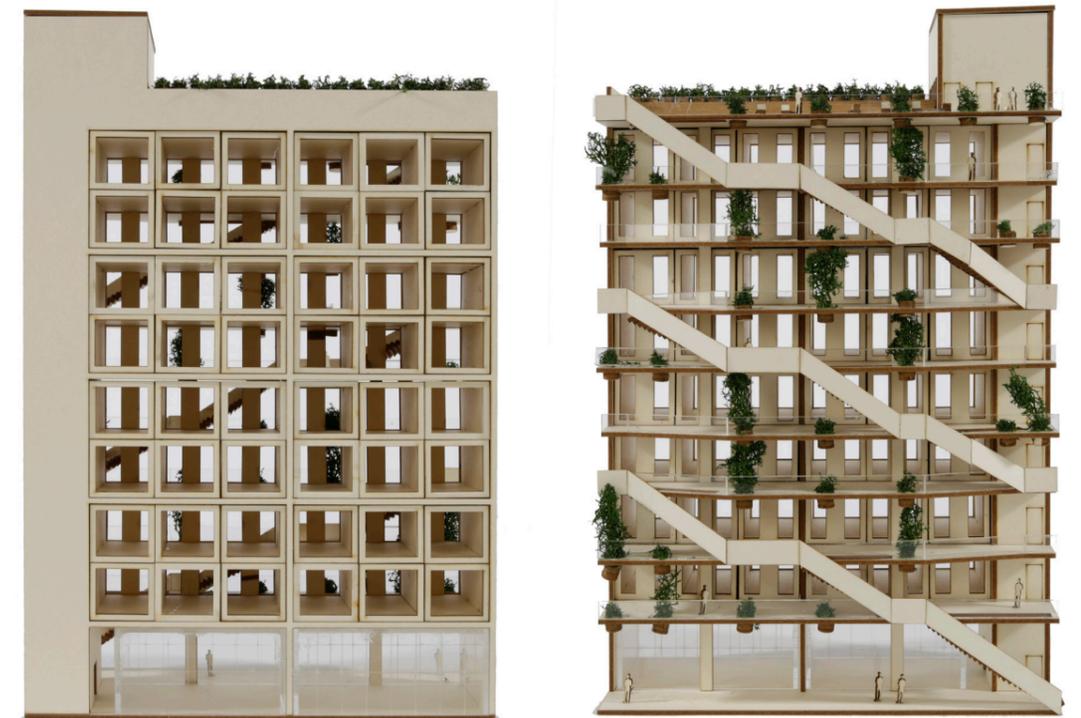


Figure 3.6. Prototype 1—Slab typology: A - Frontal Façade; B - Back Façade

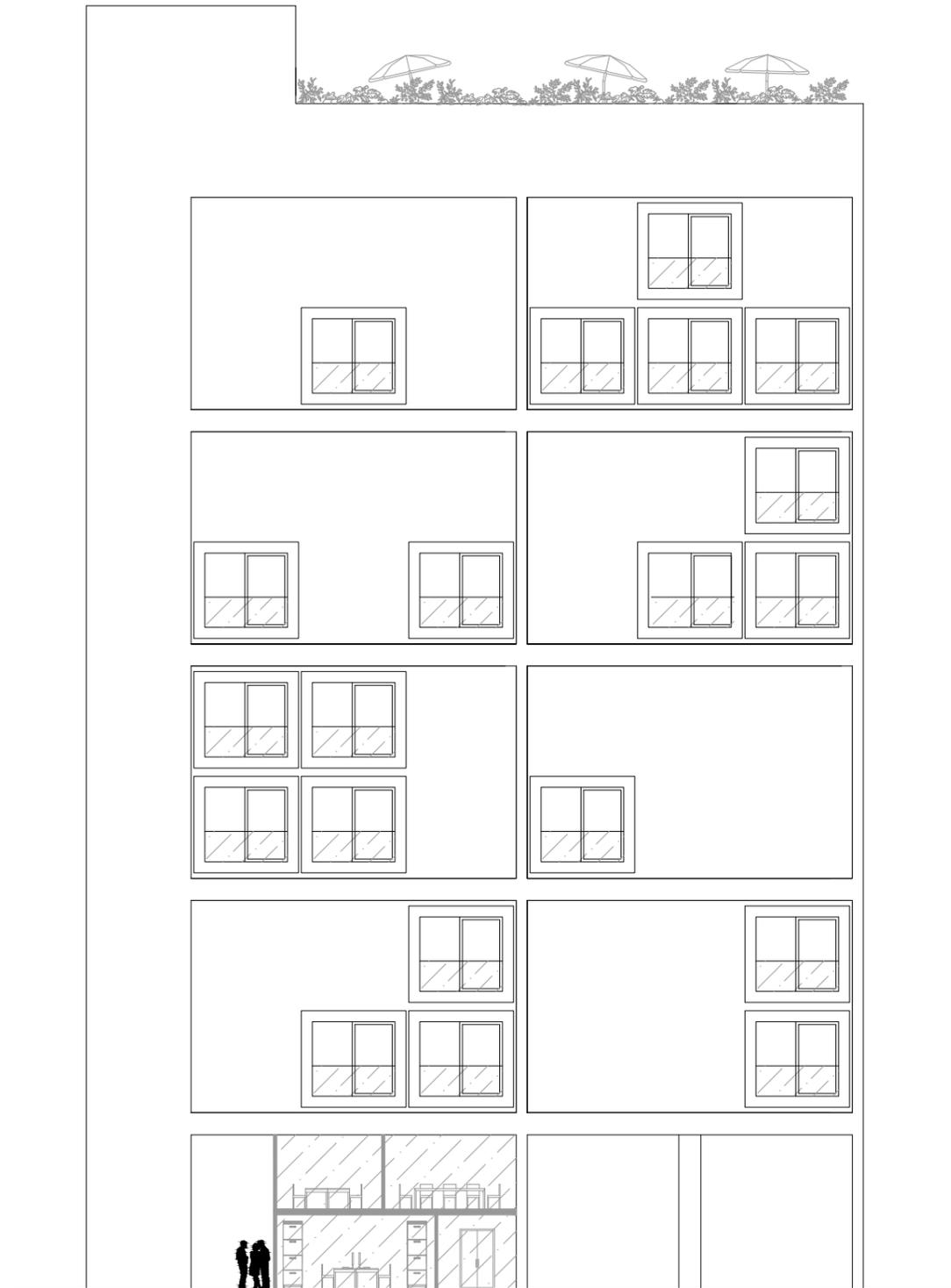


Figure 3.7. Prototype 1— Slab typology: Façade first placements

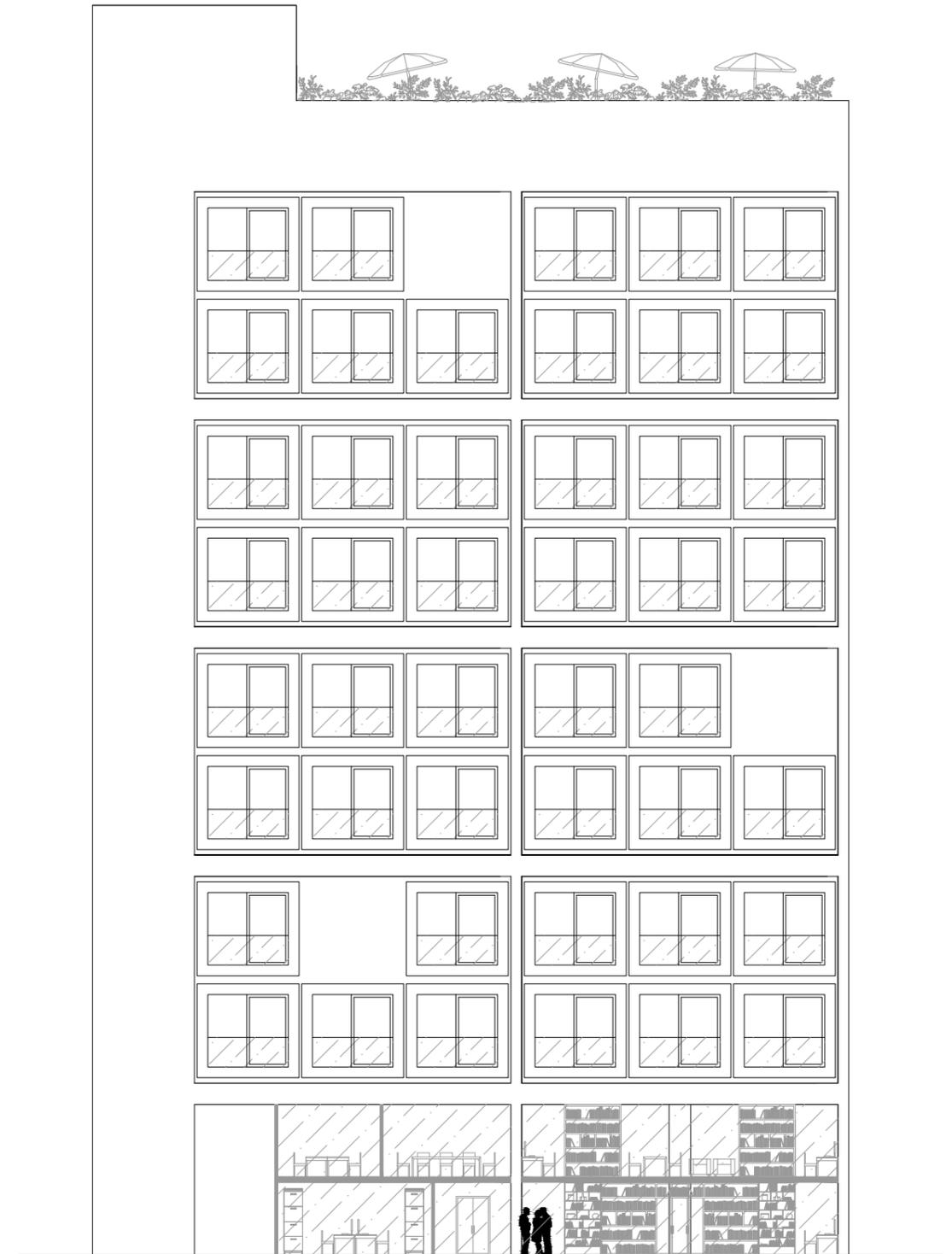


Figure 3.8. Prototype 1— Slab typology: Façade evolution through time

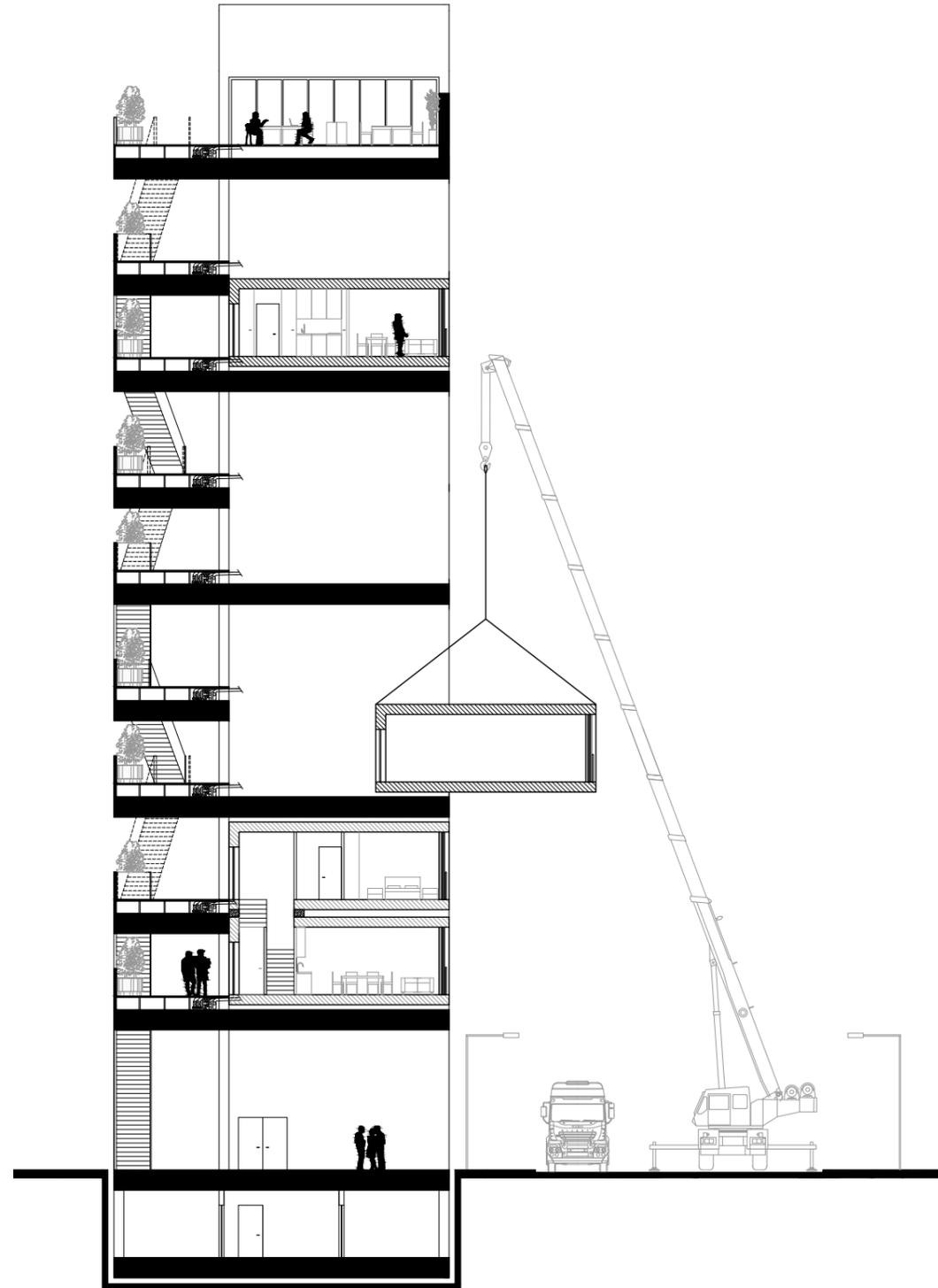


Figure 3.9. Prototype 1— Slab typology: Section - module assembly first placements

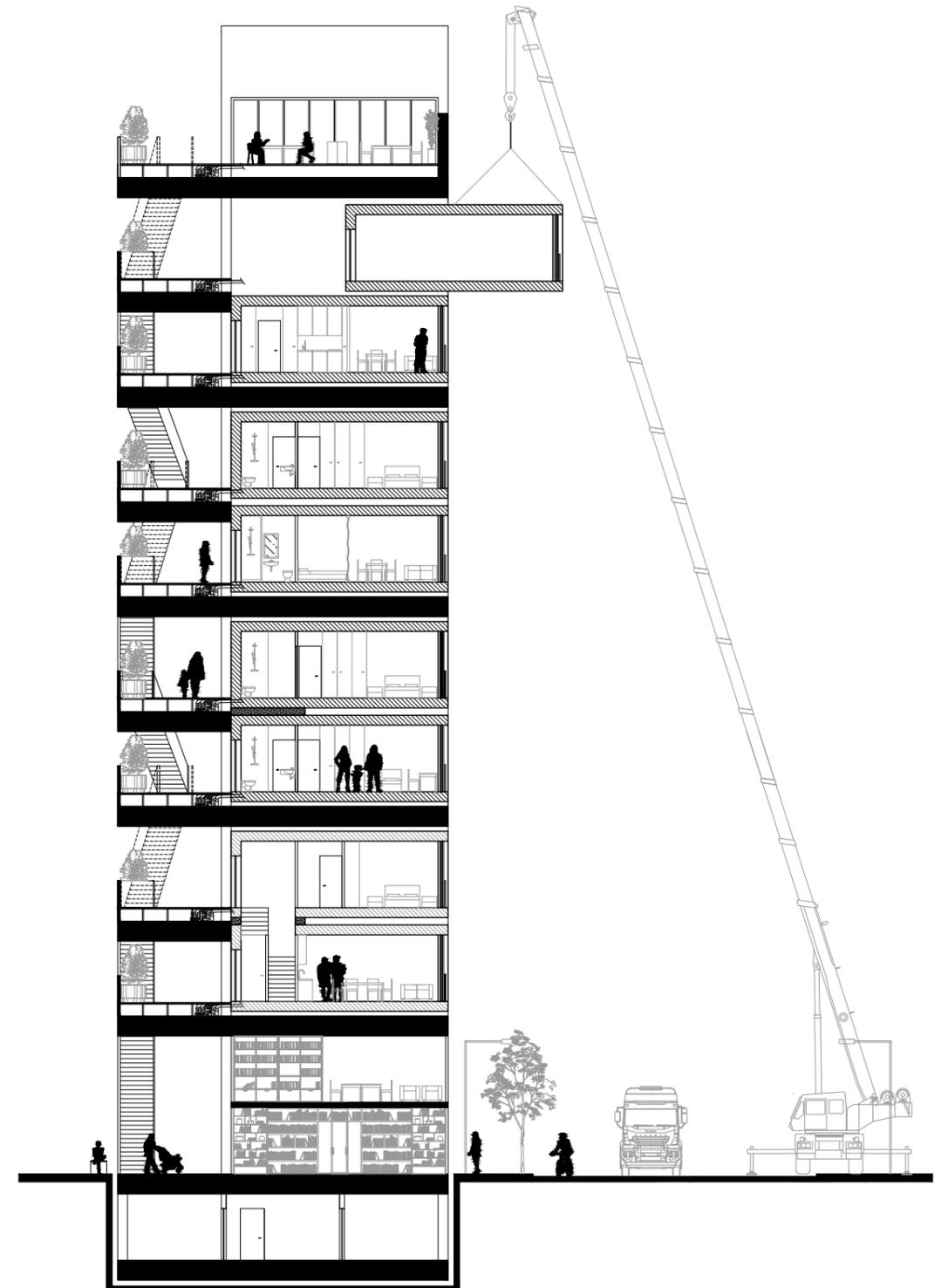


Figure 3.10. Prototype 1— Slab typology: Section - module assembly evolution through time

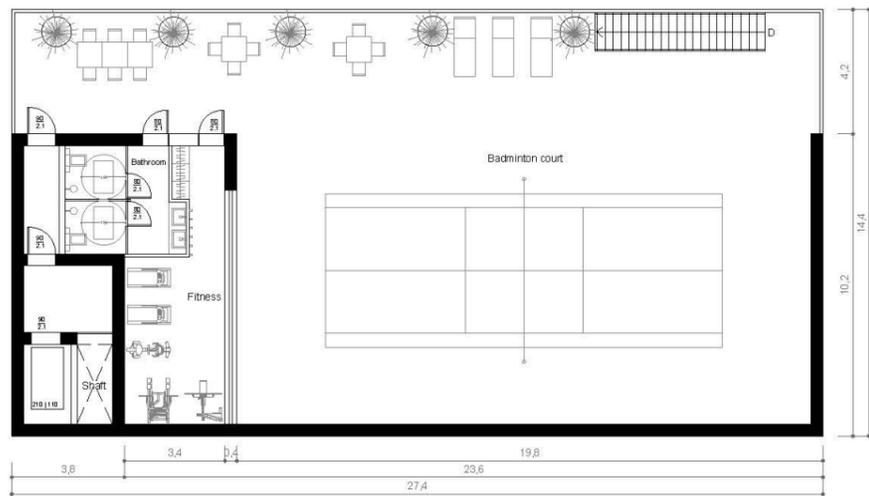
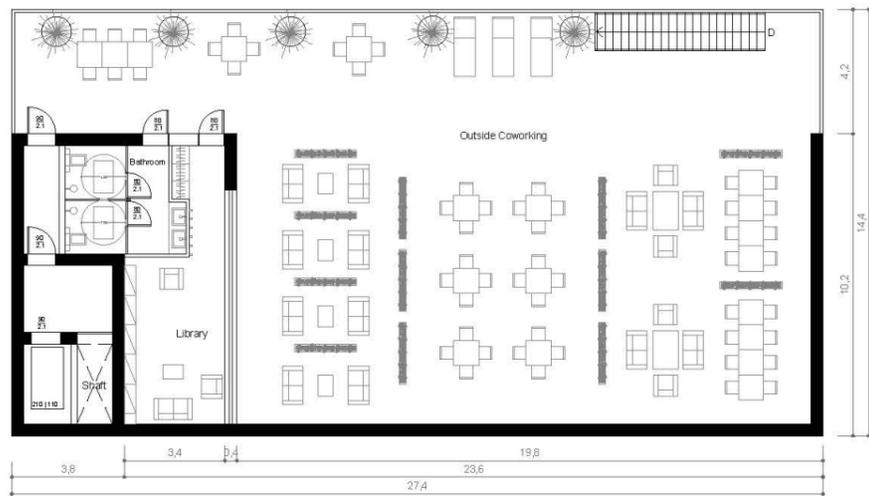
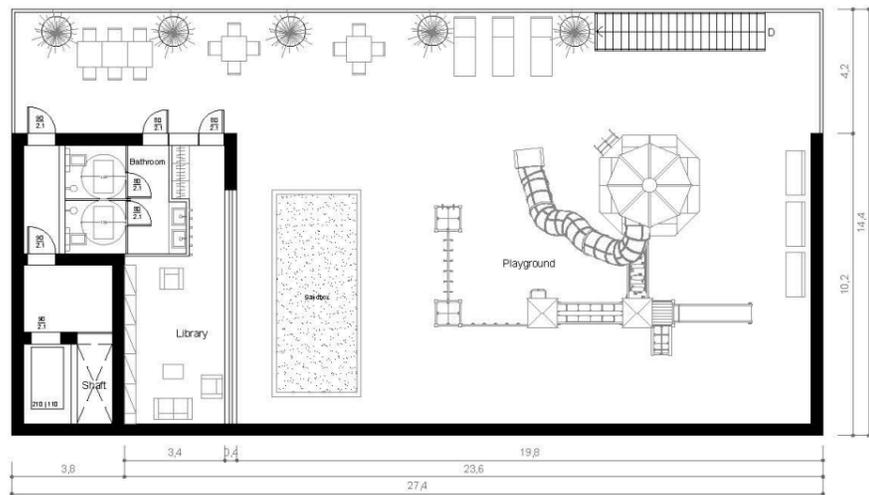


Figure 3.14. Prototype 1—Slab typology: Rooftop theme-oriented activities – playground, coworking and badminton court

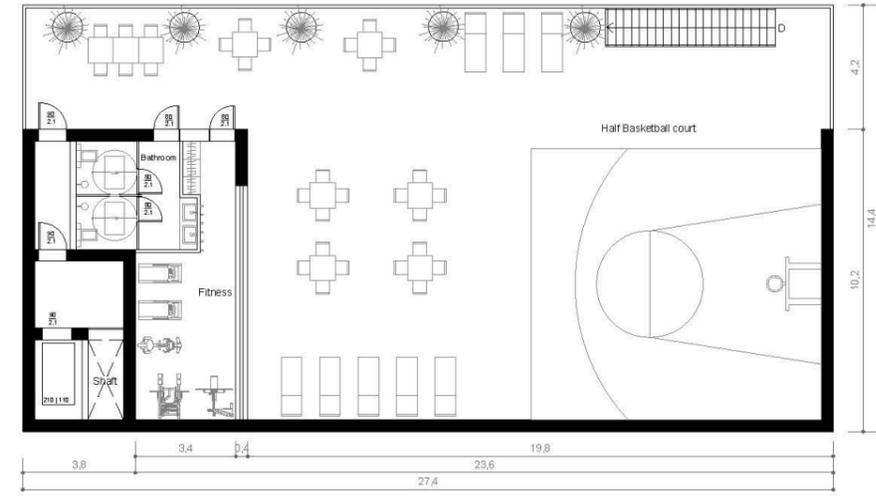
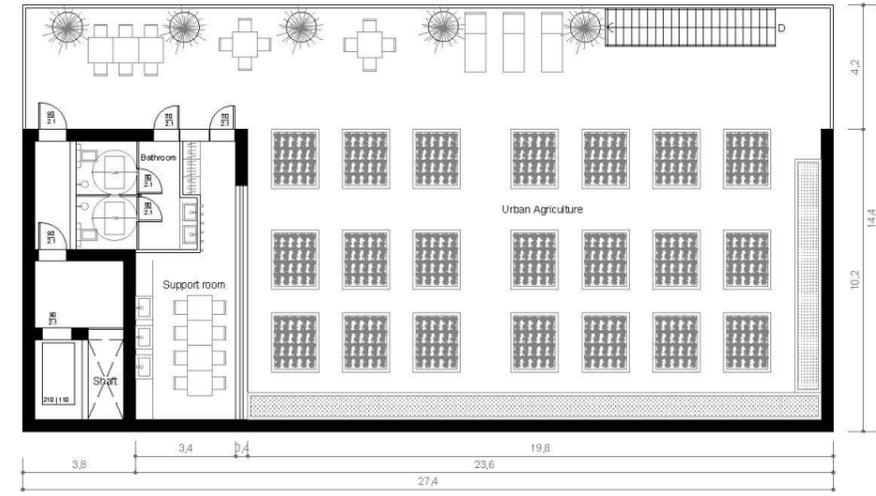
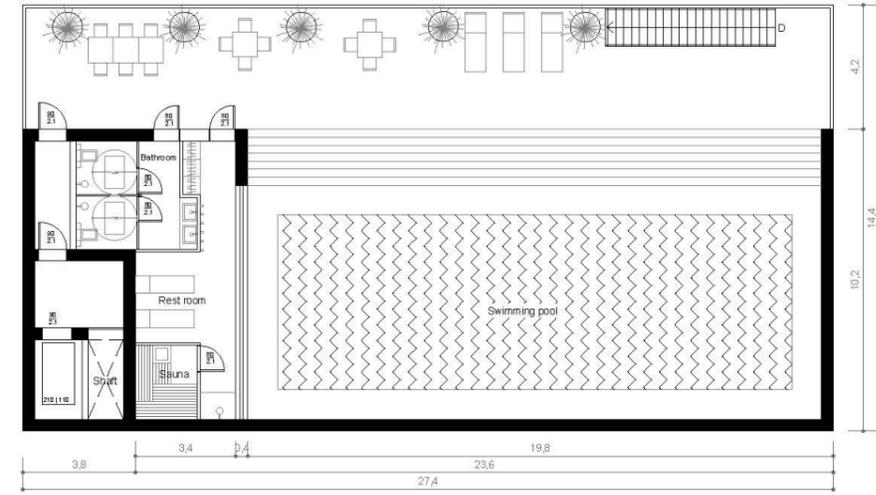


Figure 3.15. Prototype 1—Slab typology: Rooftop theme-oriented activities – swimming pool/sauna, urban garden and half basketball court

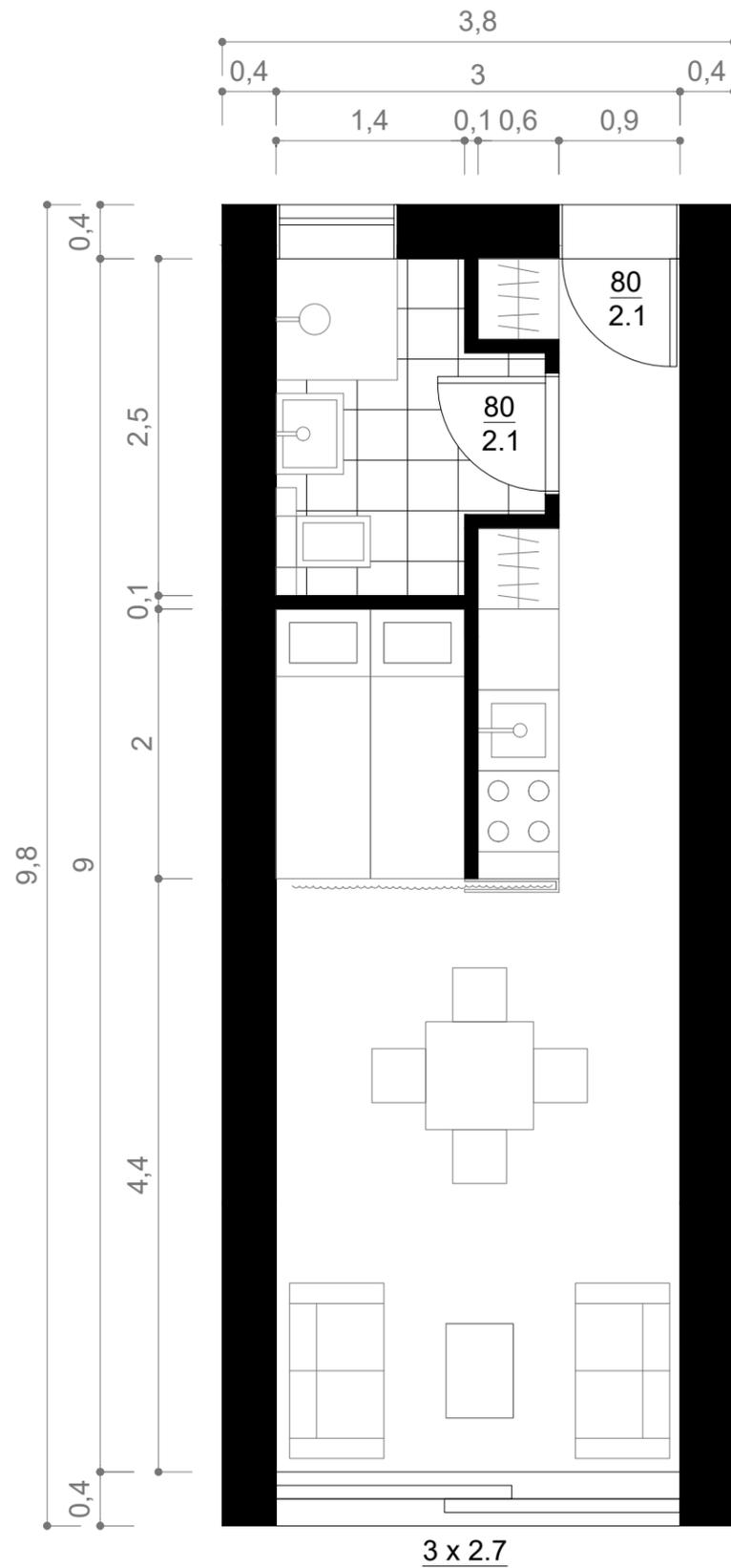


Figure 3.16. Prototype 1— Slab typology: Housing unit - optimal plan for the basic module - area 27m²

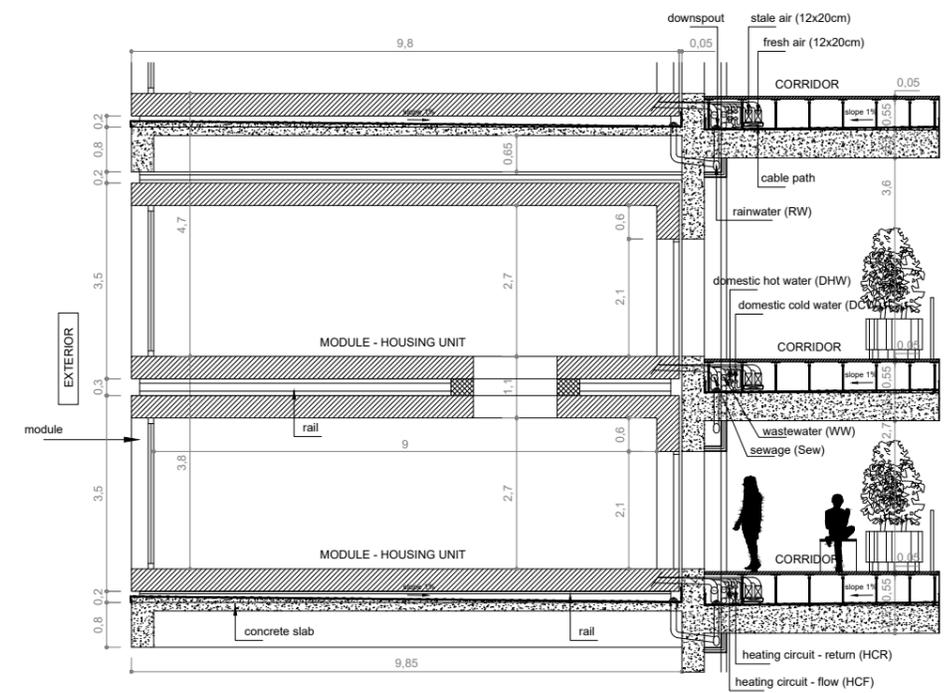


Figure 3.17. Prototype 1—Slab typology: Housing unit service and HVAC connection

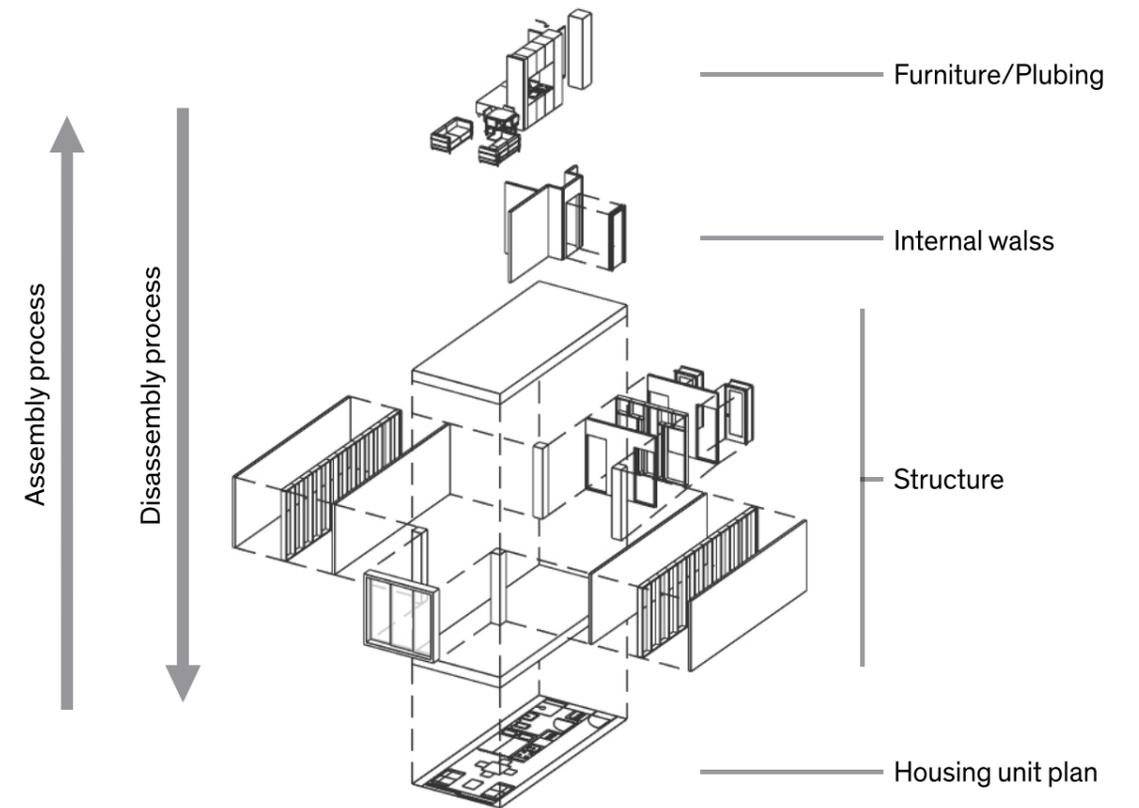
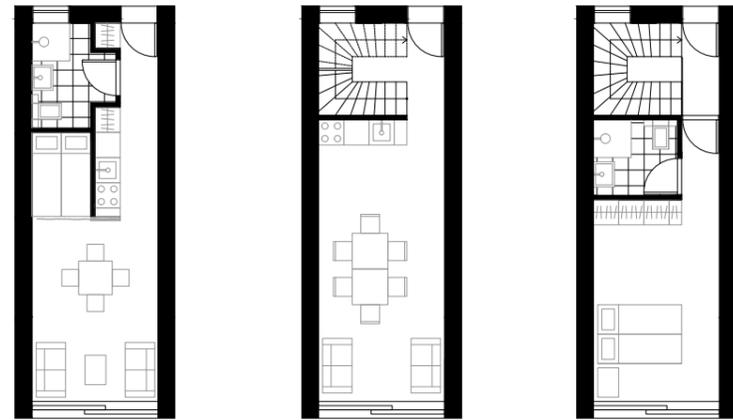
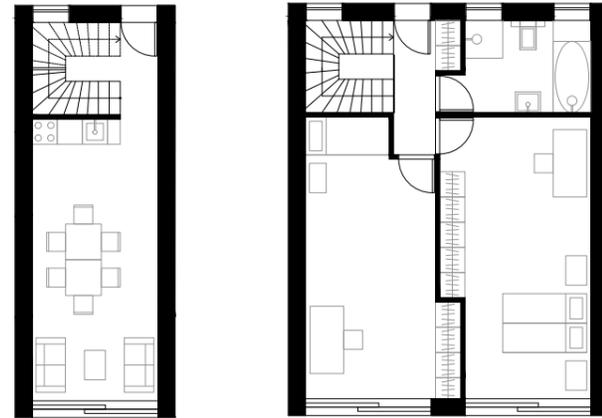


Figure 3.18. Prototype 1—Slab typology: Housing unit assembly/disassembly process



Type 1 - Module
27 m²

Type 2 - 2 Modules/Duplex
54 m²



Type 3 - 3 Modules
81m²

Type 4 - 4 Modules
108 m²

Figure 3.19. Prototype 1—Slab typology: Housing unit plans from 1 to 4 arrangement



Type 1 - Module

Type 2 - 2 Modules Duplex



Type 3 - 3 Modules

Type 4 - 4 Modules

Figure 3.20. Prototype 1—Slab typology: Housing arrangements - Type 1 – The module - optimal housing unit; Type 2 – 2 Modules: duplex; Type 3 - 3 modules; Type 4 - 4 modules

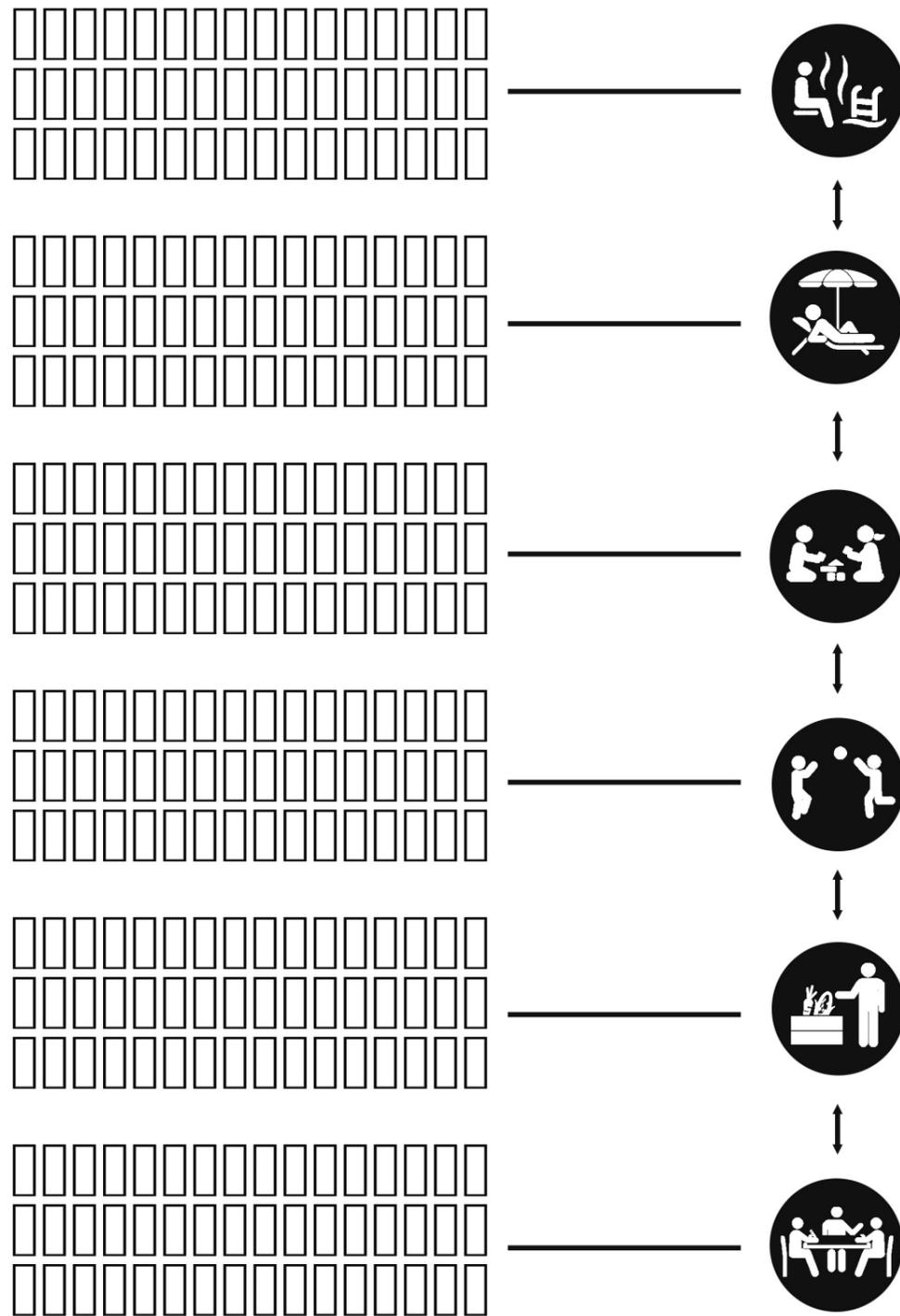


Figure 3.21. Prototype 1—Slab typology: Diagram - Distribution of shared spaces in relation to housing units

The whole Slab building is working as a module too. This combination offers more than one type of shared space and diverse activities, Figure 3.21. Depending on the terrain and demand, the structure can be extended, forming a horizontal complex and continuous building. For example, it can be a linear extension, as shown in Figure 3.22 and Figure 3.23, with three models and six modules in Figure 3.25, Figure 3.26, Figure 3.27 (height variation) and Figure 3.28, or varying the position and direction as shown in Figure 3.24 and Figure 3.29. Its structure allows the development of land that is difficult to build on such as land close to railways and railroads, narrow and remaining city plots, and linear parking areas that will no longer be needed (see Figure 3.30). Thus, the generic Slab building represents an infrastructure that can be placed in many neighbourhoods and cities for portable houses that can be plugged-in or out according to their owners' relocation. Furthermore, the housing units can move with their owners by truck and be capable of plugging into other Slab infrastructure. Figure 3.31 represents all this dynamic and circularity of Prototype 1.

In terms of recyclability and reusability, the building elements were designed to be separated and reused in other construction and projects, facilitating tracking and uploading on platforms to resell them directly, recondition or recycle them. The housing units can be connected and separated from the core. Its structure can be disassembled once it is in timber, a material whose maintenance, replacement and recyclability are simplified, responding to a circular building's demands. As this material is not exclusive to one industry, similar modules can still be fabricated by different companies if the local economy changes. Furthermore, the prototype can adapt to the occupants via continuous evolution. More generous public space and shared spaces for the occupants could be offered despite the same size as an ordinary building. Soon, the building can be used as reusable material and component banks for future buildings. Table 3.2 illustrates Slab typology possibilities with different user scenarios, structures, housing units, ground floor and rooftop.

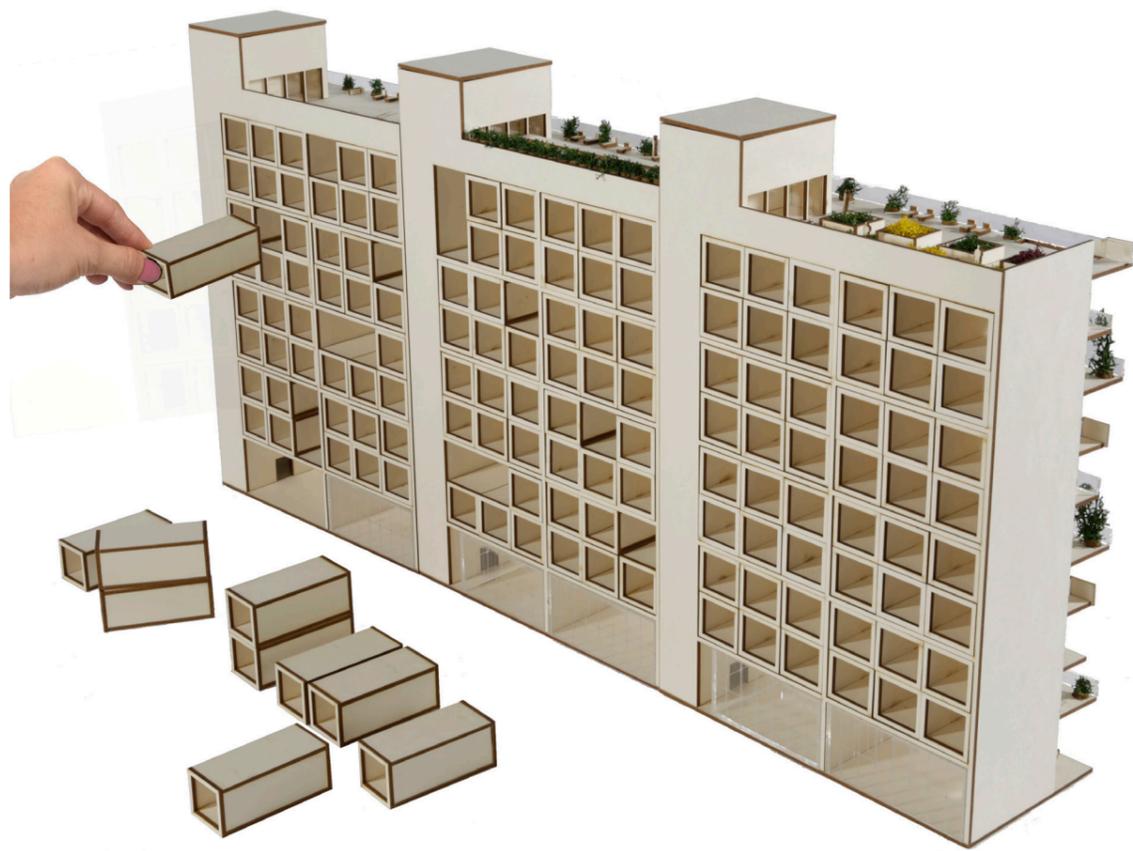


Figure 3.22. Prototype 1—Slab typology: 3D model, frontal façade with 3 models



Figure 3.23. Prototype 1—Slab typology: 3D model, back façade with 3 models

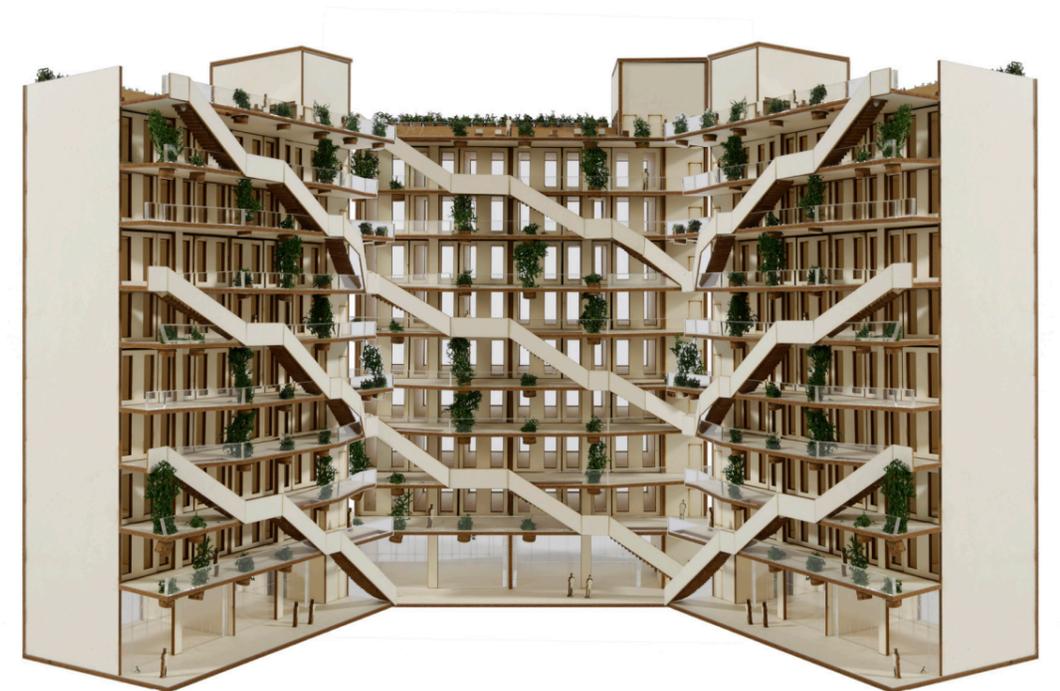


Figure 3.24. Prototype 1—Slab typology: Back Facade – Direction variation extension with 3 models



Figure 3.25. Prototype 1—Slab typology: Frontal Façade – Linear extension with 6 models



Figure 3.26. Prototype 1—Slab typology: Back Façade – Linear extension with 6 models

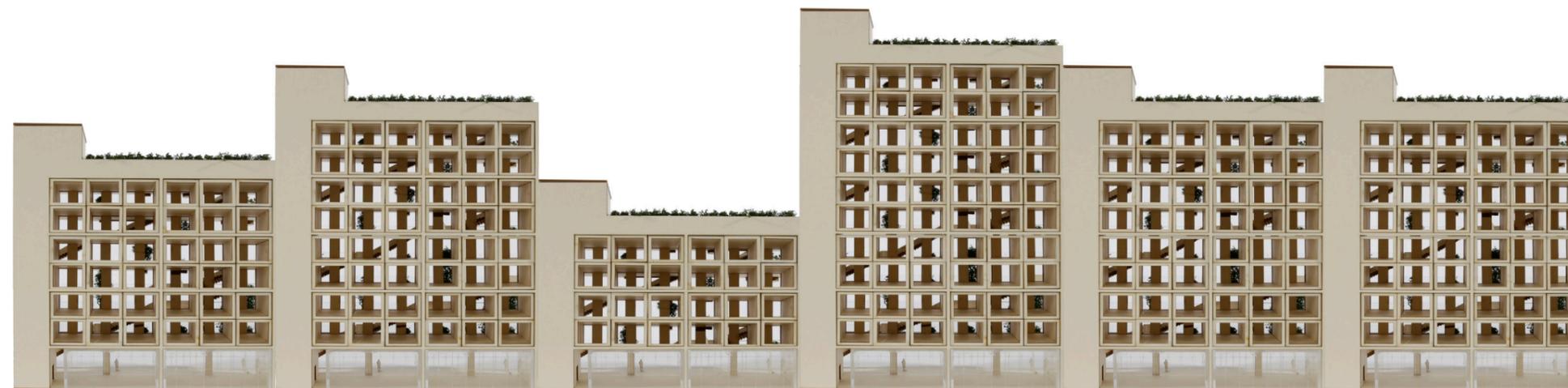


Figure 3.27. Prototype 1—Slab typology: Frontal Façade – Linear extension with 6 models height variation

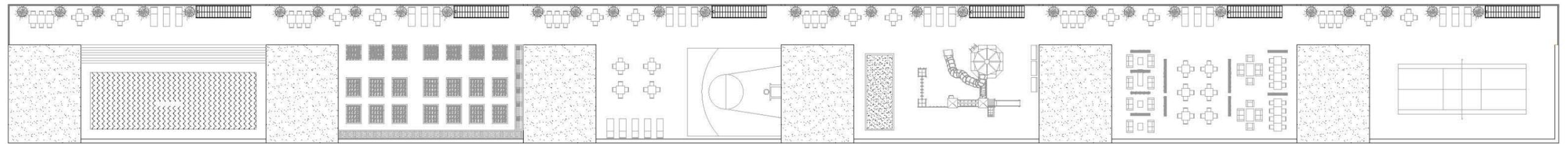


Figure 3.28. Prototype 1—Slab typology: Plan of different activities – Linear extension with 6 models

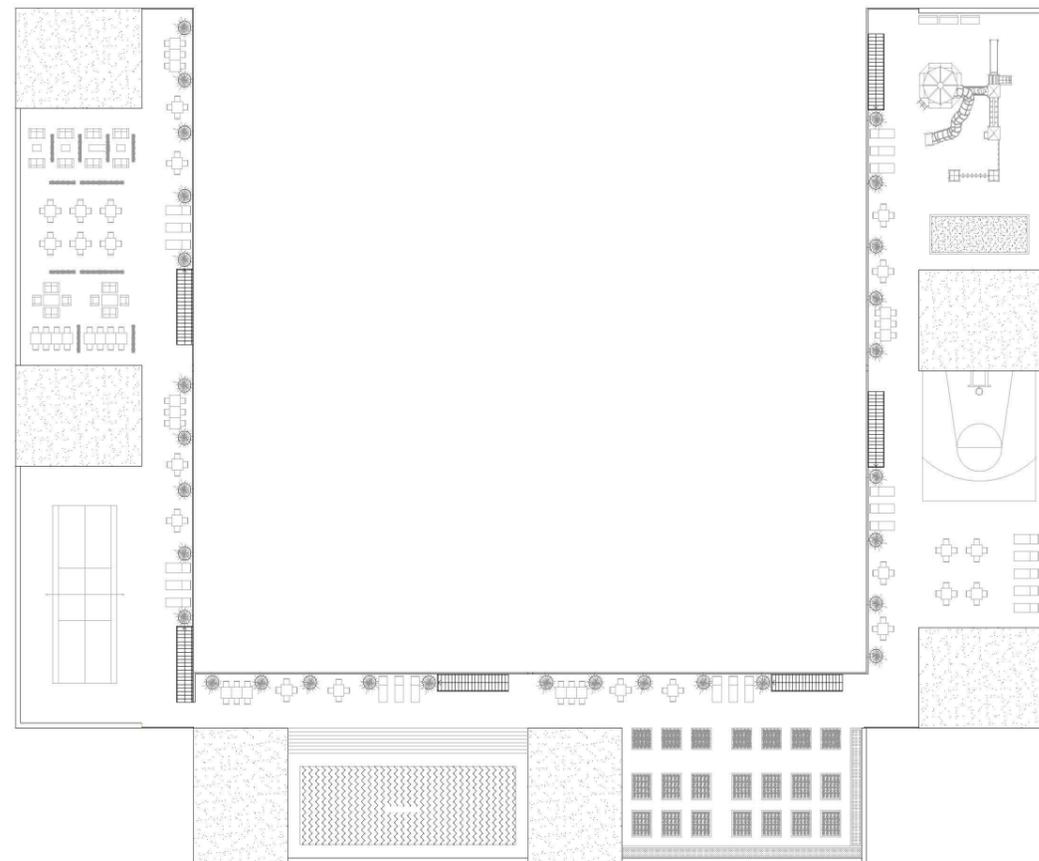
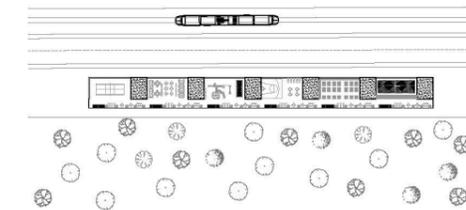
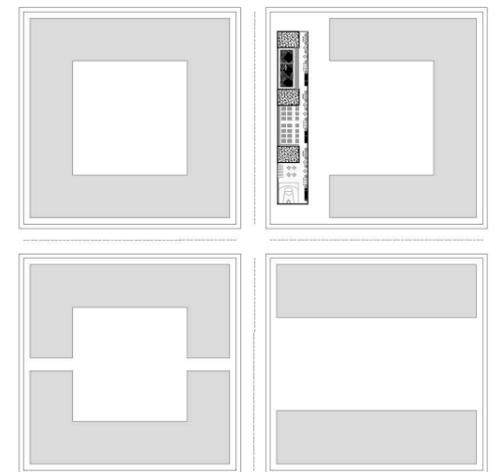


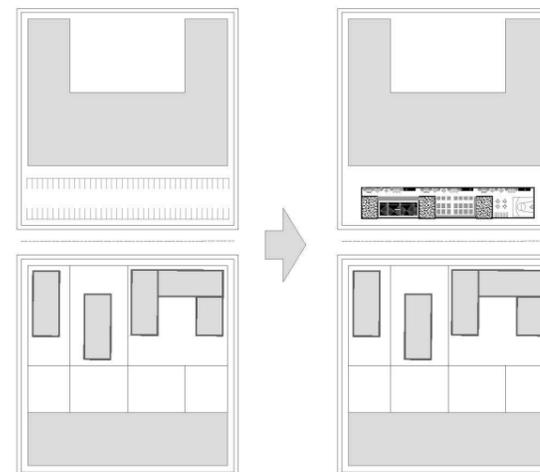
Figure 3.29. Prototype 1—Slab typology: Plan of different activities – Direction variation extension with 6 models



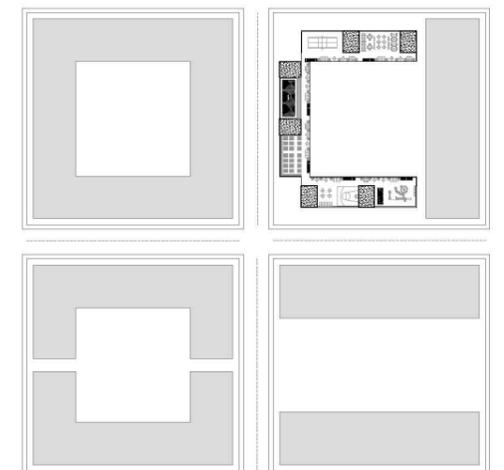
Close to railways and railroads



Narrow and remaining city plots



linear car parking areas that will no longer be needed



Courtyard configuration

Figure 3.30. Prototype 1—Slab typology: possible implementation in the city

Table 3.2. Prototype 1—Slab typology: scenarios

STRUCTURE	HOUSING UNITS	GROUND FLOOR	ROOFTOP	USERS
Same for 100 years It can be expanded by adding more building	Same for 100 years Expanded Diminish 48 housing units	Open Close Public Private Shops Markets Offices	Open Close Public Private Shared swimming pool sauna library analog lounge collaborative workspace. urban garden sports c o m m u n a l kitchen	people living alone young workers couples families with a child
Use new concrete and steel Use recycled concrete and steel	24 duplex 16 apartments with 3 units 12 apartments with 4 units			
Dismantled the concrete Concrete can be recycled				
Dismantled the wood Wood can be recycled Wood can be reuse in other construction				
Slabs are open Slabs are close				
Residential: Slabs filled with housing units Comercial: Slabs filled with of-fices Mixed				

In quantities, the Slab typology, in its total capacity, can host 48 housing units and 96 tenants considering that two people are living together in each housing unit. One housing unit has 27 m². In addition to that, the surfaces were analysed and divided into reusable and recyclable. First, the reuse division integrated the materials, same for recyclability and the space, that were subdivided into shared and functional uses and their different possibilities. Next, the recyclable surfaces were separated by their primary materials, wood (plug-in-out housing units) and concrete (infrastructure - corridors, balconies, and open and shared spaces). The subdivisions and paths can be seen in the diagram in Figure 3.32. In addition to that, Table 3.3 shows some data and the surfaces quantities for the Slab typology. Thirty-eight per cent of the surfaces are wood, a material that can be easily reused or recycled after the first life cycle. Thirty-three per cent of a usable surface area is destined for housing units, and 41% are communal spaces (rooftop, ground floor and balconies combined). Figure 3.33 shows the gross areas surfaces in % of Prototype 1. The usable area of the apartments is increased from 27 to 32 m² when we add approximately 5 metres from the rooftop shared space. Apart from the flexibility in the housing unit arrangement, another advantage to having a slab over two floors is the increased usable surface for housing units with wood instead of concrete, which consequently increases the total possible useful area of the building. The footprint for access to the structure on the ground floor represented only 12% of the area, meaning 88% of the ground floor is open for public access and can accommodate neighbourhood needs.

To give one example of context, Prototype 1 was placed in two contexts in Luxembourg. The first one is in the Belval neighbourhood in the city of Esch-sur-Alzette. The land is close to a railway on France's border, with an open green area, as shown in Figure 3.34 and Figure 3.35. Six buildings were aligned along the road making the connection and a seamless transition between the urban environment and nature. The ground floor softened this transition by mixing open and closed spaces with small local markets and coffee shops.

The second context is Route d'Arlon in Luxembourg city. The Ministry of Transport is planning to implement a new tramway which can reduce the need for cars, build parking areas and keep the city densified to avoid its expansion to nature. The sections in Figure 3.36, Figure 3.37 and Figure 3.38 demonstrate how this transformation can happen. First, the tram line will be realised by 2025. Second, the slab infrastructure can be placed on the surfaces that were parking spots before and are not needed anymore. Third, the infrastructure can be completed with more modules and families through time. The Route d'Arlon context and implementation were part of the Luxembourg in Transition (LiT) project; more information about it can be found in the Chapter Deliverables.

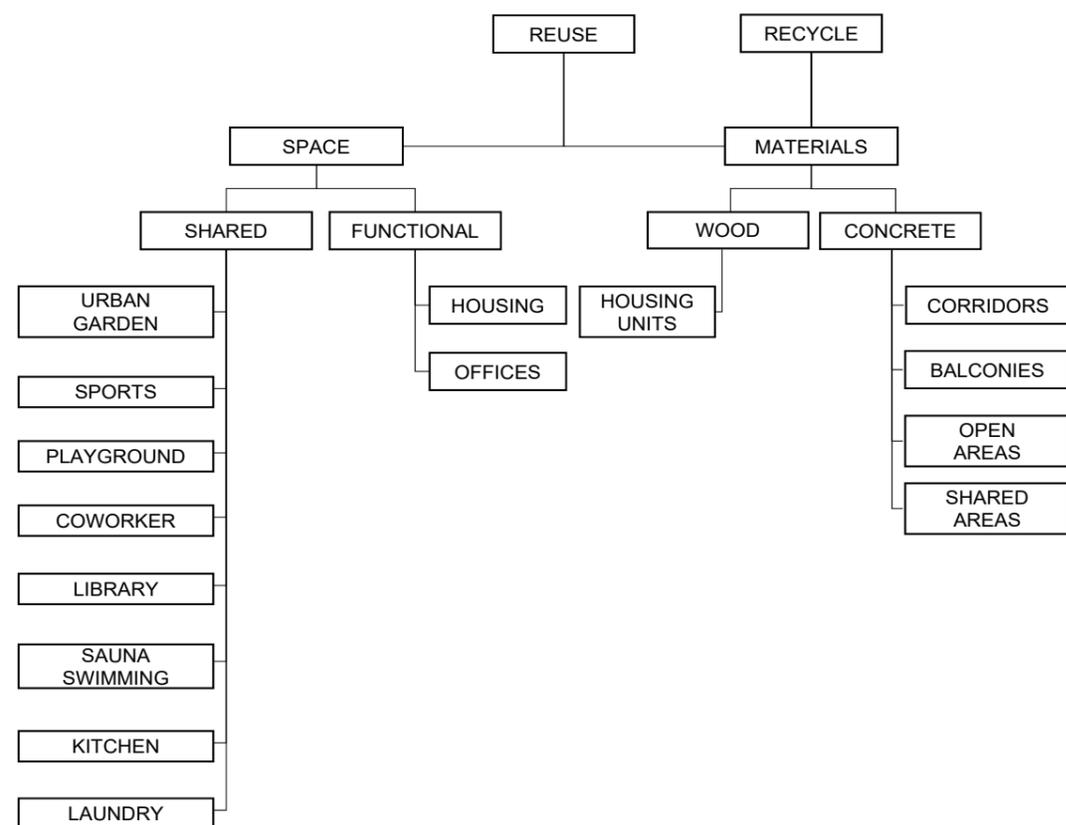


Figure 3.32. Prototype 1 - Diagram of reusability and recyclability for Slab typology

Table 3.3. Prototype 1 - Slab Typology quantities for one building

ASPECT	QUANTITY	MEASURING UNIT	PERCENTAGE
Number of apartments	48	unit	
Max number of inhabitants	96	pers.	
Housing unit gross area – wood module	37.24	m ²	
Housing unit usable area	27	m ²	
Usable areas			
Total housing unit surface	1296	m ²	33%
Rooftop - shared space	228.12	m ²	6%
Ground floor - open space for public facilities	223.44	m ²	6%
Balconies and stairs	1080.96	m ²	28%
Landry /shared space	52.56	m ²	1%
Corridors with elevators access	224.87	m ²	6%
Total net surface	3105.95	m ²	
Gross areas			
Housing unit surface	962.88	m ²	33%
Rooftop - shared space	249.63	m ²	9%
Ground floor - Open space for public facilities	240.72	m ²	8%
Balconies and stairs	1080.96	m ²	37%
Corridors to elevators access	378.69	m ²	13%
Total gross area	2912.88	m ²	
Total surface possible			
Total surface possible	3875.76	m ²	
Total footprint	394.56	m ²	
Footprint of access and structure	47.88	m ²	12%
Footprint of open space	346.68	m ²	88%
Materials			
Wood = gross total housing units surfaces	1787.52	m ²	38%
Concrete = total of all brute surfaces	2912.88	m ²	62%

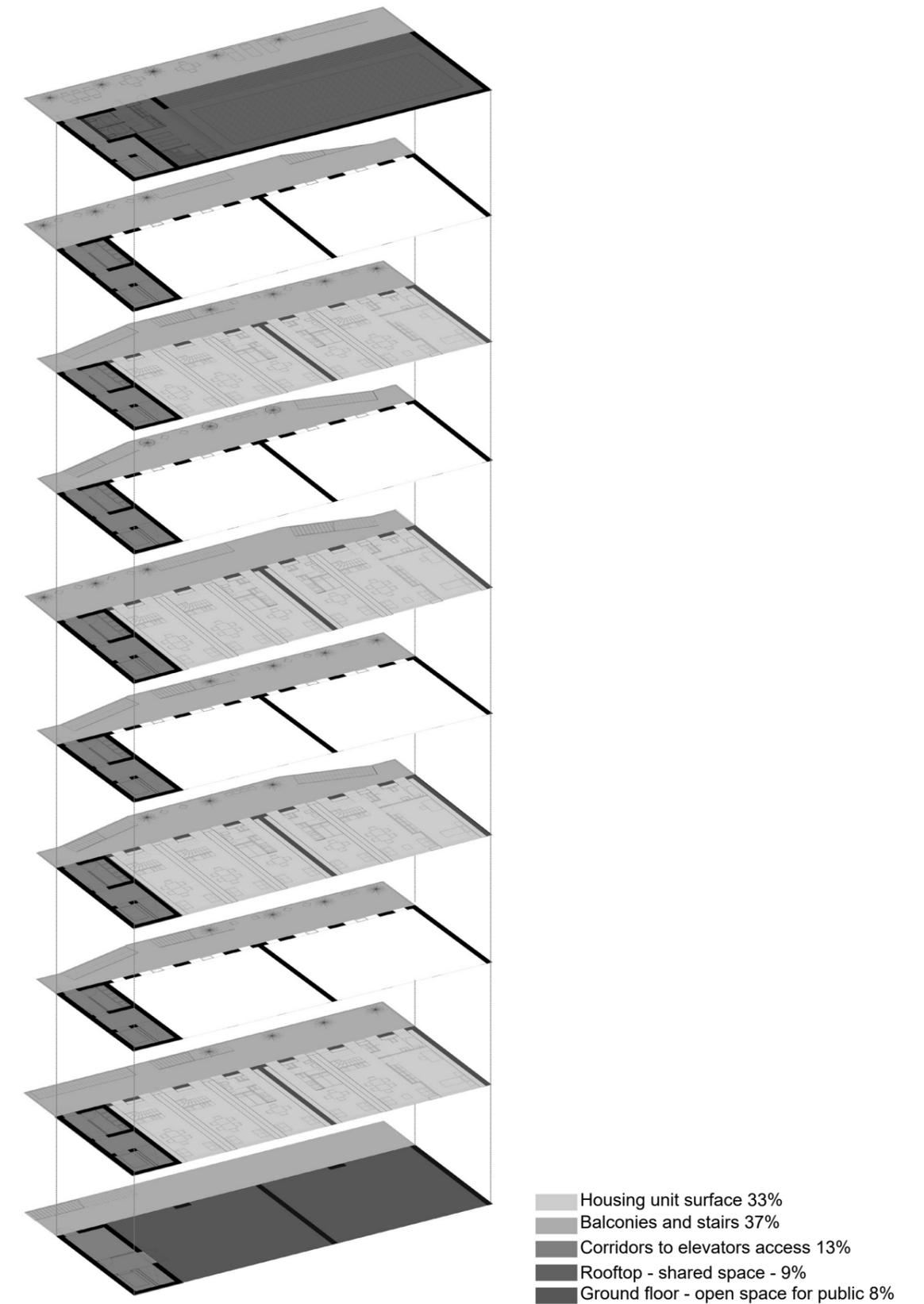


Figure 3.33. Prototype 1 – Slab typology: Diagram of gross area surfaces in %



Figure 3.34. Prototype 1—Slab: 3D simulation extension, situated at Belval neighborhood, Esch-sur-Alzette, Luxembourg



Figure 3.35. Prototype 1—Slab typology: situation map in Belval neighborhood, Esch-sur-Alzette, Luxembourg

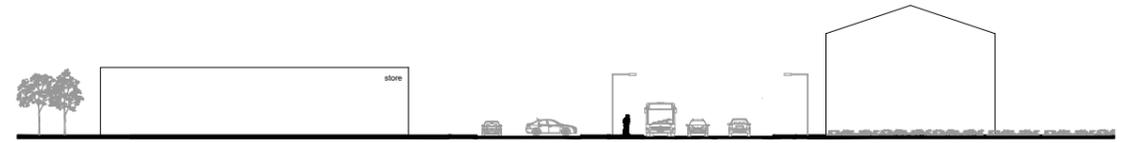


Figure 3.36. Prototype 1—Slab typology: Section on Route d'Arlon 2021

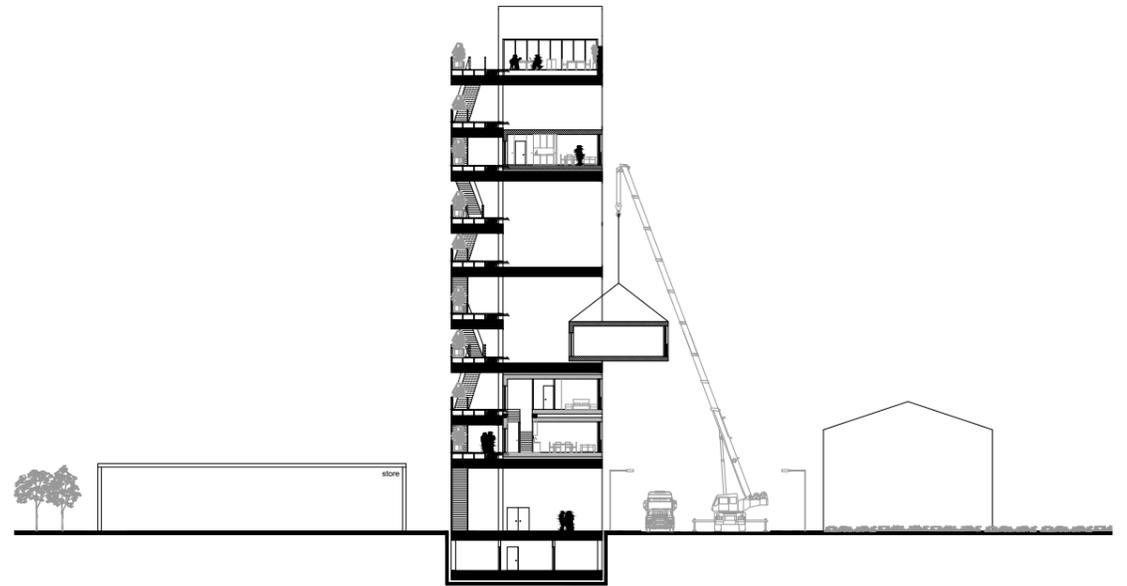


Figure 3.37. Prototype 1—Slab typology: Section on Route d'Arlon 2026

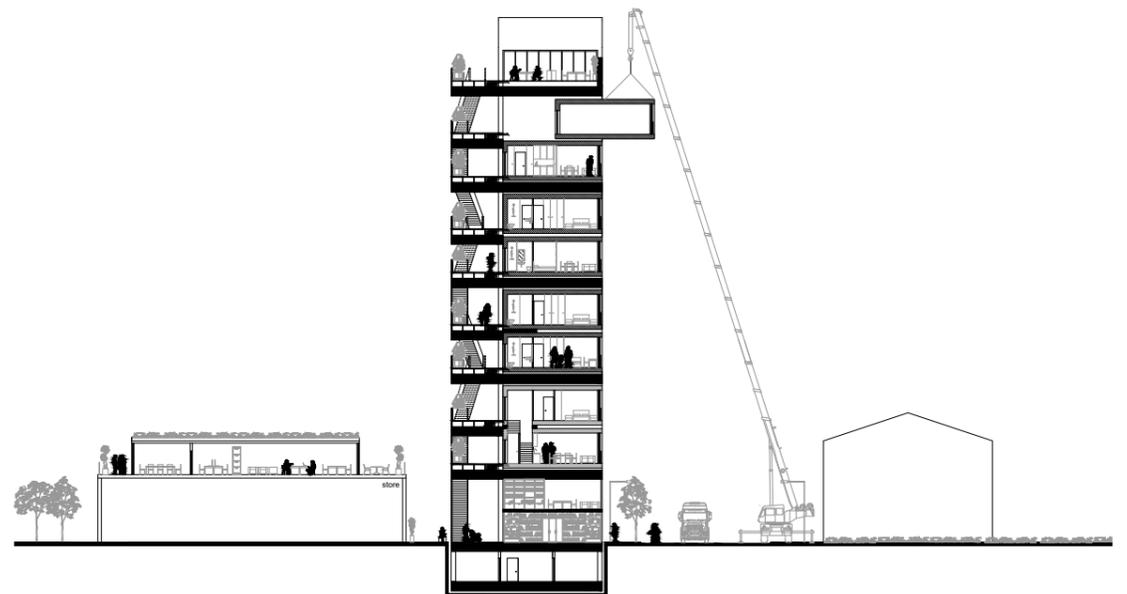


Figure 3.38. Prototype 1—Slab typology: Section on Route d'Arlon 2031

3.3. Prototype 2- Tower typology

The design process of the Tower started with the question of how a high-rise building can be flexible enough to adapt to society's evolution, incorporate inhabitants from various social classes and community activities while at the same time be recyclable. The structure should allow disassembly at the end of its life and then be recyclable or reused in another building. In this way, the mixed idea of tree shape and symmetric pyramidal was proposed for the Tower typology.

Initially, a generic model was developed to bring the Tower's ideas to the physical world, with a central core supporting open slabs of different sizes like a tree (Figure 3.39). The building complex seeks a mixture of living and working. The form strives to reduce the footprint to a minimum to allow for more open space on the ground floor, aiming to support shared activities, like open gardens and urban farming, which brings the community together, reduces the unnatural ground and has more natural light. The variations in slab sizes enable different floor organisation and use, including offices and apartment dimensions for different social classes combined with community facilities and shared spaces. The lower and upper floors can accommodate a pre-school, living room, kitchen, sports venue and greenhouse. The central floors with a large surface area are dedicated to collaborative workspaces, while the intermediate levels are for residence. The internal arrangement of walls, bathrooms and kitchens is adaptable since the technical floor integrates the infrastructure services.

A second model was made to develop the concept further. The structure and main walls were placed in superposition at the external facade to keep the interior as free from pillars as possible, increasing flexibility for different layouts. The slabs' sizes became more regular, bringing symmetry and stabilising the whole structure (Figure 3.40). That strategy brings a style to the building, simultaneously exposing the structure and facilitating the material separation for reusability or recyclability at the end of its life cycle. Due to the complex shape of a tree concept, two types of structures and distinct materials were necessary, according to the engineers of the ECON4SD project. Thus, two structures were proposed for this typology. The first one used timber and the second one used steel.

The timber typology refers to a 25-storey high-rise building with an external and visible wooden structure wrapped around a reinforced concrete core. The building was expanded, duplicating each floor to increase its density compared to the second model. Figure 3.41 and Figure 3.42 shows the façade with the duplicated floors. The higher density compensates for the reduced area of the lower and upper floors. The slabs were designed with a 3.2x3.2 metre grid to facilitate the prefabrication by rationalising elements and recyclability. Figure 3.43 show the grid and the ground floor plan. Figure 3.44 shows the 10th floor, the biggest slab sizes with central core access and Figure 3.46 one proposed office layout. Figure 3.45 shows the proposed layout for apartments on the 3rd floor. The section in Figure 3.47 presents the different uses proposed for the Tower typology.

The timber Tower typology can have approximately 290 apartments with the smallest housing units proposed in this research having an area of 27 m² and room for 580

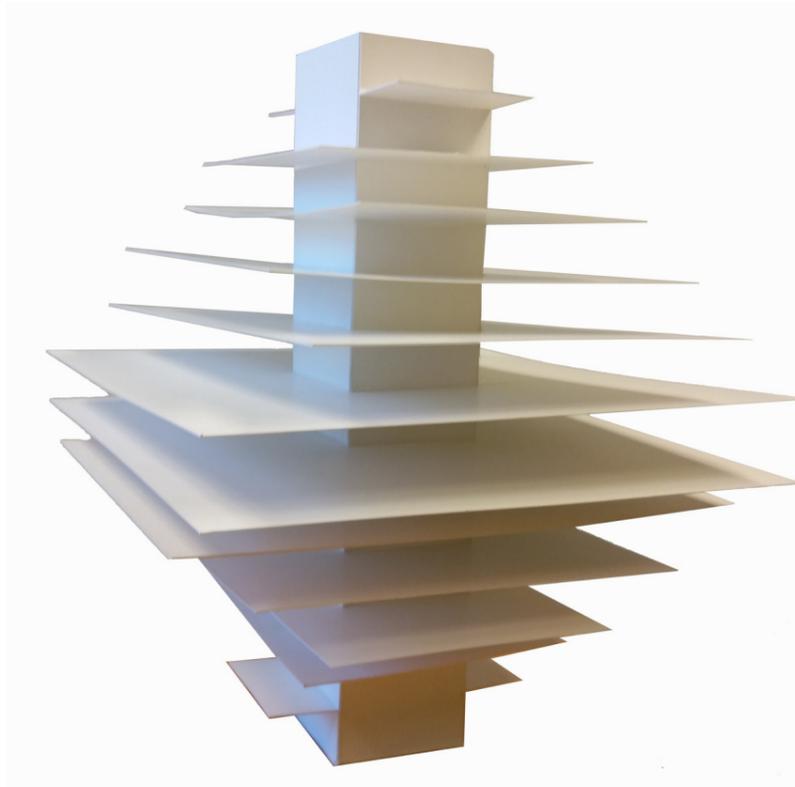


Figure 3.39. Prototype 2 – Tower typology: the first and generic model



Figure 3.40. Prototype 2 – Tower typology: second model

tenants. Table 3.4 presents the square metre quantity of its surfaces. The building footprint represents only 12% of the building projection on the ground, making the space completely open for the city. The amount of surface for housing and office is balanced, 32% and 38%, respectively. Even having 5 floors for shared space represents only 9% of the total usable surface, which can be more attractive for investors. Six per cent of the surfaces are destined to be the exposed wooden portion of the structure against 94% of the concrete surfaces. However, the slab accounts for 76% of the concrete, and it was designed to be completely disassembled, making it possible to reuse and recycle it. Considering the reusability of the spaces, 77% of the usable surfaces can change their use during the lifespan of the structure since the floors are entirely open to hosting new configurations. Figure 3.48 shows the reusable and recycled gross area surfaces in % of Prototype 2. WGP3 from ECON4SD project tested the timber trusses of the structure following the architectural composition and his general simulation showed that it is feasible for construction. Nevertheless, more detailed calculations should be done.

In parallel, the WGP2 analysed a steel structure of a similar configuration, but it was concluded that it is not suitable for steel construction due to the high demand and a massive quantity of materials. Consequently, the structure changed due to steel's materiality adaptation, leading to the fourth model, as shown in Figure 3.49 and Figure 3.50. The steel Tower has 14-stories for construction balance, and the prefabricated and recyclable steel structures were placed inside the façade and clamped to a reinforced concrete core where diagonal pillars were added. The steel skeleton is enveloped by a glass facade, remaining apparent in the interior (Figure 3.51). Nevertheless, the steel Tower typology kept the timber tower's main characteristics, which can be seen in Figure 3.52. The walls can be allocated close to the diagonal pillars for more favourable internal space or in the middle of the larger living environments as partitions, as presented in the plan of Figure 3.53 and Figure 3.54, and 3D for housing Figure 3.55. The building was designed on a 2x2 metre grid (Figure 3.56) to facilitate prefabrication by rationalising elements and implementing a dismantlable slab system developed by the WG2 from ECON4SD project. The dismantlable floor system is built based on a dismantlable shear connector and modular solid concrete slab elements with transverse and equidistant rails embedded with welded anchors⁴⁹⁹, Figure 3.57 and Figure 3.58.

⁴⁹⁹ Fodor and Schäfer 2021.

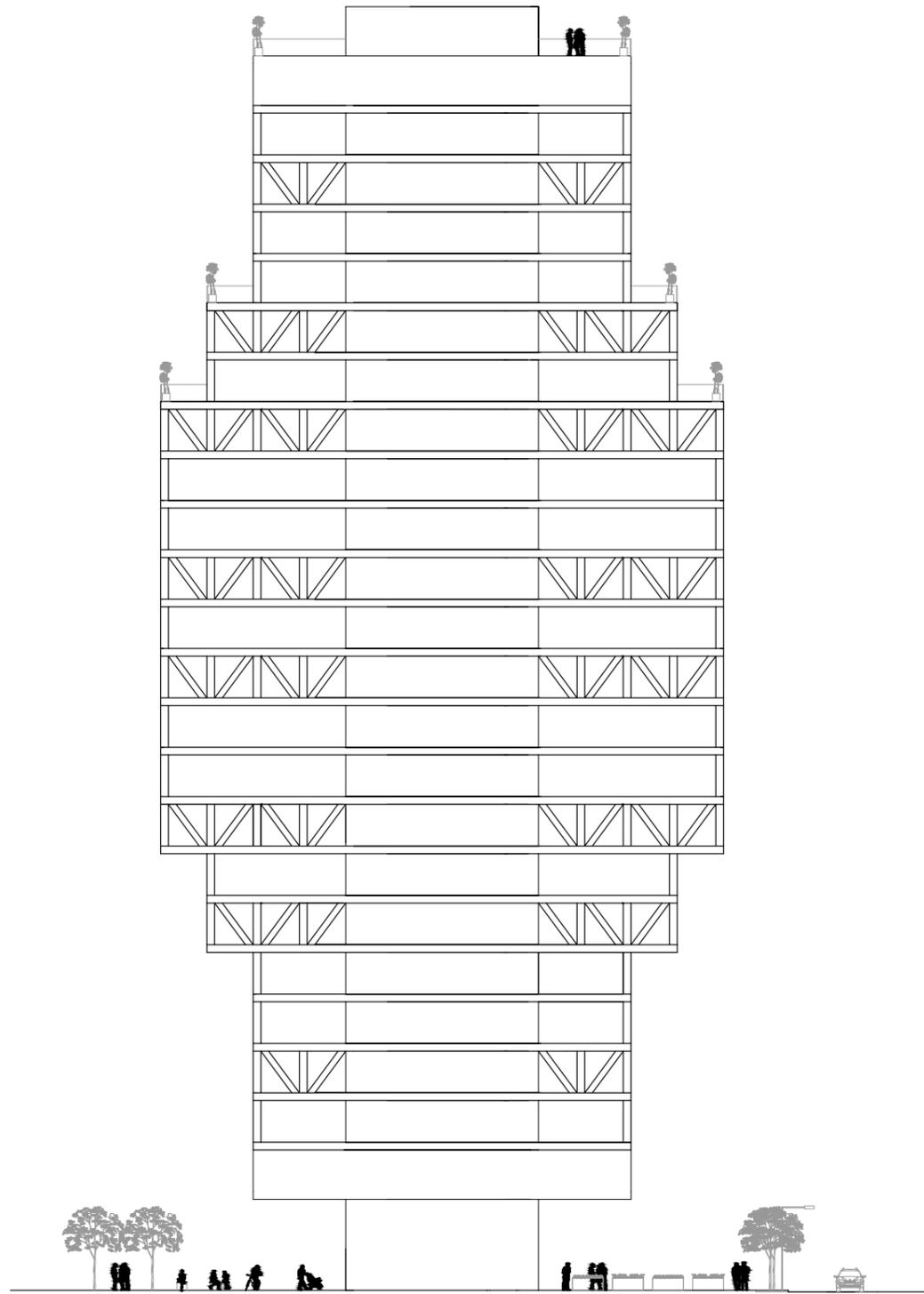


Figure 3.41. Prototype 2 – timber Tower typology: façade

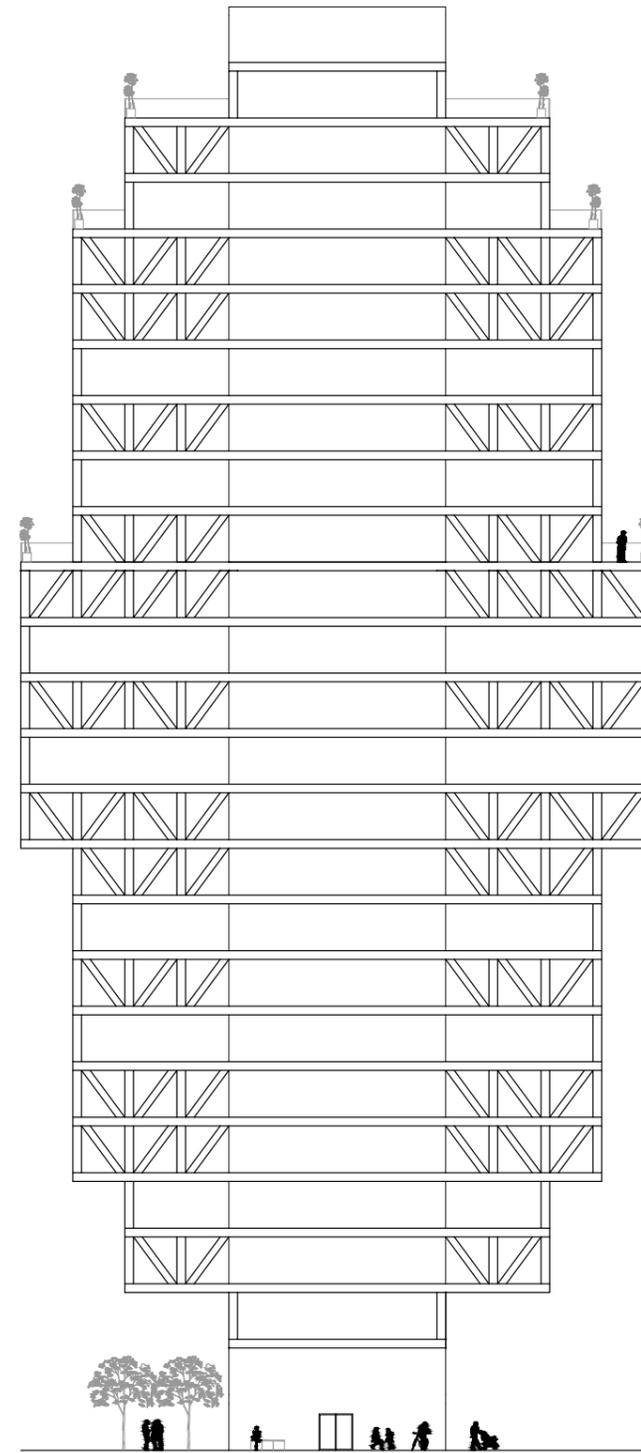


Figure 3.42. Prototype 2 – timber Tower typology: façade

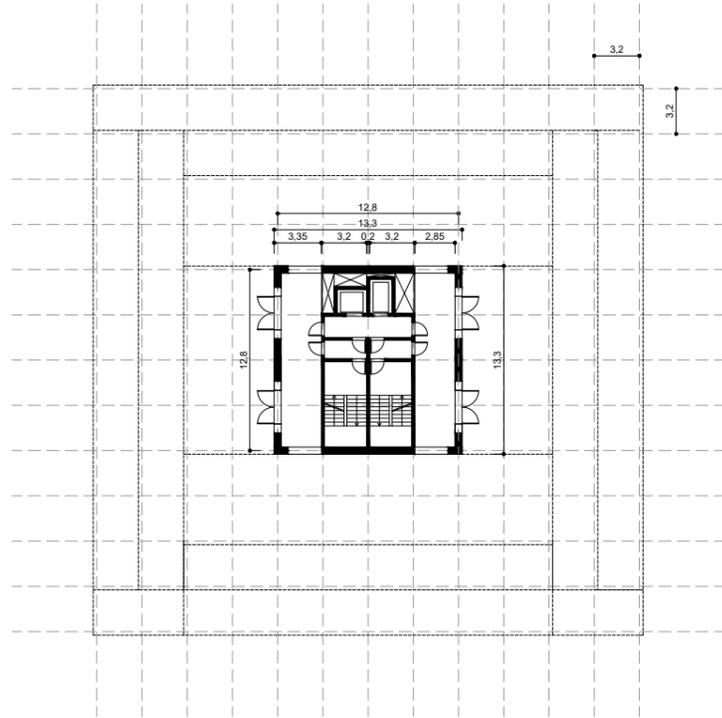


Figure 3.43. Prototype 2 – timber Tower typology: Ground floor with the grid of 3.2 × 3.2 meters

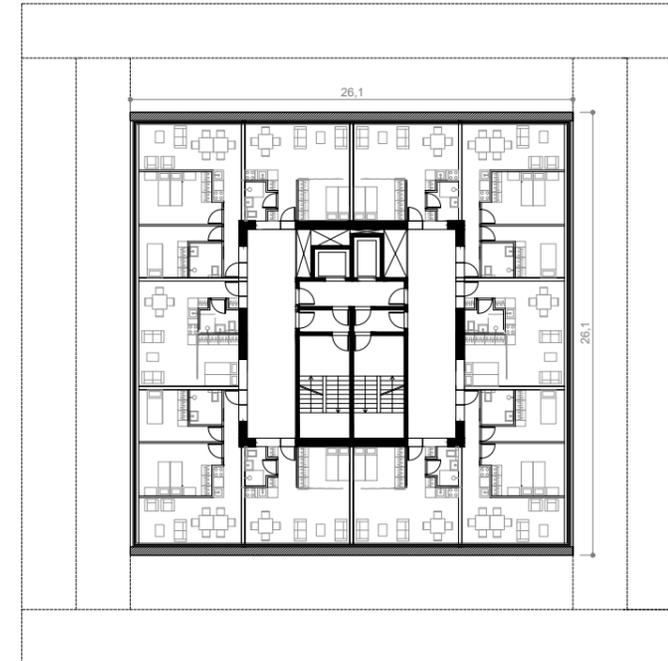


Figure 3.45. Prototype 2 – timber Tower typology: 3rd floor, grid of 3.2 × 3.2 meters housing layout

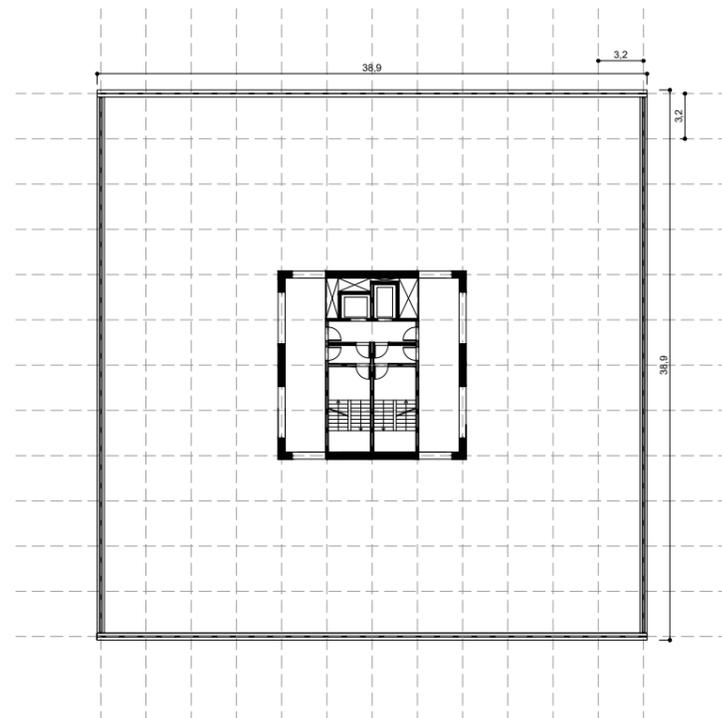


Figure 3.44. Prototype 2 – timber Tower typology: 10th floor with the grid of 3.2 × 3.2 meters

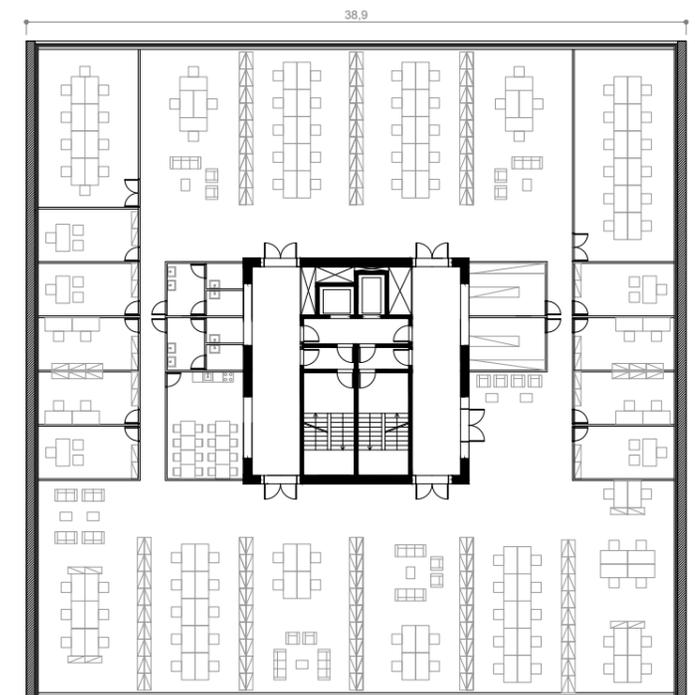


Figure 3.46. Prototype 2 – timber Tower typology: 10th floor, grid of 3.2 × 3.2 meters

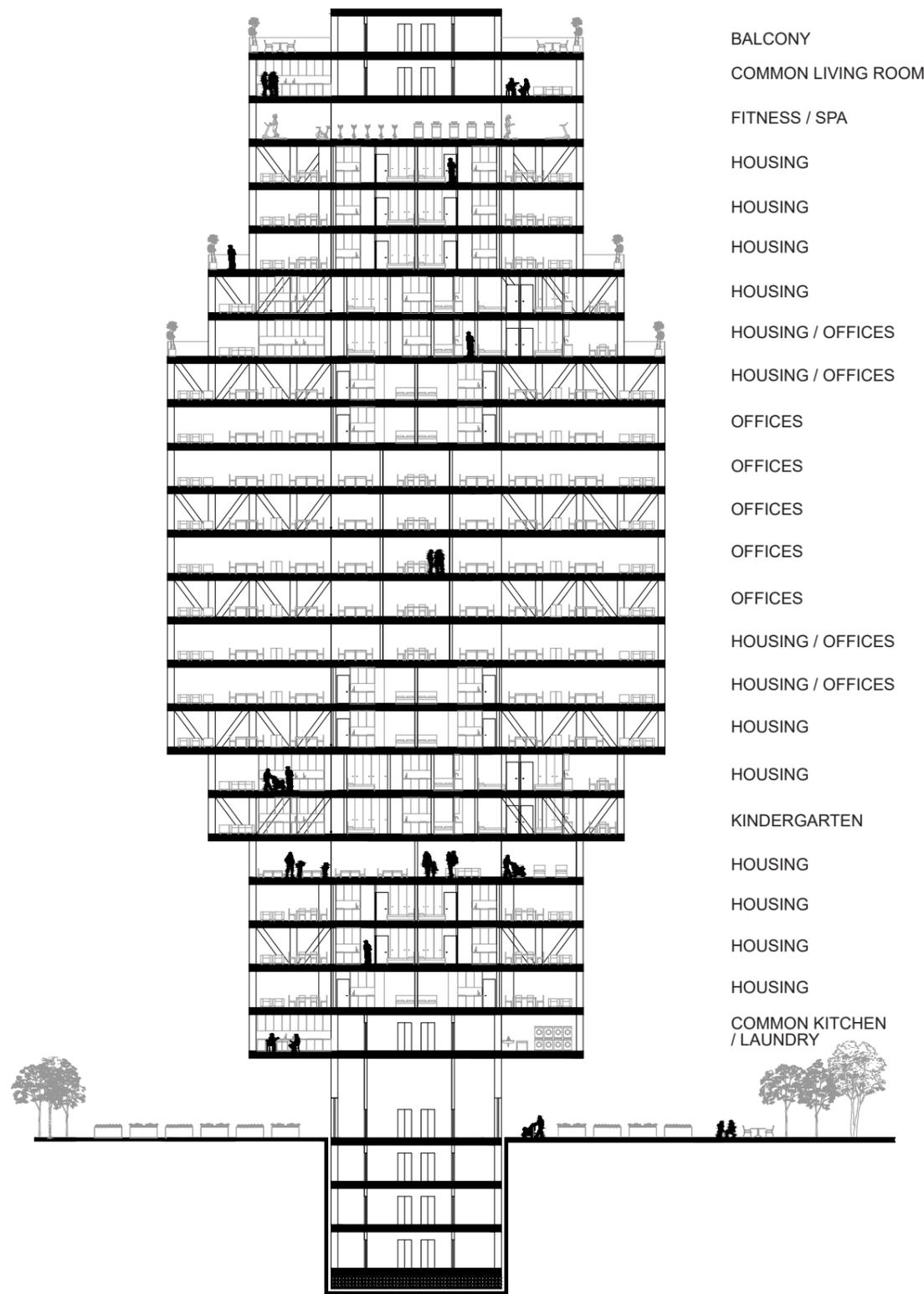


Figure 3.47. Prototype 2— timber Tower typology: Section showing different uses

Table 3.4. Prototype 2 – timber Tower typology: Quantities for one building ⁶²¹

ASPECT	QUANTITY	MEASURING UNIT	PERCENTAGE	
Number of apartments	290	units		
Max number of inhabitants	580	pers.		
Smallest apartment size	27	m ²		
Usable areas				
Total housing unit surfaces	7883.44	m ²	31%	
Shared spaces	2240.36	m ²	9%	
Total offices surfaces	9397.2	m ²	37%	
Corridors and stairs	2855	m ²	11%	
Elevators access and shafts	650	m ²	3%	
Total usable surface	23026	m ²		
Gross areas				
Total apartment surfaces	8570.24	m ²	32%	
Shared spaces	2348.16	m ²	9%	
Office surfaces	10009.6	m ²	38%	
Corridors and stairs	3588.75	m ²	13%	
Elevators access and shafts	833.5	m ²	3%	
Total gross surface	25350.25	m ²		
Total footprint				
Total footprint	1513.21	m ²		
Footprint for access and structure	176.89	m ²	12%	
Open footprint	1336.32	m ²	88%	
Materials				
Wood = external structure	1552.14	m ²	6%	
Concrete	Core	4422.25	m ²	18%
	Slabs	19375.9	m ²	76%
	total	23798.1	m ²	94%

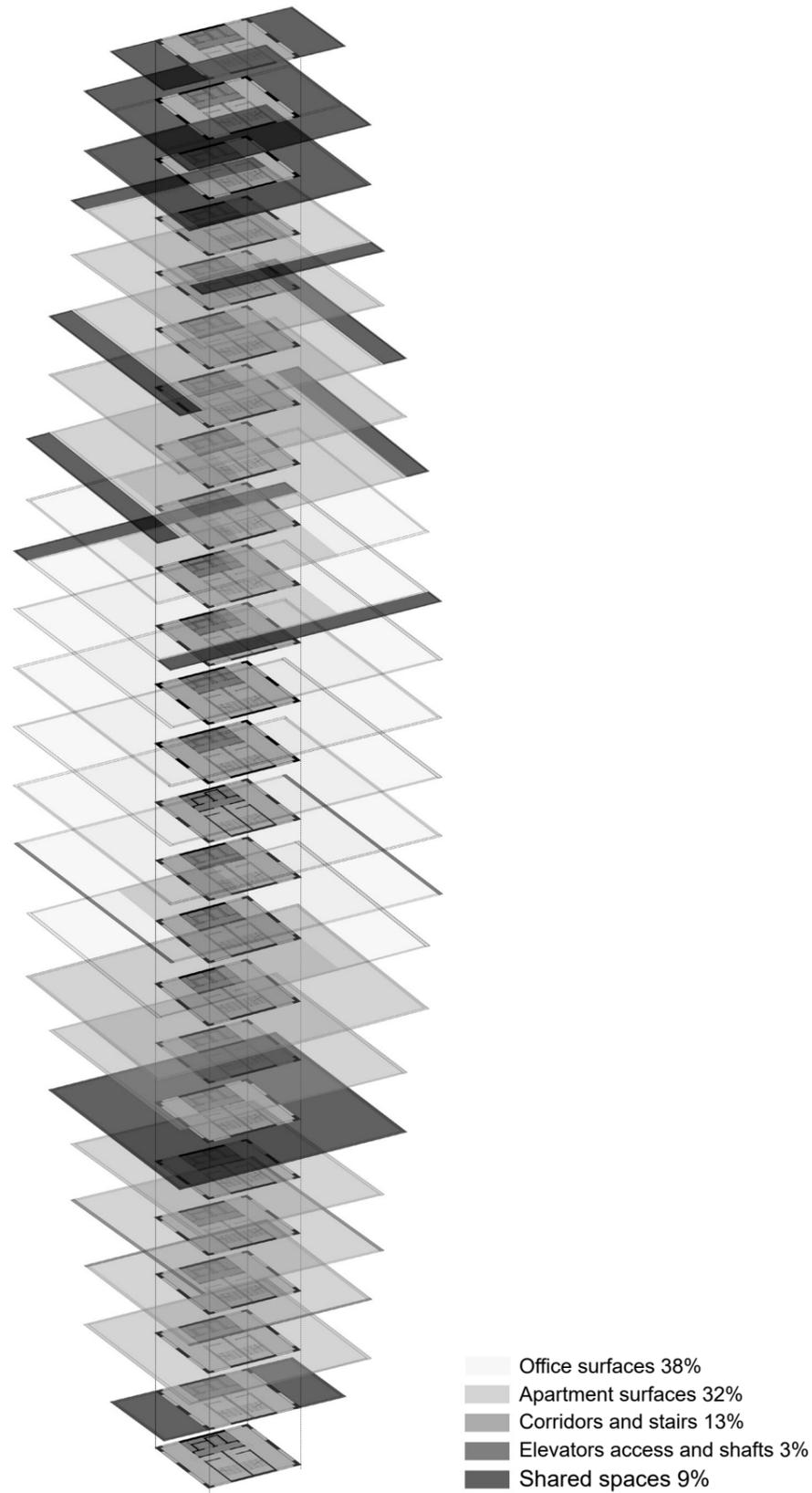


Figure 3.48. Prototype 2 – timber Tower typology: Diagram of gross area surfaces in %



Figure 3.49. Prototype 2 – steel Tower typology: Fourth model perpendicular view



Figure 3.50. Prototype 2 – steel Tower typology: Fourth model front view

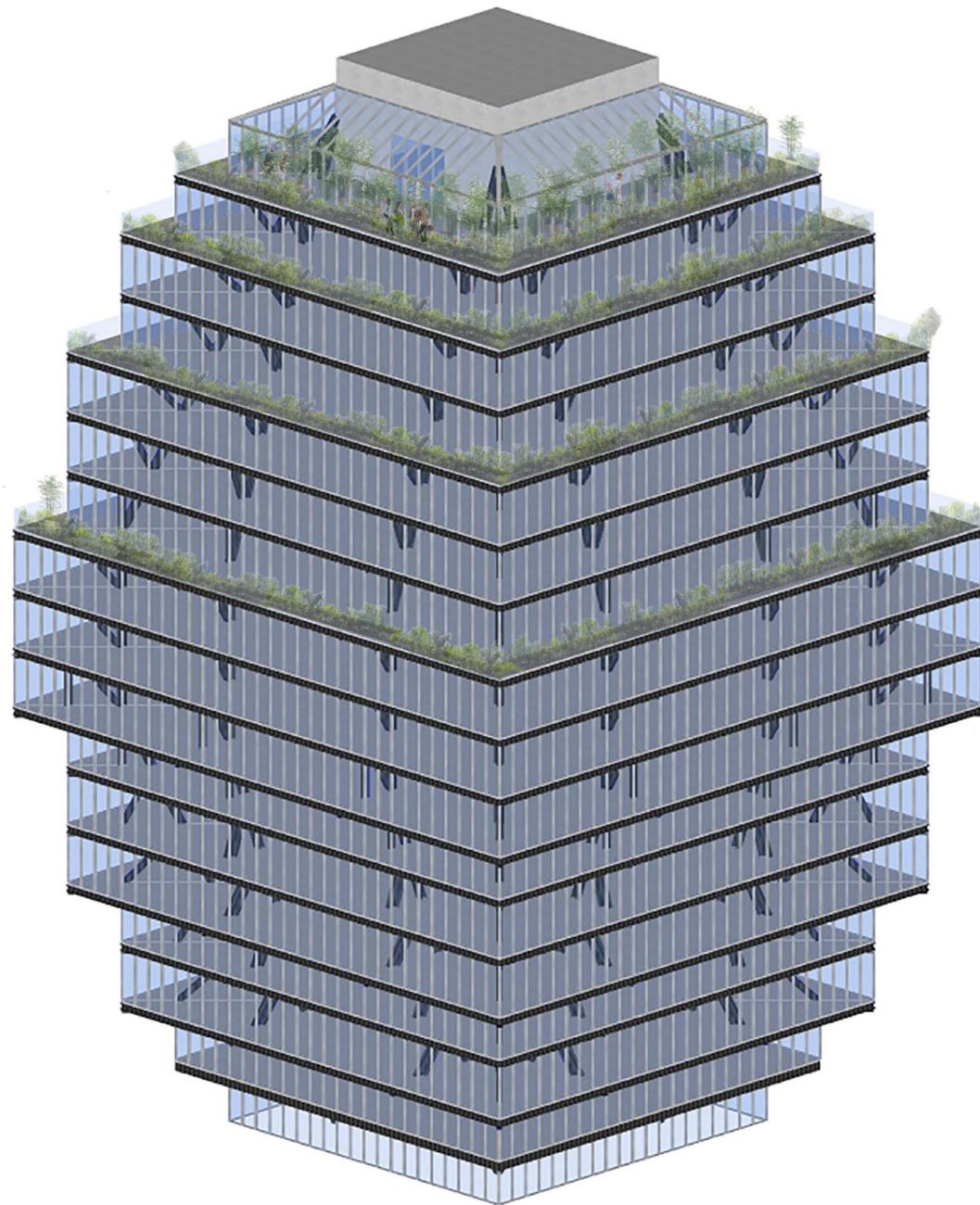
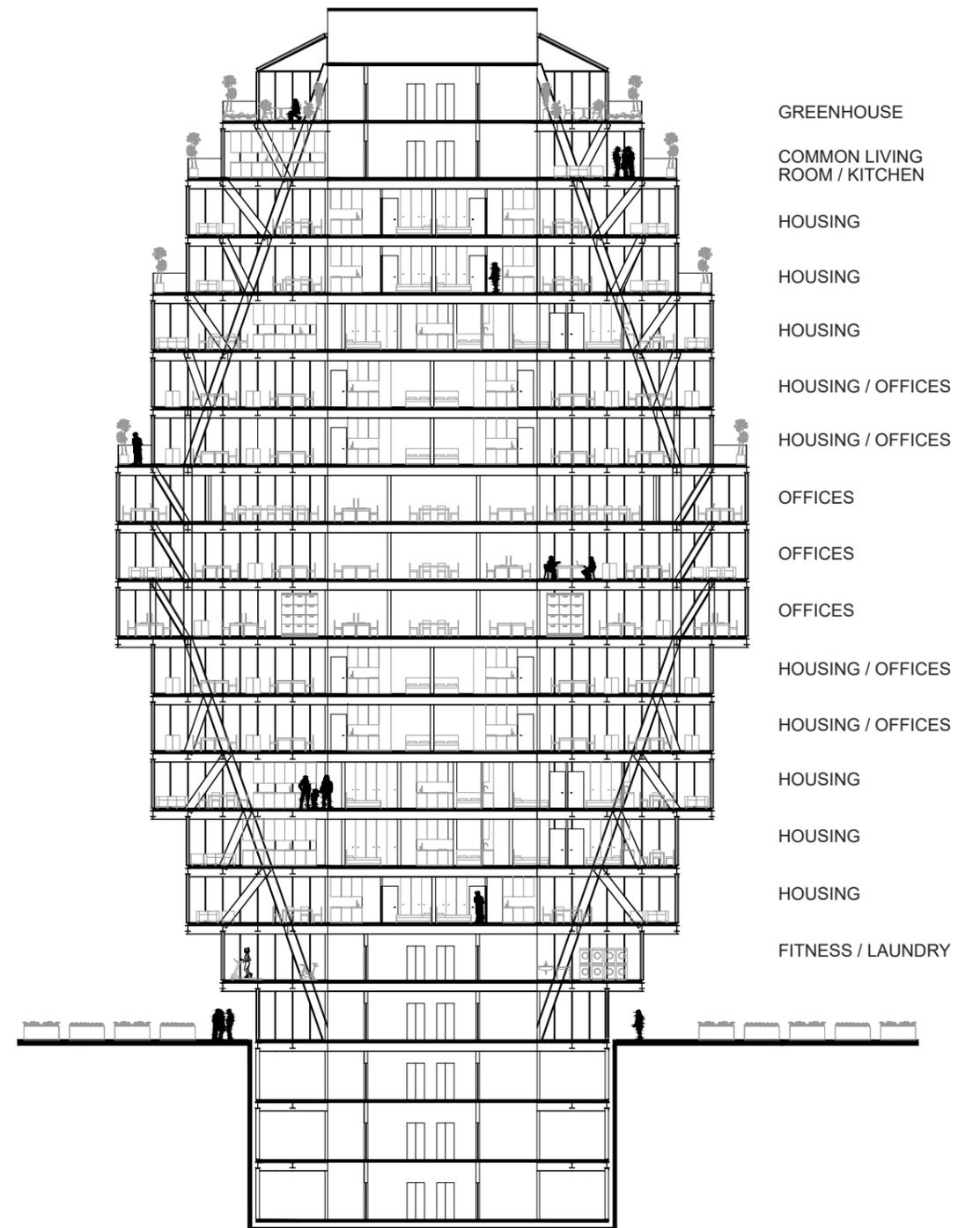


Figure 3.51. Prototype 2 – Steel Tower typology: 3D model



- GREENHOUSE
- COMMON LIVING ROOM / KITCHEN
- HOUSING
- HOUSING
- HOUSING
- HOUSING / OFFICES
- HOUSING / OFFICES
- OFFICES
- OFFICES
- OFFICES
- HOUSING / OFFICES
- HOUSING / OFFICES
- HOUSING
- HOUSING
- HOUSING
- FITNESS / LAUNDRY

Figure 3.52. Prototype 2—steel Tower typology: Section showing different uses

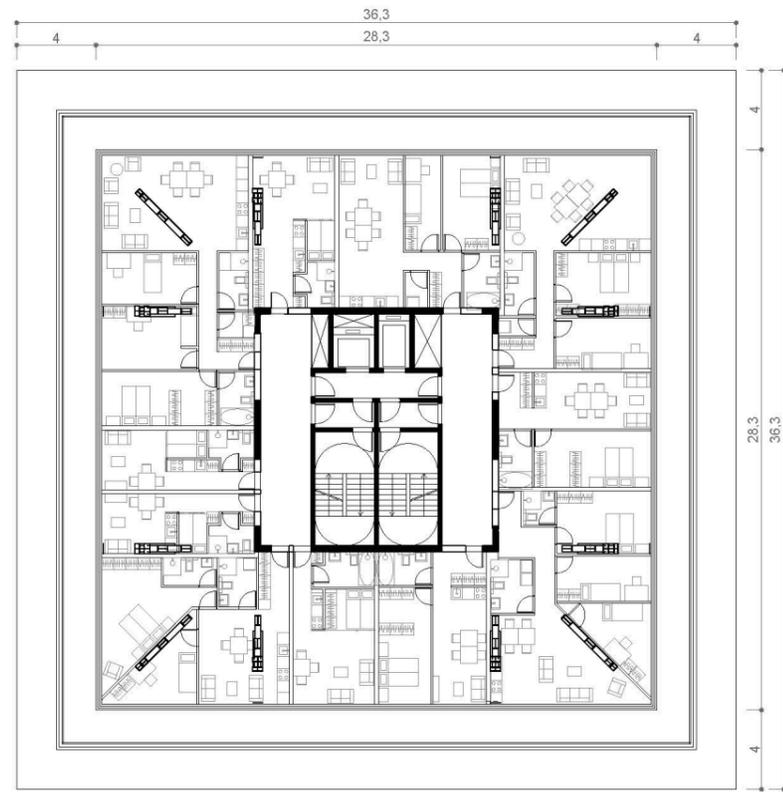


Figure 3.53. Prototype 2 – Steel Tower typology: Plan type for apartments

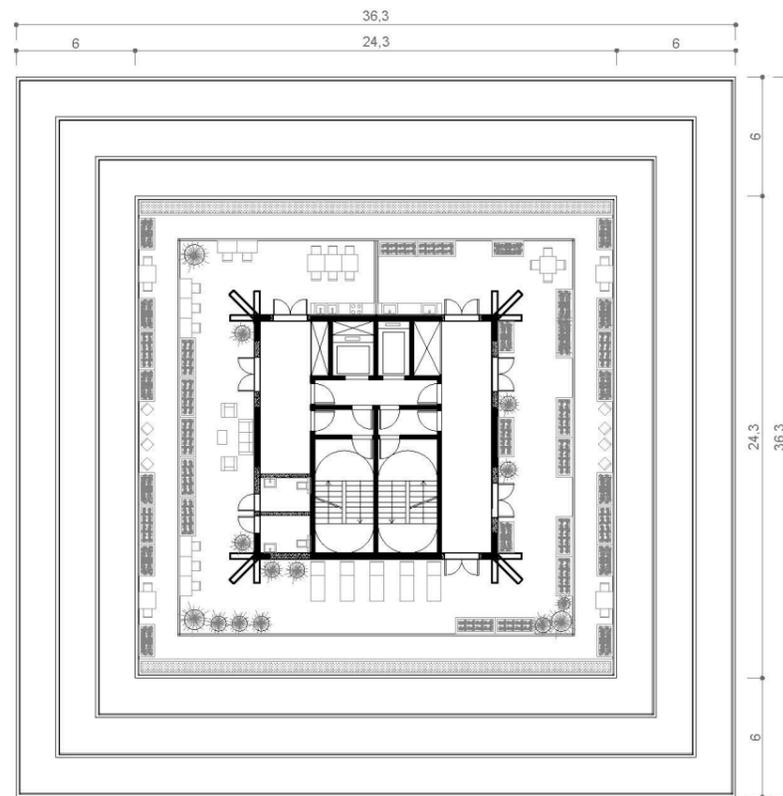


Figure 3.54. Prototype 2 – Steel Tower typology: Rooftop plan



Figure 3.55. Prototype 2 – Steel Tower typology: 3D housing layout

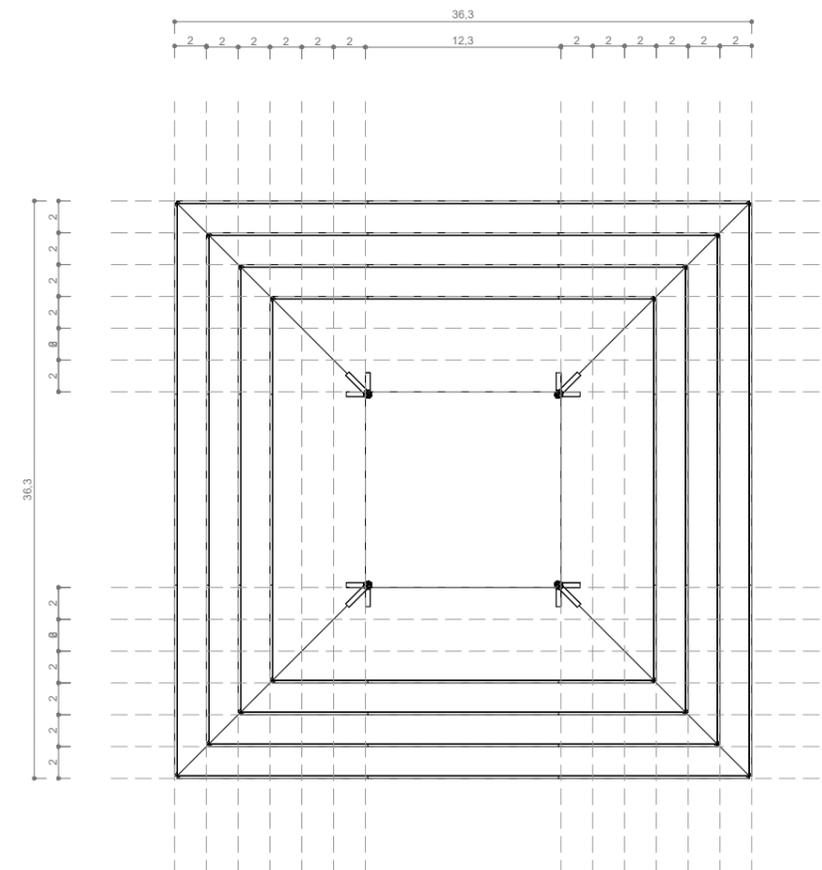


Figure 3.56. Prototype 2 – Steel Tower typology: Grid plan

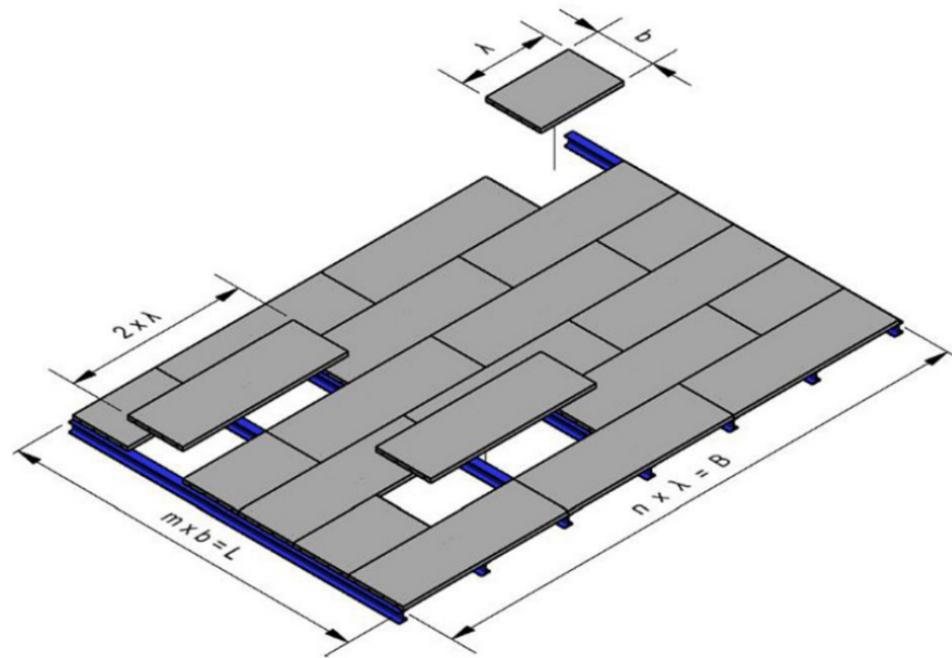


Figure 3.57. The layout of the demountable composite floor

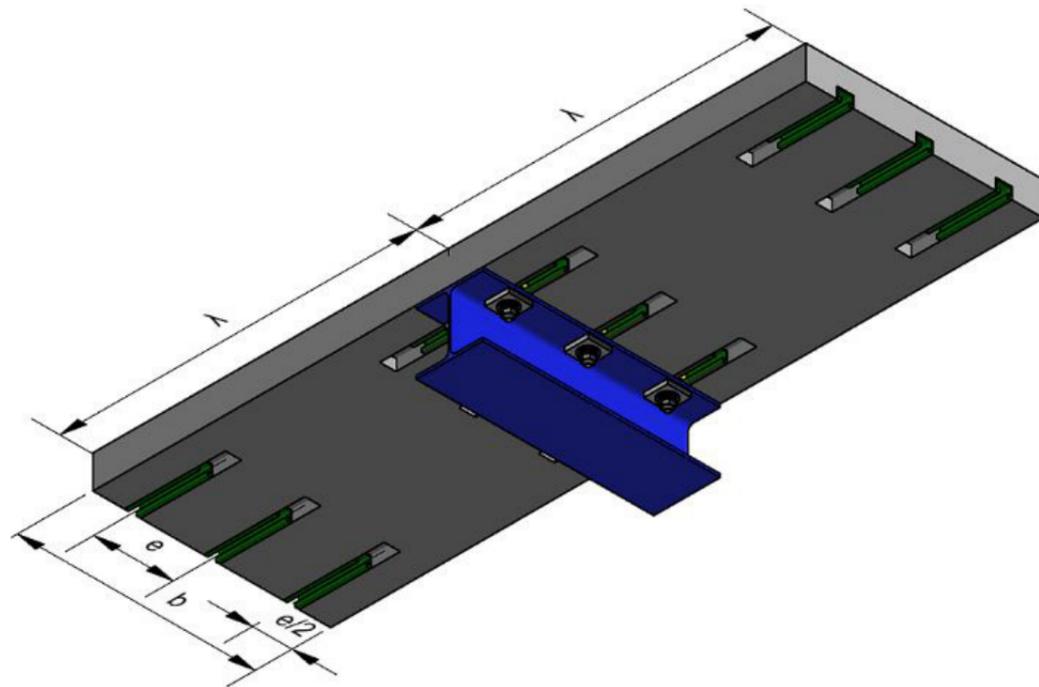


Figure 3.58. Demountable slab elements - composite floor

As both towers are similar, they have the same possible scenarios presented in Table 3.5 regarding structure usability, internal function, ground floor uses and users. In terms of surface, the spaces were subdivided as shared space or private space. The materials of the Tower typology were separated into timber or steel, and concrete. The wood and steel materials are used mainly for the exoskeleton and concrete in the core and slabs. The subdivisions and paths can be seen in the diagram in Figure 3.59. The generic Tower typology can be implemented in the city where mixing uses are required. For example, in commercial or city centres with big empty plots, densify urban centres entrances, due to their shape, see Figure 3.60. To conclude, the two towers offer the possibility for of adaptation through time. The slabs can have their layouts reorganised for housing, office and shared facilities, diminishing the waste since the structure remains for a second purpose and life cycle. After the practical limit for the structure or the need for space in the city and to avoid demolition, the wood and steel components can be disassembled and reused or remanufactured, and the concrete core can be recycled and used as aggregates for other structures, Figure 3.61.

To exemplify how the Tower prototype could be implemented, two scenarios were simulated in the context of Luxembourg. First, the timber Tower was placed in the Kirchberg neighbourhood of Luxembourg city. Figure 3.62 shows the site implementation and Figure 3.64 shows a 3D simulation. The district is memorable due to Luxembourg's high-rise building and one of the three seats of the European Union institutions. This makes it the right place for a mix-used tower, keeping the focus on office spaces but also bringing housing units close to it. The Second scenario is the area of Foetz, an industrial environment that needs a transition towards eco-design and a circular concept. Both Towers, timber and steel, were implemented at the entrance to Foetz, Figure 3.63 and Figure 3.65. The reduced footprint and slab size variation will support the transition of the area with more shared activities as well as different uses and sizes for housing units. In both scenarios, the floor layout of the Towers can adapt through time to change the infrastructure's purpose for a second and third life cycle. Afterwards, the structure can be disassembled, reused and recycled. The Foetz context and implementation were part of the Luxembourg in Transition (LiT) project; more information about it can be found in the Chapter Deliverables.

Table 3.5. Prototype 2 –Tower typology: possible scenarios

STRUCTURE	FUNCTIONS	GROUND FLOOR	USERS
Same for 100 years Same for 50 years	Same for 100 years Change every 25 years Change by demand	Open Close	People living alone Couples
Concrete core Use recycled concrete for core Concrete can be recycled	Public Private	Public Private Shared	Families with a child Young workers
Timber structure The timber structure can be disassembled The timber can be recycled The timber can be reused in another structure	Shared Residential Commercial	Shops Markets Offices	Big offices Independent workers
Steel structure Use recycled steel for the structure The steel structure can be disassembled The steel can be recycled The steel can be reused in another structure	Mixed Housing Office Kindergarden Fitness / spa Analog lounge Collaborative workspace. Communal kitchen Library	Urban farming Urban garden Sports	
Open slabs Divided slabs			

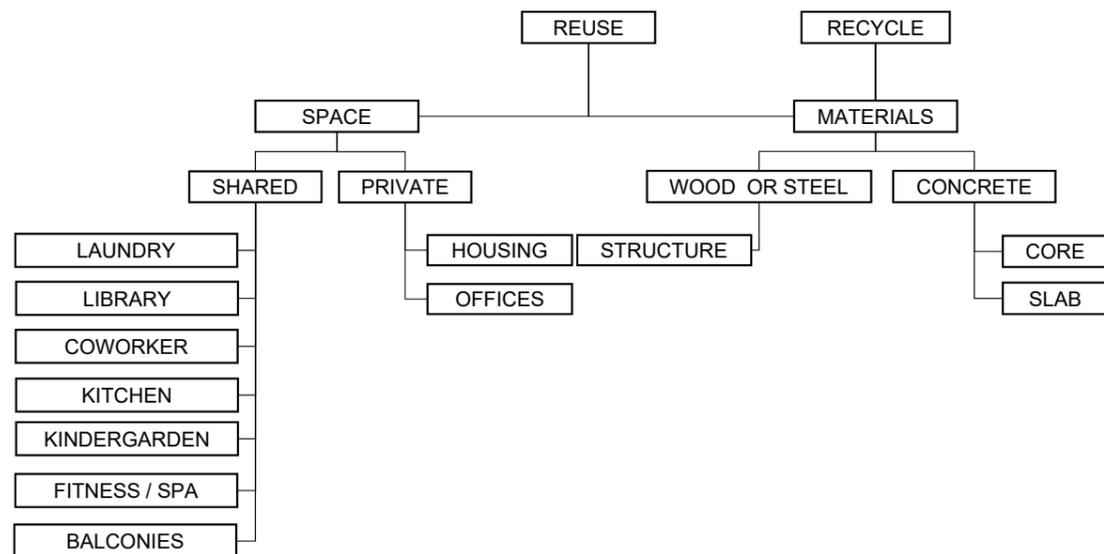
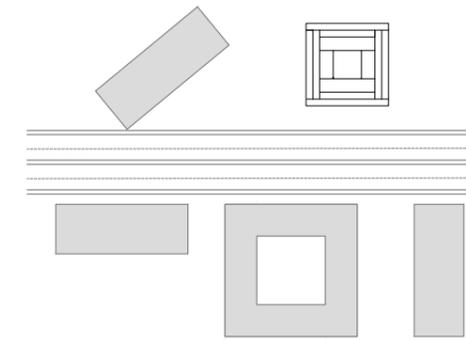
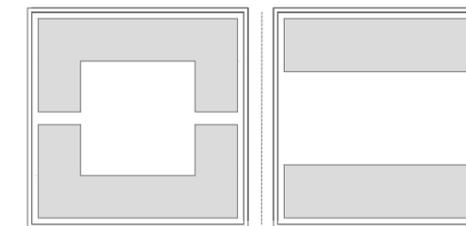
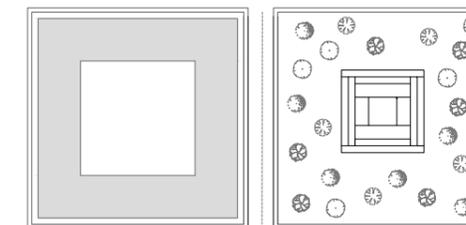


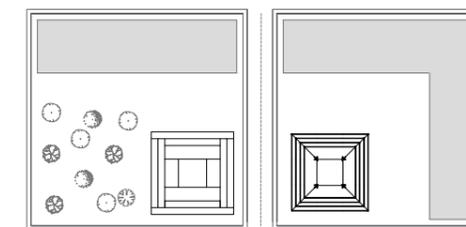
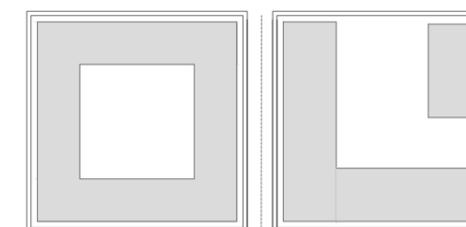
Figure 3.59. Prototype 2 –Tower typology: Diagram of reusability and recyclability



commercial centers



commercial or city centers / big plots



neighborhoods' entrances / big plots

Figure 3.60. Prototype 2 — Tower typology: possible implementation in the city

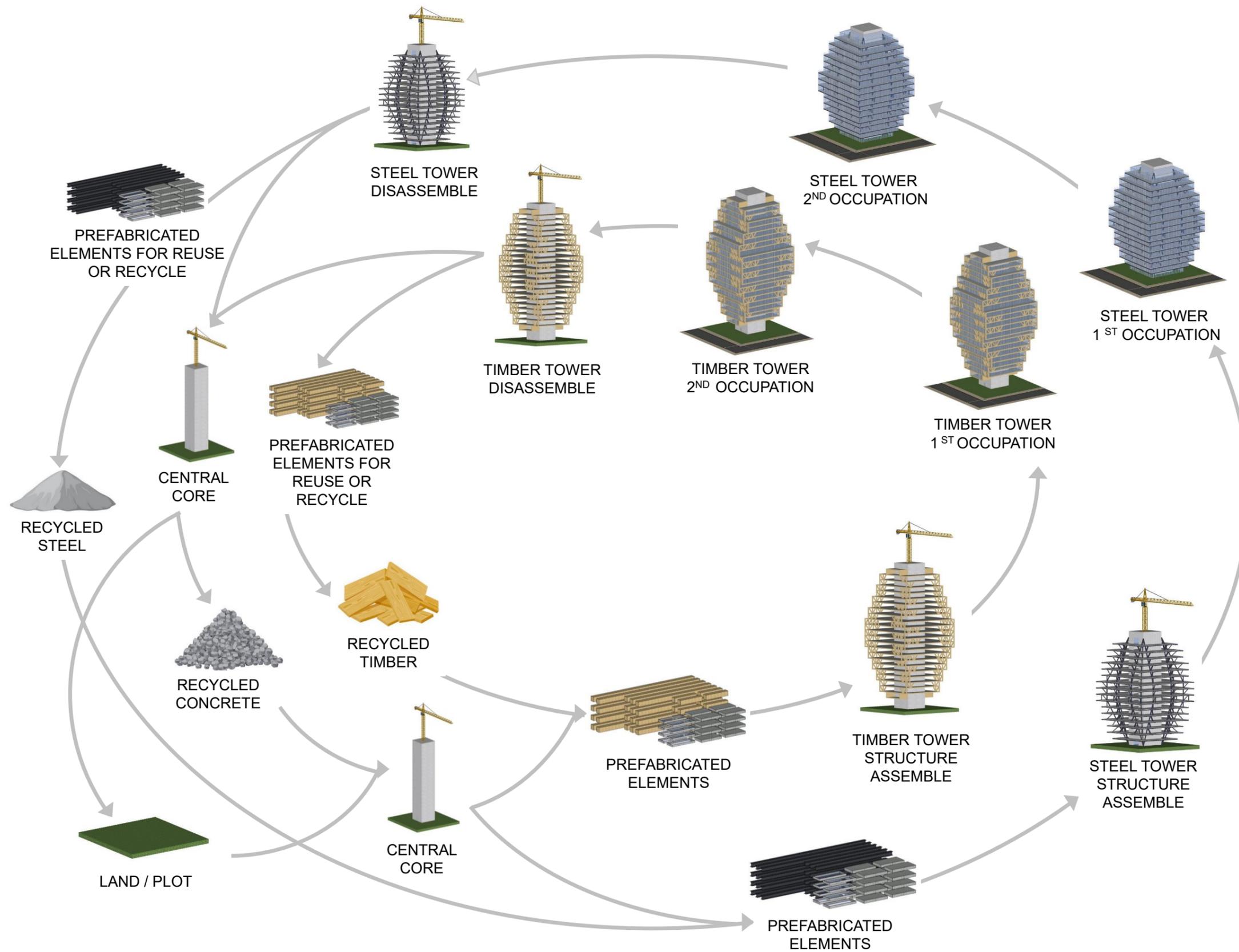


Figure 3.61. Prototype 2 –Tower typology: Circular diagram



Figure 3.62. Prototype 2 — timber Tower typology: Situation map in Kirchberg neighborhood, Luxembourg city

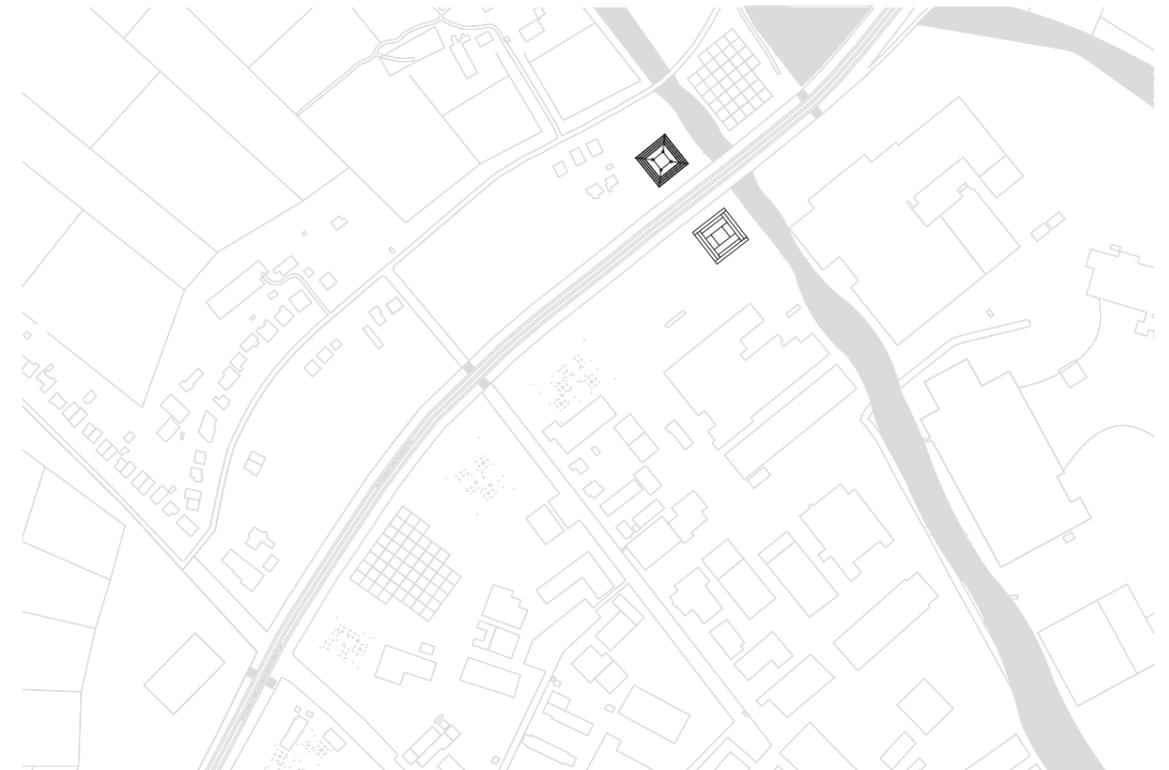
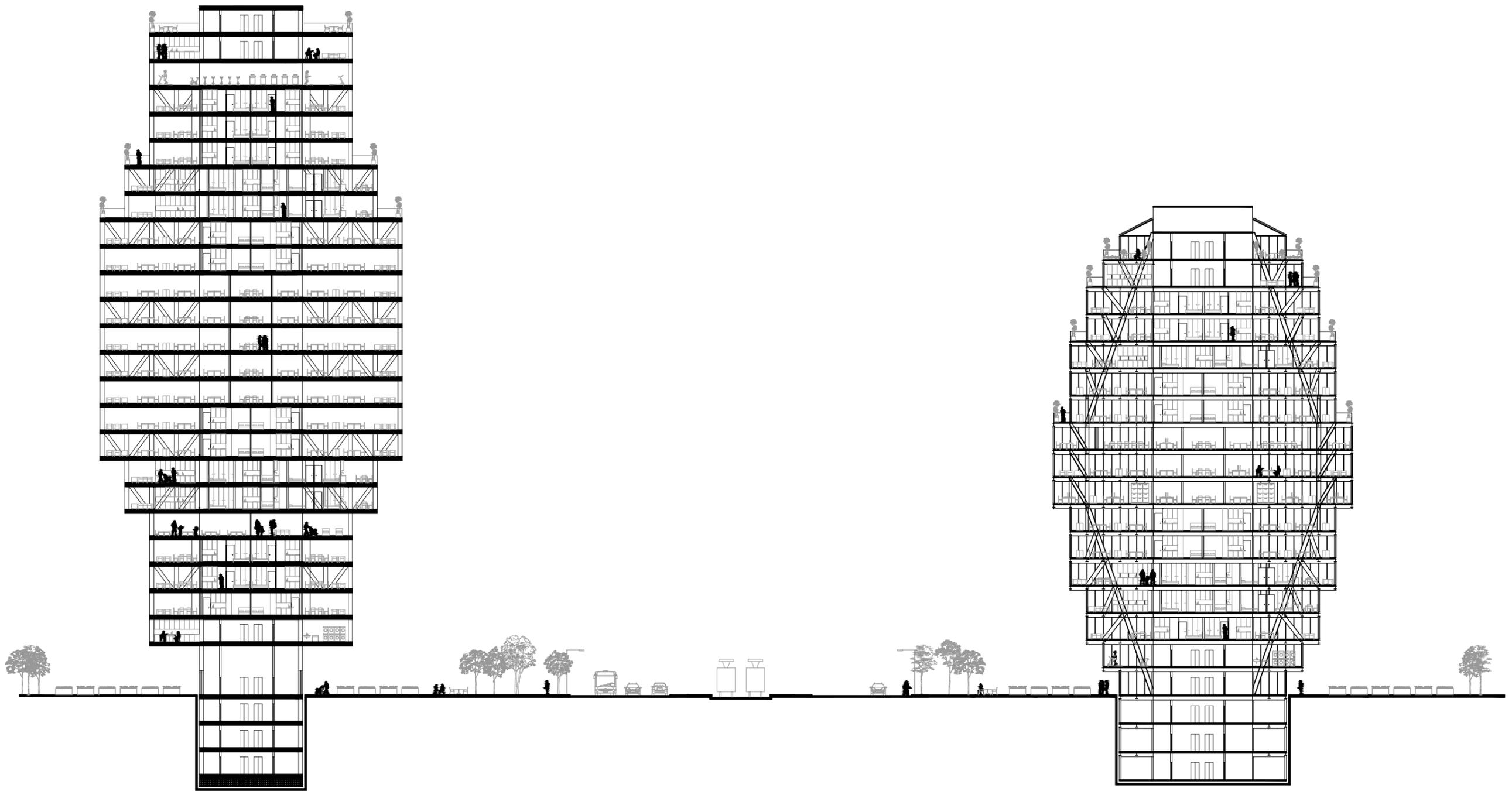


Figure 3.63. Prototype 2 — Tower typology: Situation map in Foetz



Figure 3.64. Prototype 2— timber Tower typology: 3D simulation



Timber Tower

Steel Tower

Figure 3.65. Prototype 2 — Tower typology: section in Foetz

3.4. Prototype 3 - Block typology

The concept of a completely disassembled and recyclable building is implemented in the third prototype named Prototype 3 Block typology. The typology can vary physically in all senses and has more significant contact with the ground floor than the Slab and Towers typologies. The building is adaptable in many situations, with an adjustable interior layout and slab openings, the possibility to reconfigure the exterior format and volume by extension and reduction, and by disassembling and reassembling in another place to adapt to future needs. Since the structure can no longer be reused, they must be recycled into new materials. This concept closes the material loop, and the construction life becomes circular. This Section presents the design evolution and possible life cycle scenarios for Prototype 3. Beyond that, it shows a simplified Life Cycle Assessment (LCA) for the Block typology since it presents the maximum potential components that can be disconnected, reused directly after the first cycle or recycled to become new material.

The Block typology's design process was focused more on the building's usability and recyclability for many life cycles. For this reason, the simplest form that a building can have was taken as a starting point as an empty block, where all the parts can be separated later to be reused and recycled. Then, the block's grids, sizes and combinations started to be tested for different uses and materials. The dimensions required for dwellings, offices and parking facilities were considered in the design as well as the maximum possible truck transportation dimensions in Europe of 4 metres in height, 2.55 m in width and 12 m in length for automobile and trailer vehicles⁵⁰⁰, and a maximum of 13.7 m in length for transport operations of one or more containers or swap bodies⁵⁰¹.

The first generic module proposed by architects was based on a grid of 9x9 metres. The typology host parking for cars with public facilities on the rooftop. A physical model was made to illustrate its scale and grid, with a possible covered area on the rooftop for activities, such as sauna and gym, as shown in Figure 3.66. For the same combination, the engineers of WP2 proposed a 10.8x10.8 grid for steel design and WP3 a 10.8x10.8x5.4 for timber design, as shown in Figure 3.67. The three possibilities for the block were tested and presented to the ECON4SD team during the workshops, and it was agreed that the 10.8x10.8 metre grid was the best fit for the architectural and material adaptation for the steel and timber components.

The modularity of and prefabrication of the block allows for the block to grow in all directions, adding more components or whole blocks if needed to facilitate the disassembly process, as illustrated in Figure 3.68 and Figure 3.69. Furthermore, the open internal span length and combination of generic models offer the possibility of designing buildings for different uses, such as parking, public facilities, gyms, saunas, shops, offices, housings or any combination of these. Figure 3.70 shows the 10.8x10.8 grid and the different possible uses and layouts. The building can be small or expanded according to the size of the site and neighbourhood necessities. Linear and full block

500 The Council of the European Union 1996; Wilson 2015.

501 European Parliament 2015.



Figure 3.66. Prototype 3 - Block typology: first model

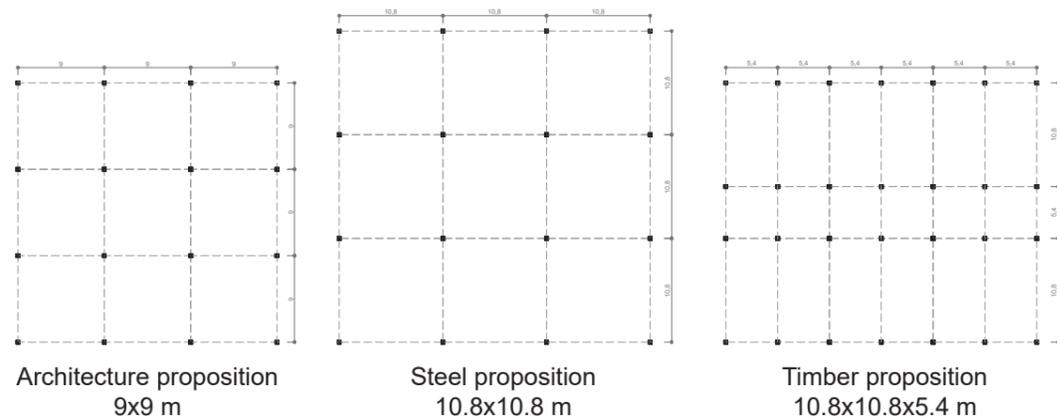


Figure 3.67. Prototype 3 – Block typology: grids' proposition

configurations are more suitable to host parking facilities and more open dynamic arrangements to host housing units or offices as permitted by the availability of natural light, as shown in Figure 3.71 and Figure 3.72. For natural lighting, regulations consider that windows be at least 1/10 of the total surface⁵⁰². In the project, we have 116, 64 m² (10.8x10.8), so the minimum should be 11,7m² in this case, and the window surface is 30 m², which is bigger than the recommended.

This study presents five life cycle scenarios to demonstrate the typology's flexibility, adaptability and recyclability. The first configuration is a parking garage with seven floors. The rooftop is a public space that brings residents together with a swimming pool, sauna, gym and sports courts (Figure 3.73). Vertical access for pedestrians was placed inside, while the access for the parking garage is outside to keep the space and structure as open as possible and facilitate the repurposing of space. Thus, the constructed environment can be adapted to accommodate future demands through time while keeping the same structure for a second life cycle. The second configuration alters the purpose of the interior space. The street level has been transformed into shops, markets and a covered square for citizens. The second and third levels became offices, and the three upper floors remained as parking, as shown in Figure 3.74. As a third scenario, the parking garage could be transformed into housing with the addition of interior walls, Figure 3.75. To represent the evolution of this structure though time, three sections are presented in Figure 3.76, Figure 3.77, and Figure 3.78. The plans for the rooftop with public activities, parking, office space, and housing scenarios can be seen in Figure 3.79, Figure 3.80, Figure 3.81 and Figure 3.82, respectively.

The second model and the fourth scenario, shown in Figure 3.83, show the same structure for the parking garage but with a different rooftop. The last floors were opened up to offer more light for the housing units, the ground floor was opened up to host shops and local markets, and the middle floors were maintained as offices. The floor plans for the housing with the courtyard are presented in Figure 3.84. Since this configuration is no longer needed at the exact location or no longer used, the whole building can be disassembled and relocated using the parts from the old configuration, creating a fifth life cycle. The building can maintain the same form or be adjusted to other needs, such as a housing complex or an office building with different heights and quantities of blocks. All the remaining parts from the old structure will be reused in other construction projects or remanufactured for the production of new materials. The physical model was made with pieces that can be disassembled and reassembled in a different configuration, simulating a real case. This variant can be seen in Figure 3.85, Figure 3.86 and Figure 3.87, following the expansion process and the possibility of growth and open spaces like terraces. Just like the previous option, the buildings can be designed to be smaller or much larger. Prototype 3 can be placed in the parking areas to increase the density without exploiting more natural ground, expand the city and remain close to public transportation to avoid traffic jams and facilitate the connection for commuters, Figure 3.88.

502 Neufert, Neufert, and Kister 2012

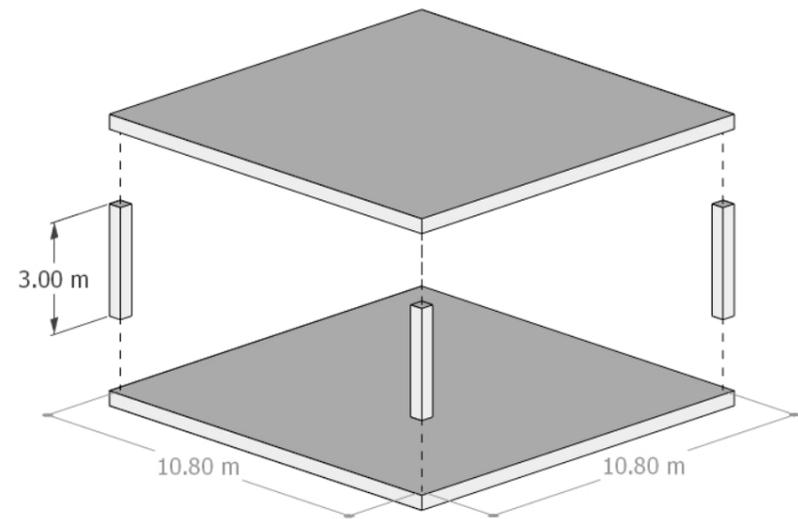


Figure 3.68. Prototype 3 - Block typology: architectural concept for the standard block

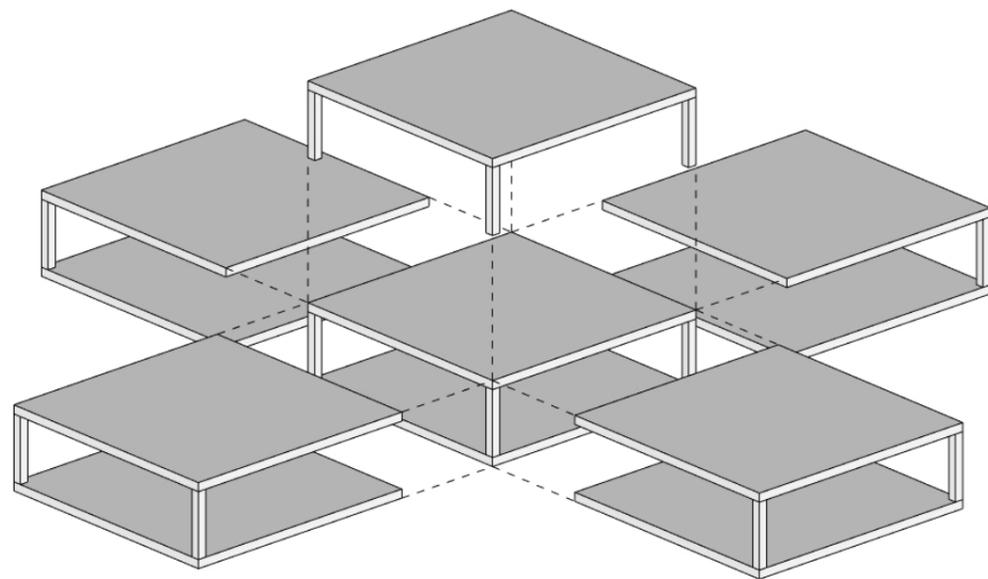


Figure 3.69. Prototype 3 - Block typology: expansion

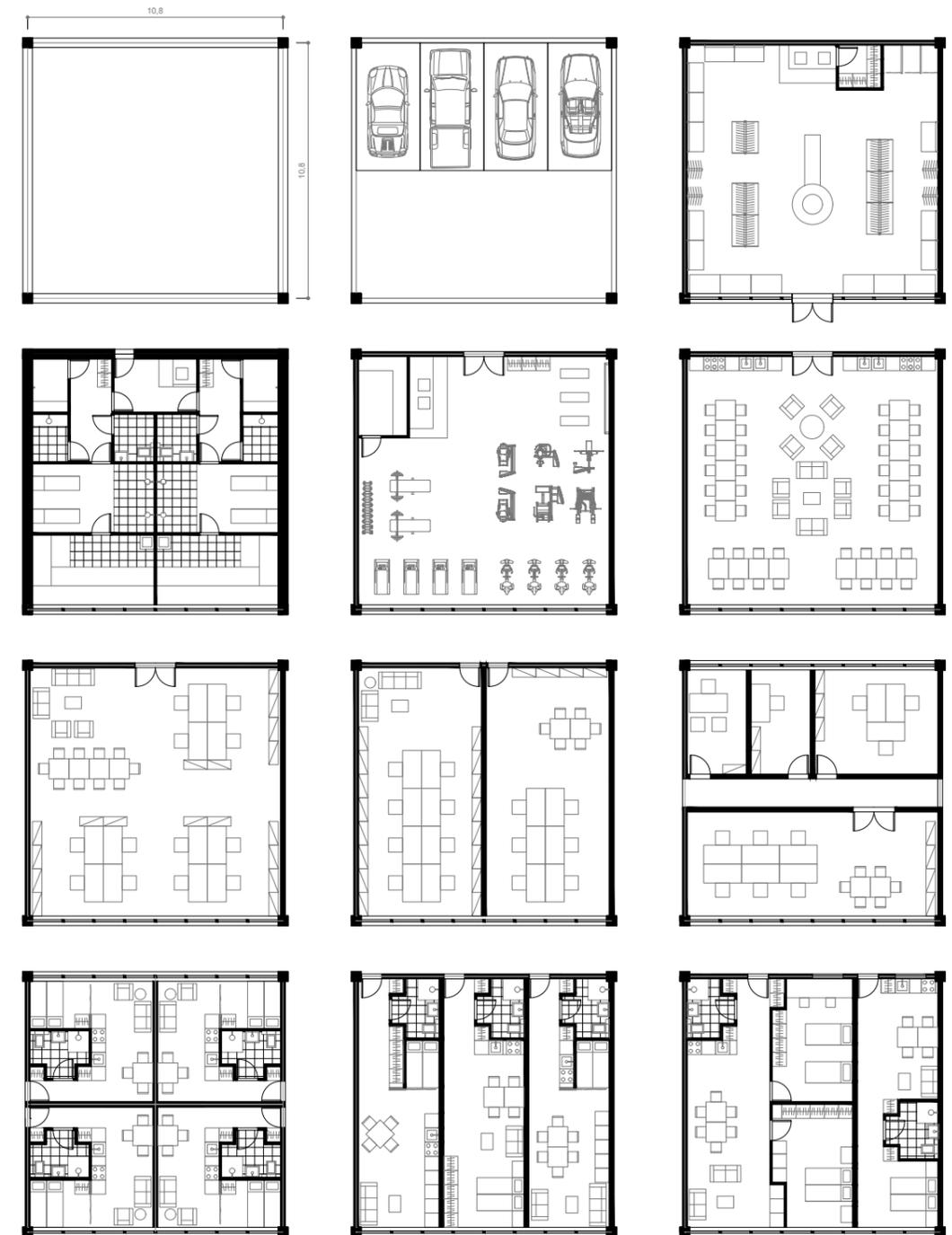


Figure 3.70. Prototype 3 – Block typology: different possibilities of usages and layouts

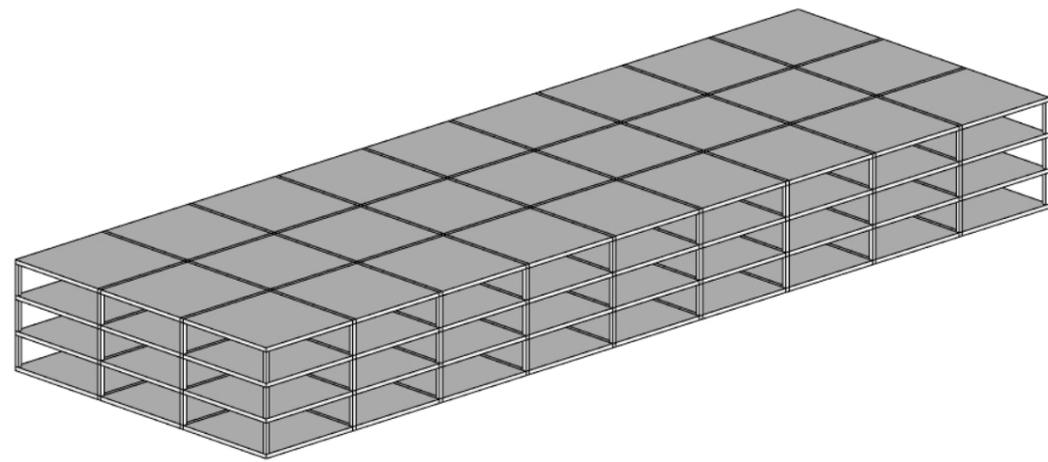
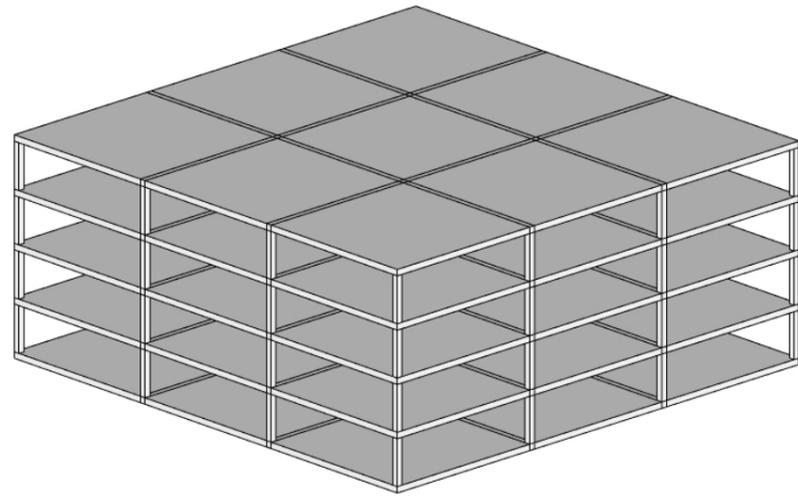


Figure 3.71. Prototype 3 - Block typology: parking building and their extension

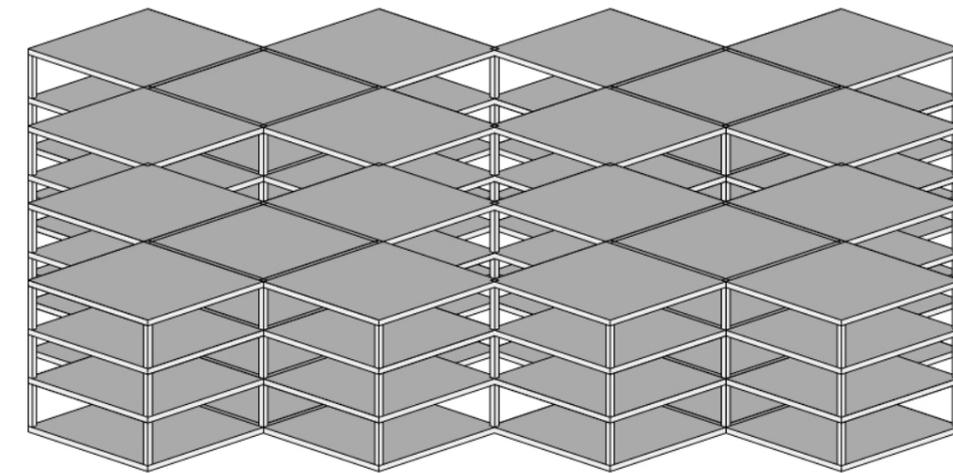
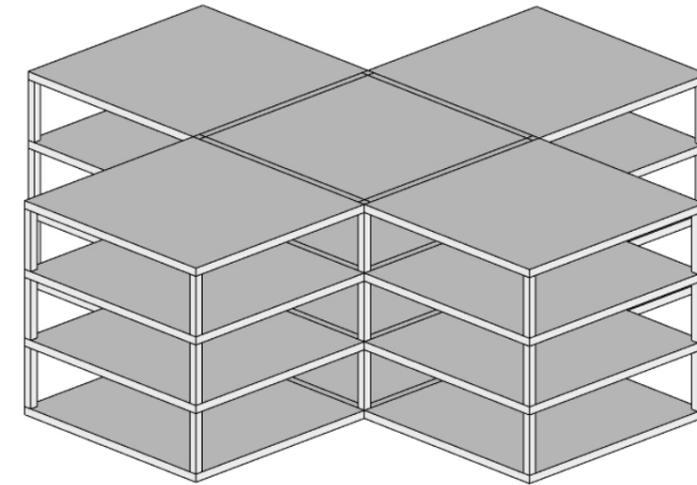


Figure 3.72. Prototype 3 - Block typology: housing complex/office building and their expansion

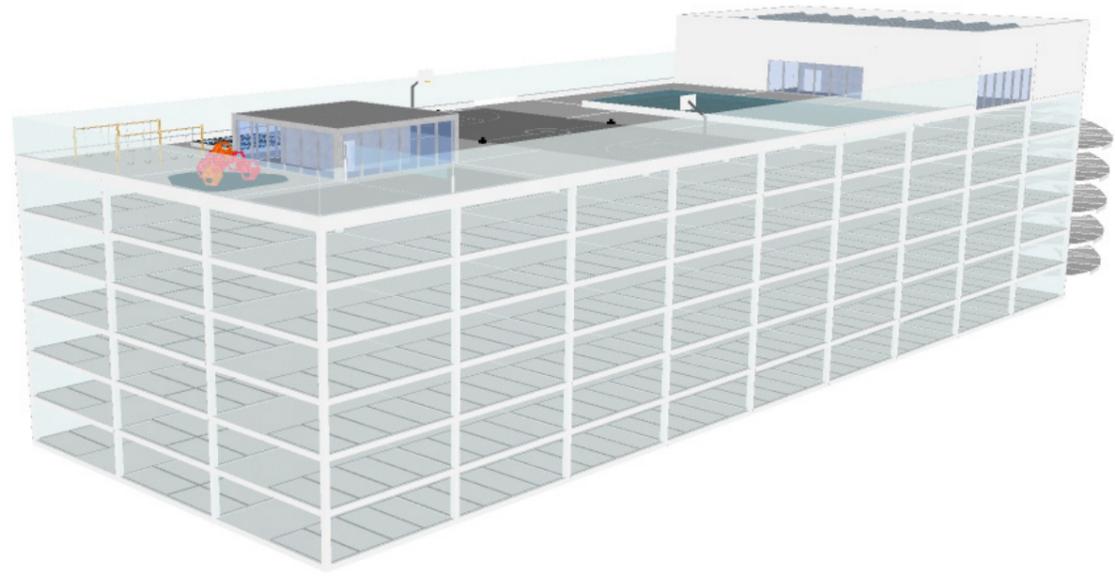


Figure 3.73. Prototype 3 — Block typology: first life cycle, parking, and public space, 3D simulation

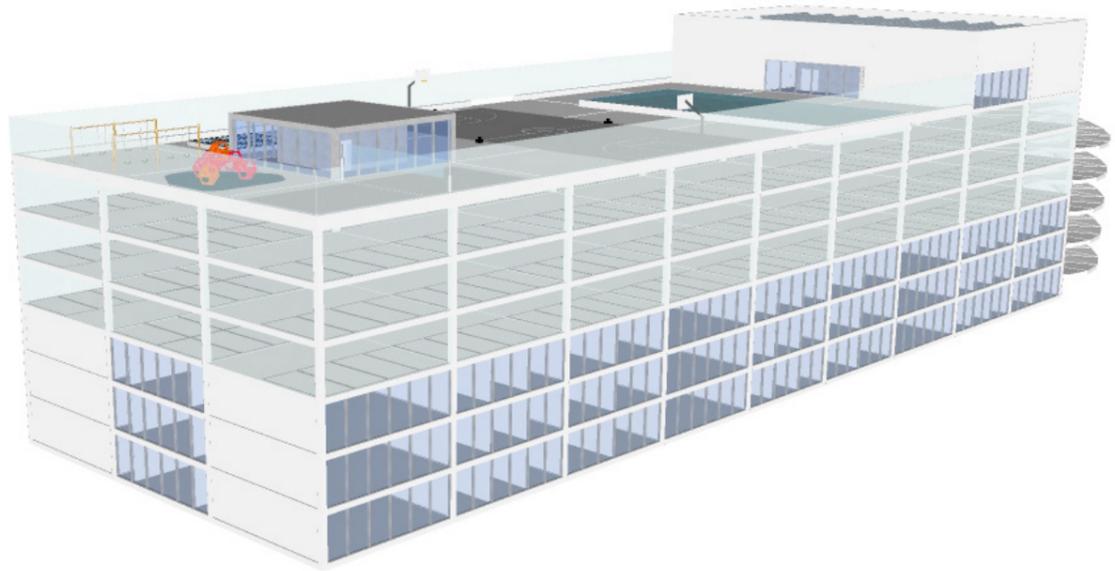


Figure 3.74. Prototype 3 — Block typology: second life cycle, public facilities, parking, and offices, 3D simulation



Figure 3.75. Prototype 3 — Block typology: third life cycle, public facilities, housing, and offices, 3D Simulation

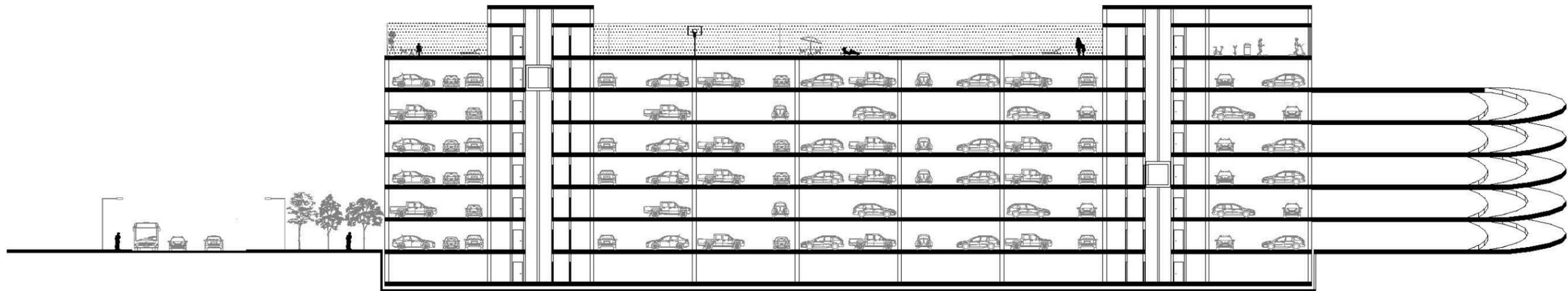


Figure 3.76. Prototype 3 — Block typology: section of the first life cycle with public facilities and parking

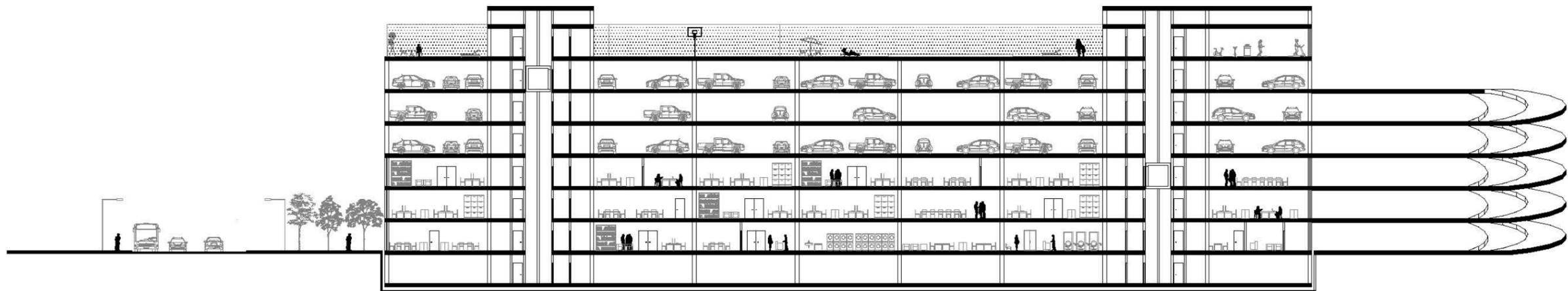


Figure 3.77. Prototype 3 — Block typology: section of the second life cycle with public facilities, parking, and offices

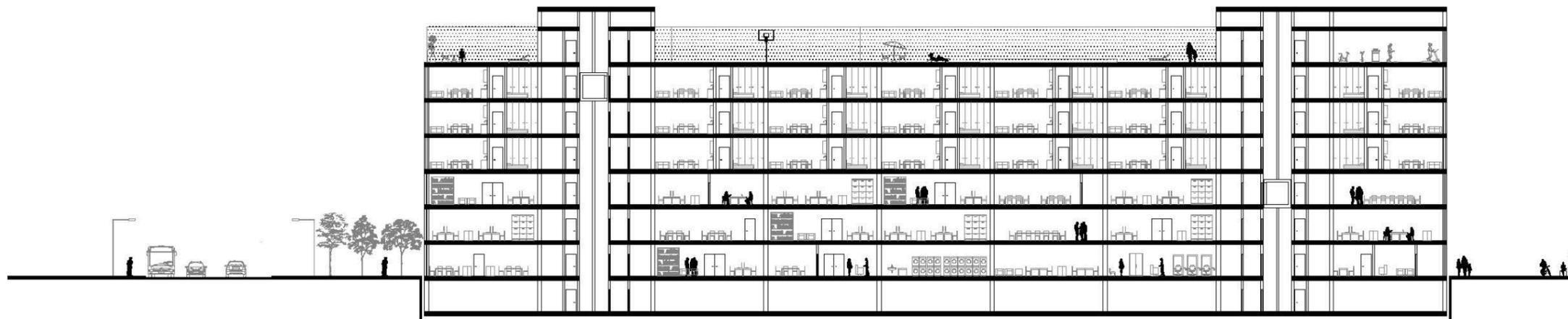


Figure 3.78. Prototype 3 — Block typology: section of the third life cycle with public facilities, offices, and housing units

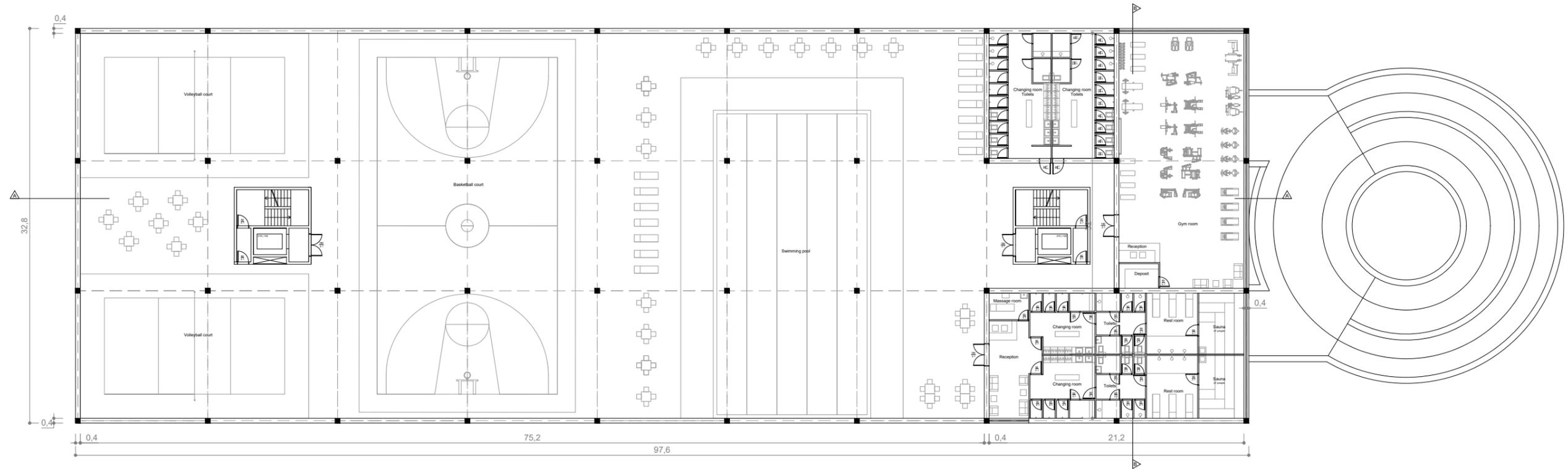


Figure 3.79. Prototype 3 — Block typology: public space

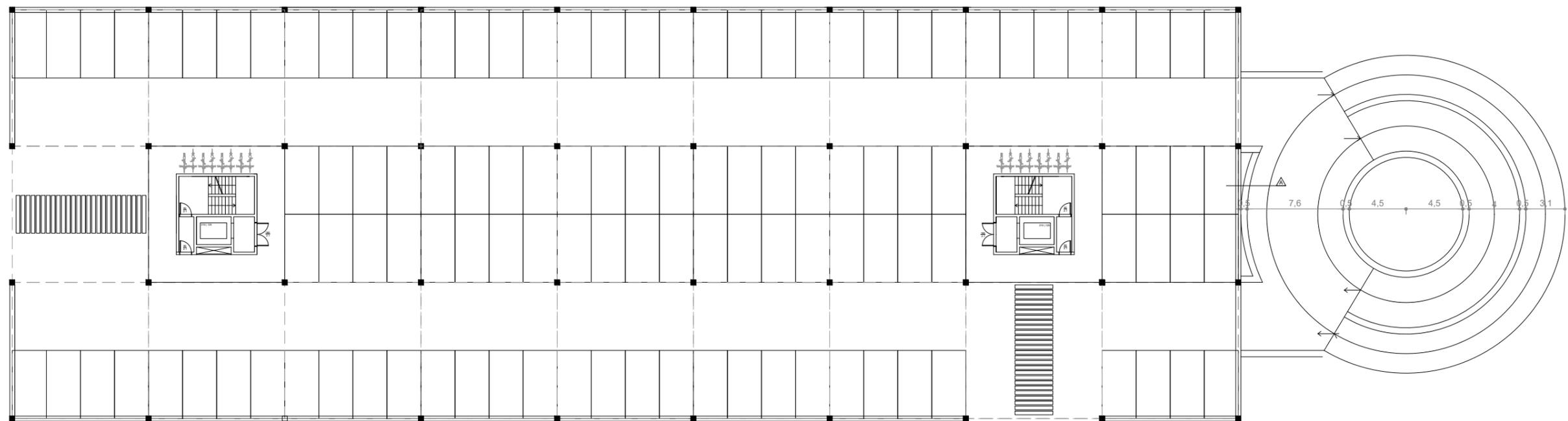


Figure 3.80. Prototype 3 — Block typology: parking plan

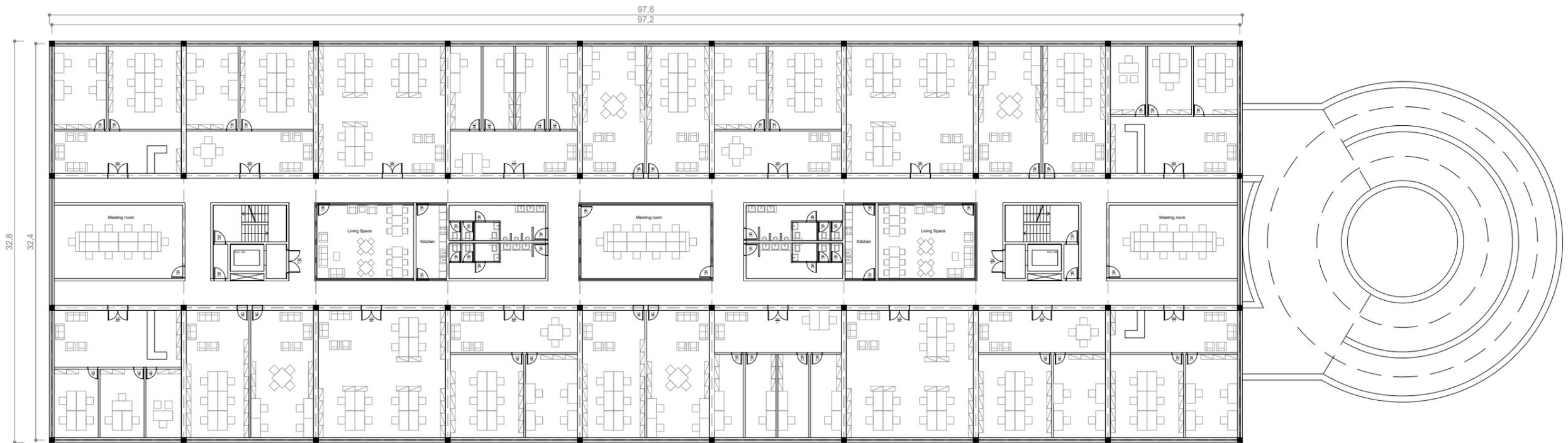


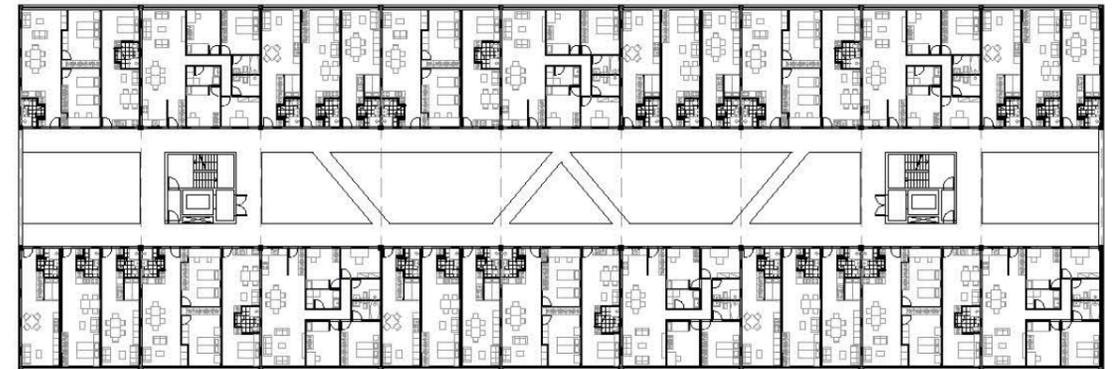
Figure 3.81. Prototype 3— Block typology: office plan



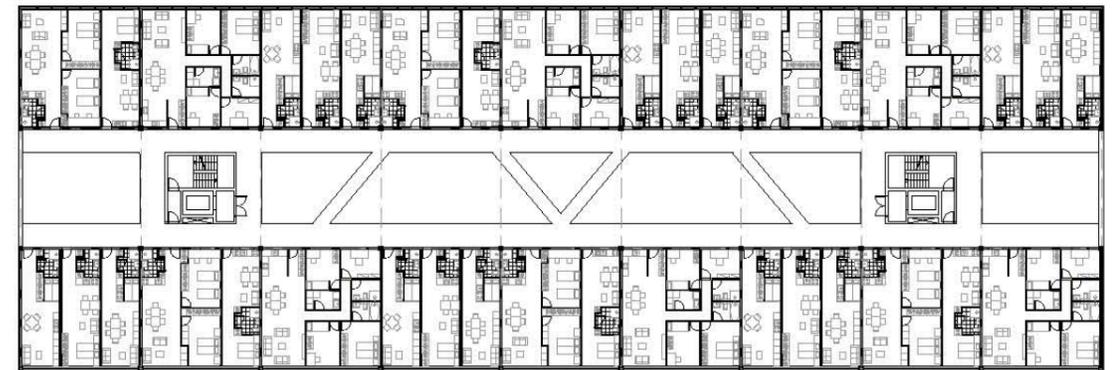
Figure 3.82. Prototype 3— Block typology: housing plan



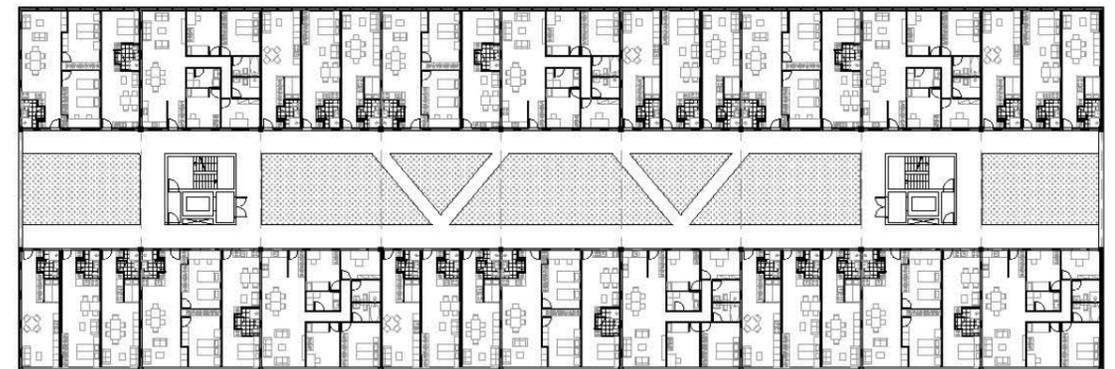
Figure 3.83. Prototype 3 — Block typology: the second model with an opening to integrate more light for housing units



6 floor plan of housing units with walkways for more connection



5 floor plan of housing units with walkways for more connection



4 floor plan of housing units with interior garden

Figure 3.84. Prototype 3—Block typology: the plan of rooftop with an opening to integrate more light for housing units.



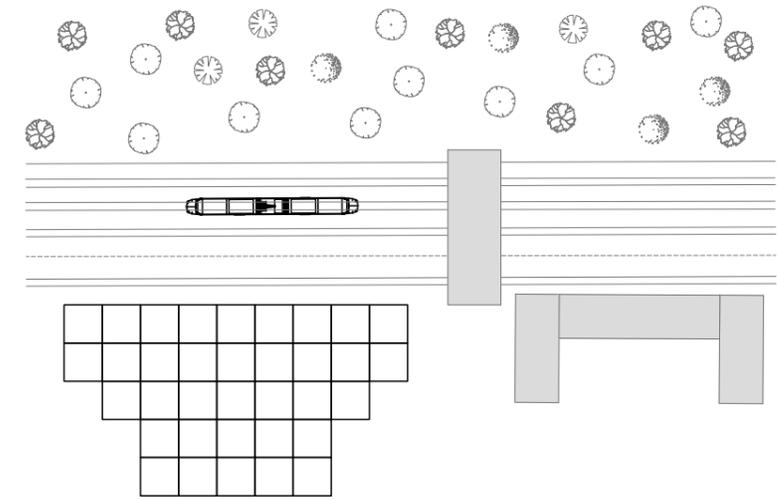
Figure 3.85. Prototype 3—Block typology: the second model variation



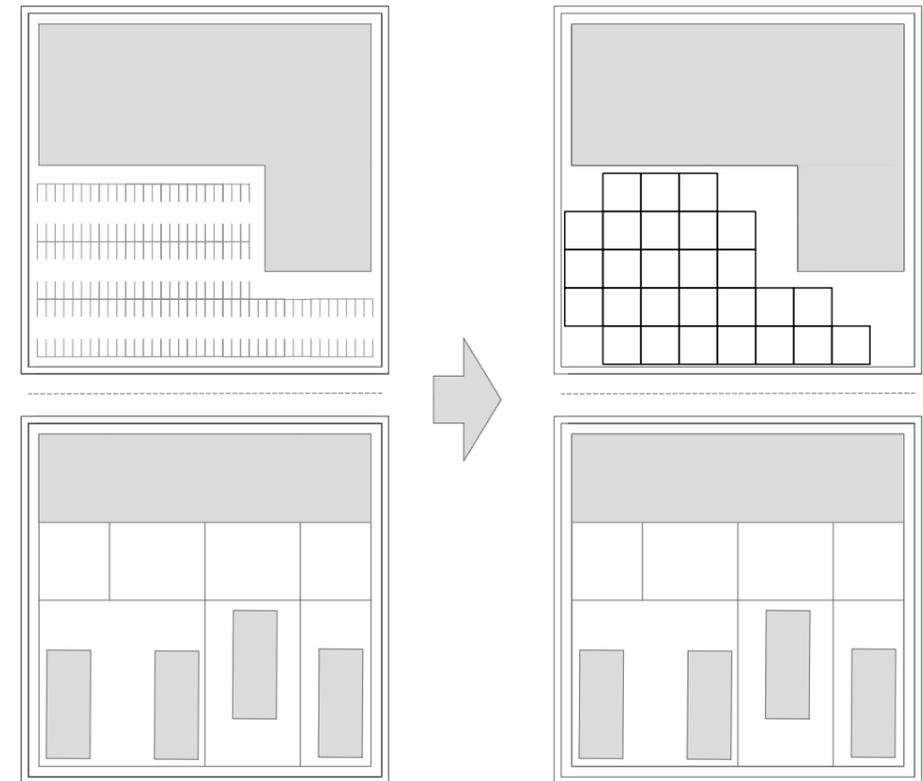
Figure 3.86. Prototype 3—Block typology: the second model variation extension and assembly



Figure 3.87. Prototype 3—Block typology: the second model variation extended



close to public transportation



replace parking areas

Figure 3.88. Prototype 3 — Block typology: possible implementation in the city

Besides the possibility of integration into the city in different scenarios, the typology is also suitable for different construction materials. Within the ECON4SD project, two solutions were proposed for the floor system: timber-concrete composite (TCC) (see Figure 3.89) developed by engineering WP3, and steel-concrete composite (see Figure 3.90) by the engineering WP2. The structural floor system was designed considering sustainability, prefabrication, (re)assembly, and demountability of the slab while respecting the modular floor grid of 10.8x10.8 meters and the possible load cases according to the usage change. Complementary to the thinking process of structure assembly and disassembly, conceptual steel connections are presented in Figure 3.91 and Figure 3.92.

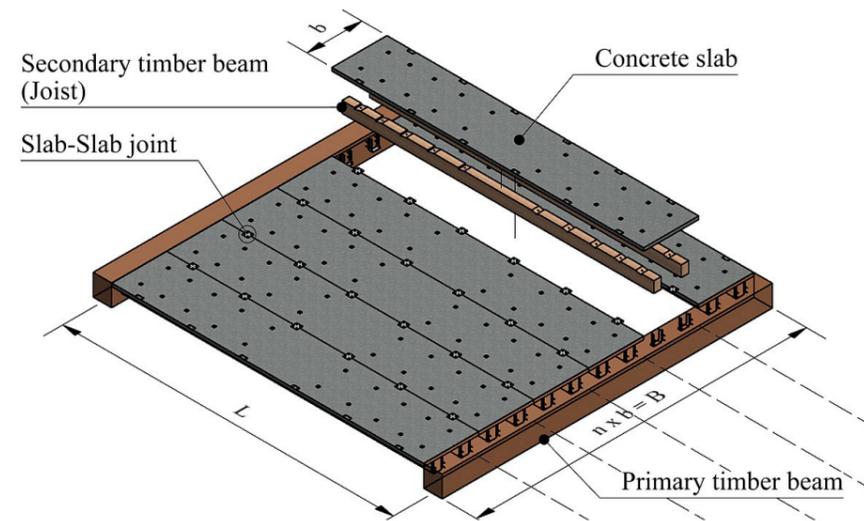


Figure 3.89. Prototype 3 — Block typology: demountable floor – timber-concrete

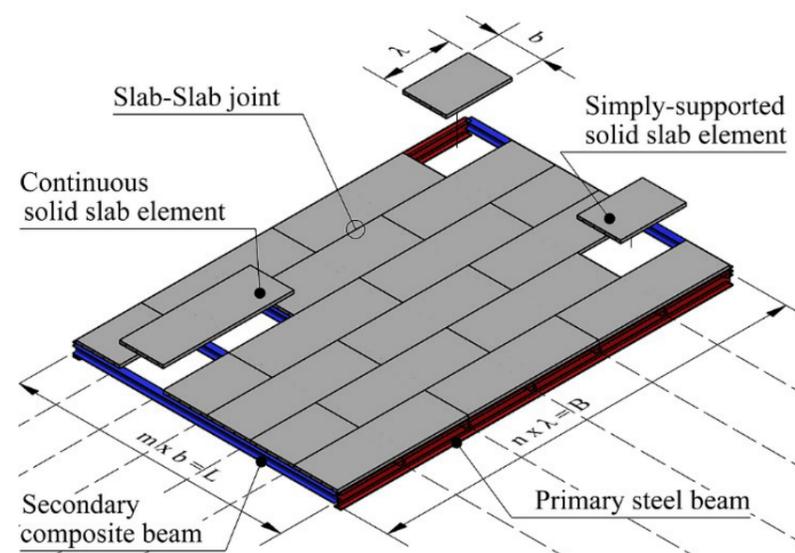


Figure 3.90. Prototype 3 — Block typology: demountable floor – steel-concrete

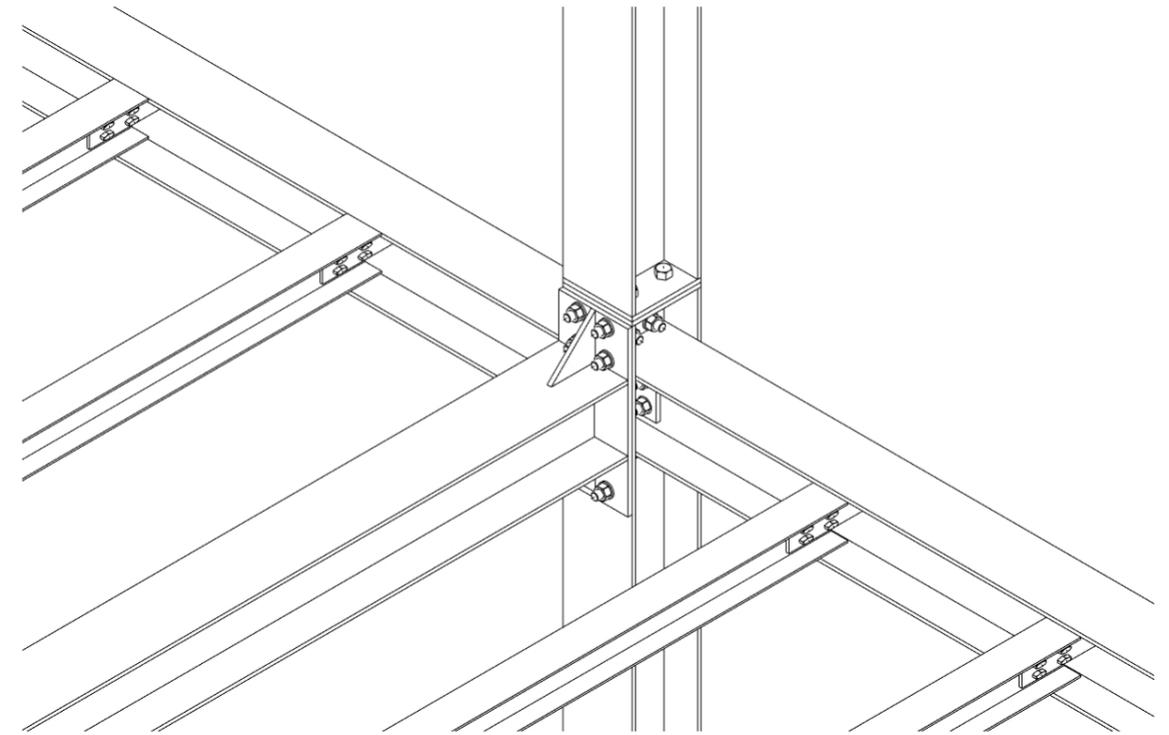


Figure 3.91. Prototype 3 — Block typology: steel connection assembled

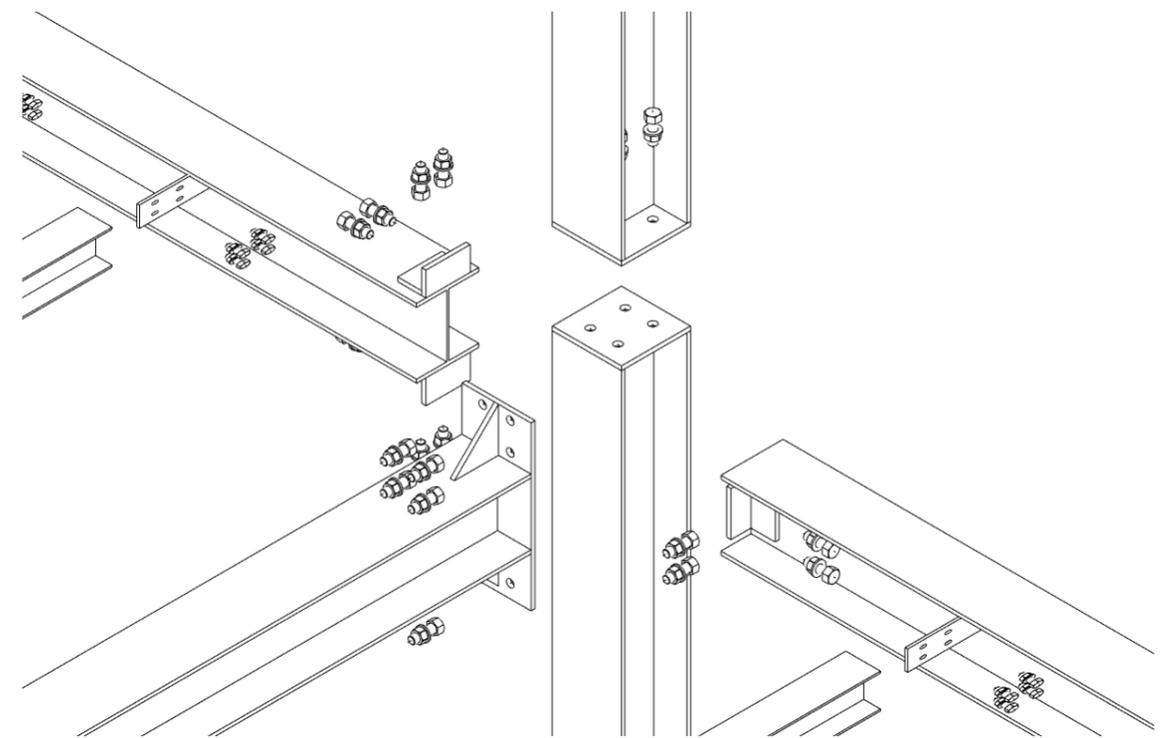


Figure 3.92. Prototype 3 — Block typology: steel connection disassembled

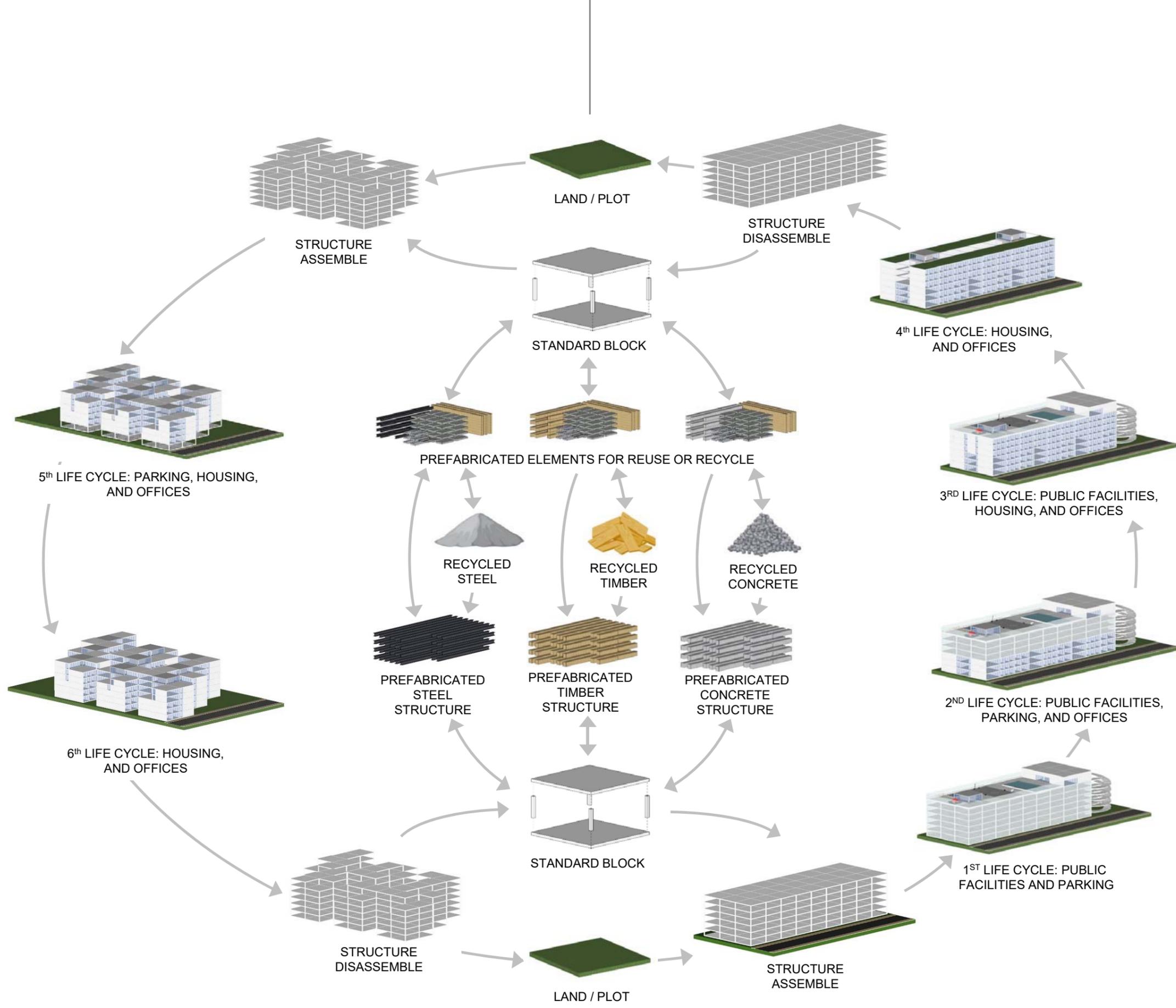


Figure 3.93. Prototype 3 –Block typology: Circular diagram

Table 3.6. Protocol_Prototype 3_ Block typology: possible scenarios

STRUCTURE	OCCUPANCY	GROUND FLOOR	ROOFTOP	USERS
Same for 100 years Same for 50 years Expanded by adding more components Shortened Part remains, and part be disassembled Completed disassembled, and reassembled in another location Completed disassembled and components reuse in another construction Completed disassembled and components recycled In steel In timber Use new steel and timber Use recycled steel and timber Timber can be recycled Timber can be reused in other construction The steel can be recycled The steel can be reused in another structure Open Slabs Close Slabs The stairs can be in The stairs can be out of it	Same for 100 years Same for 50 years Change every 25 years Change by demand Public Private Shared Communal Residential Commercial Mixed Parking building Housing Office Kindergarten Fitness / spa Analog lounge Collaborative workspace. Communal kitchen Library	Open Close Public Private Communal Shared Parking Shops Markets Offices	Open Close Public Private Shared Communal Swimming pool Sauna Library Analog lounge Collaborative workspace Urban garden Sports kitchen	People living alone Young workers Couples Families with a child Big offices Independent workers Car users Companies Public organizations

The Block building, as seen previously, was designed to have more than one life cycle. To summarise, the diagram on Figure 3.93 show the different cycles that the Block typology can have. Besides, Table 3.6 presents the possibilities for Block typology with different structural, occupancy, ground floors, rooftop and user scenarios for all life cycles. Therefore, as a simplification, only the second and the third life cycles were considered for calculating the surface. The surfaces were divided into reusable and recyclable. The space was subdivided as shared or private. The materials were separated into wood, steel and concrete. The wood and steel materials are used mainly for the exoskeleton and the concrete for the core and slabs. The subdivisions and paths can be seen in the diagram in Figure 3.94.

The quantities and the number of users are shown in Table 3.7. The second life cycle of the dismountable building includes 360 parking spaces, 1,080 working spaces for offices, and is able to accommodate 672 people for athletic activities. This calculation considered the Neufert book for general considerations for minimum spaces and people. For example, the usable space allocation of 4 m²/inhabitant in catchment areas for sports facilities, 40-45 people min. 200 m² for gym room size⁵⁰³. In the third life cycle, the parking garage becomes residential, and will support 54 housing units with areas of 34.7 m², three of them in one block unit. Moving on to the analysis of the surfaces, the two core footprints that gives access to the upper floors of the building represents just 3% of the total occupational area. The usable office surface represents 26% of the building, the parking 23%, and the public facilities 19%. When the parking turns into housing, this number increases to 25%, since corridors are no longer needed for the manoeuvring area and the shared spaces become 21%. Evidently, the project brings a balance between leisure, housing and work. In terms of material reusability, 100% of the structure can be disassembled and recycled since the basic block structure and the slab components can be separated for reuse or remanufactured. 100% of the spaces can change through time for reusability due to the basic layout-block versatility. Nevertheless, these two scenarios show the layout modification of 3 floors from parking to housing, representing approximately 43% of the total building surface. Figure 3.95 and Figure 3.96 shows the reusable and recycled gross surfaces areas in % of Prototype 3 for the second and third life cycle respectively.

As a simulation, the Block typology was placed at the huge open parking area of Belle Etoile, located in Route d'Arlon, Bertrange, Luxembourg. Figure 3.97 shows the car park before implantation and Figure 3.98 shows the implantation of Prototype 3. The road will pass by a transformation, and the tram will be included. The space and the building itself will work as a park and ride for the people who want to travel to Luxembourg City, decongesting the city centre of vehicles. In the first stage, the structure will ensure parking spaces on the ground floor for multimodal mobility with the tram, allowing coworking spaces and apartments on the first and second floors, Figure 3.99. Furthermore, this structure makes it possible to accommodate different uses over time. For example, once the tram line has been extended to Arlon, the entire ground floor will be able to be used for coworking spaces, see Figure 3.100. Figure 3.101 and Figure 3.102 present office and house plans.

503 Neufert, Neufert, and Kister 2012.

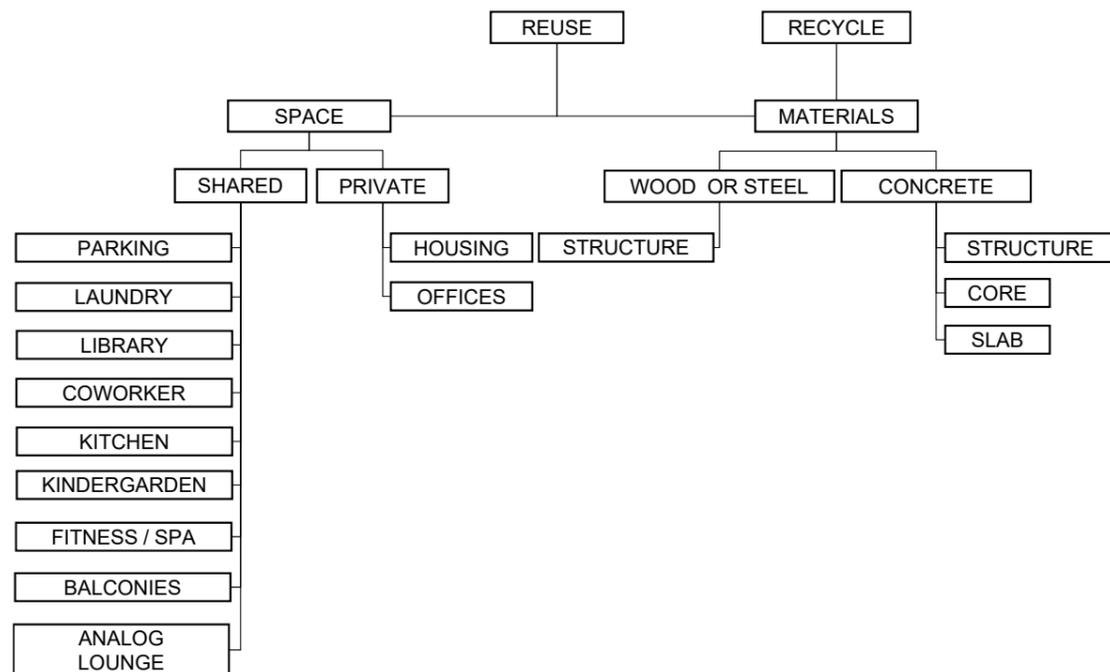
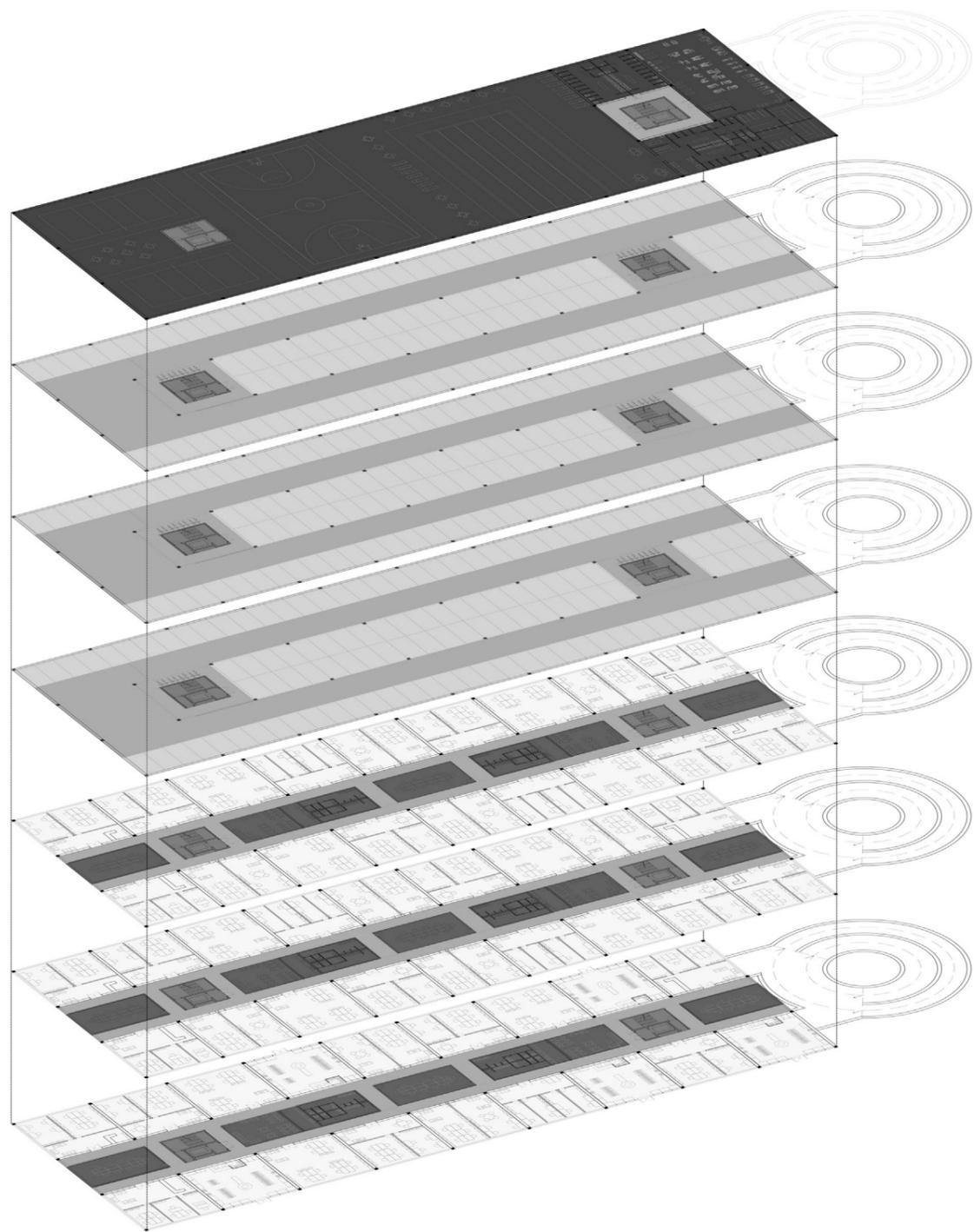


Figure 3.94 . Prototype 3 –Block typology: Diagram of reusability and recyclability

Table 3.7. Prototype 3 – Block typology quantities for one building

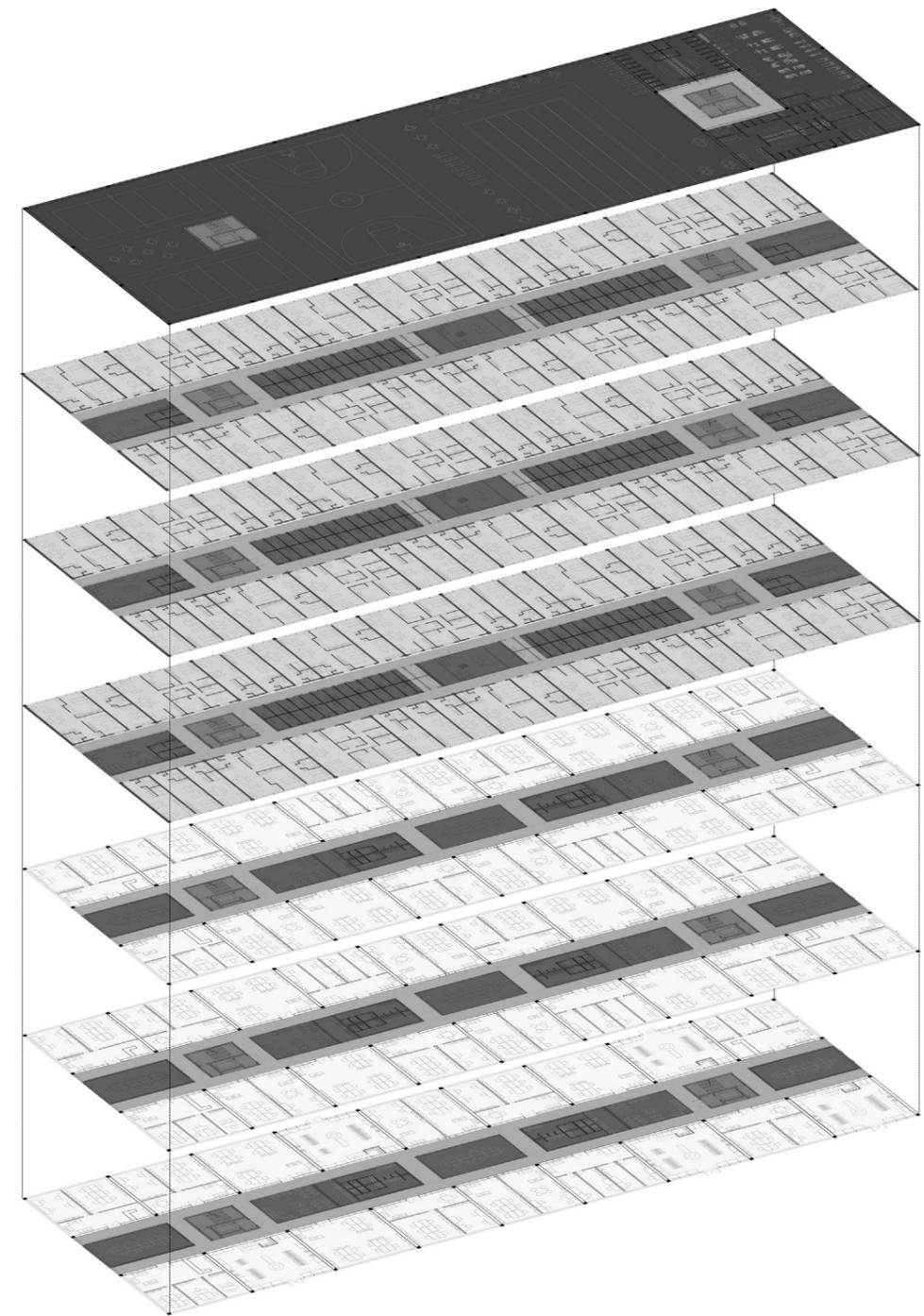
ASPECT	2 ST LIFE CYCLE OFFICE/PARKING/PUBLIC SPACE			3 ND LIFE CYCLE OFFICE/HOUSING/PUBLIC SPACES		
	QUANTITY	MEASUR- ING UNIT	%	QUANTITY	MEASUR- ING UNIT	%
Number of parking places	360	spots		0	spots	
Number of apartments	0	units		54	units	
Max number of inhabitants	0	pers.		108	pers.	
Max number of the user sport area	600	pers.		600	pers.	
Max number of the user gym room	45	pers.		45	pers.	
Max number of user sauna	27	pers.		27	pers.	
Max number of a post office	1080	pers.		1080	pers.	
Total of user	2112	pers.		1914	pers.	
Block units gross area	125.44	m ²		125.44	m ²	
Block units usable area	108.16	m ²		104	m ²	
One Floor usable area without walls	3015.68	m ²				
Usable areas						
Total housing unit surfaces	0	m ²	0%	5616	m ²	25%
Shared spaces	4142.16	m ²	19%	4628.16	m ²	21%
Total offices surfaces	5840.64	m ²	26%	5840.64	m ²	26%
Parking	5113.2	m ²	23%	0	m ²	0%
Deposit / laundry	0	m ²	0%	693.84	m ²	3%
Corridors	5408.72	m ²	24%	2863.04	m ²	13%
Core-elevator/stairs/shafts	471.52	m ²	2%	471.52	m ²	2%
Total usable surface	20976.24	m ²		20113.2	m ²	
Gross areas						
Total housing unit surfaces	0	m ²	0%	6558.72	m ²	29%
Shared spaces	4414.72	m ²	20%	4963.84	m ²	22%
Total offices surfaces	6558.72	m ²	29%	6558.72	m ²	29%
Parking	5372.4	m ²	24%	0	m ²	0%
Deposit / laundry	0	m ²	0%	837.12	m ²	4%
Corridors	5489.68	m ²	24%	2917.12	m ²	13%
Core-elevator/stairs/shafts	573.44	m ²	3%	573.44	m ²	3%
Total gross surface	22408.96	m ²		22408.96	m ²	
Total footprint	3201.28	m ²				
Footprint for access and structure	81.92	m ²	3%			
Footprint of occupancy surface	3119.36	m ²	97%			
Considering just structure without walls						
Materials	one block		N° of blocks	total		
Block structure	17.28	m ²	168	2903.04	m ²	14%
Slabs	108.16	m ²	168	18170.88	m ²	86%

As a second possible implementation, the dismantlable and recyclable structures were placed next to the road at the entrance of Foetz, Luxembourg, see Figure 3.103. The road will pass by a transition, in which the highway will have one lane for e-busses and the other for high occupancy vehicles (HOV) that will reconnect Foetz village to the new neighbourhood. The dismantlable building will concentrate the parking garage and car-sharing and bikes systems in the first phase, Figure 3.104. With the tram's arrival, the number of cars will be significantly reduced, and the building will be able to host other activities such as public, working and housing Figure 3.105 and Figure 3.106.



- Office 29%
- Car parking 24%
- Corridors 24%
- Elevators access and shafts 3%
- Public / Shared spaces 20%

Figure 3.95. Prototype 3 – Block typology: Diagram of gross area surfaces in %, second life cycle



- Office 29%
- Apartment 29%
- Corridors 13%
- Elevators access and shafts 3%
- Public / Shared spaces 26%

Figure 3.96. Prototype 3 – Block typology: Diagram of gross area surfaces in %, third life cycle

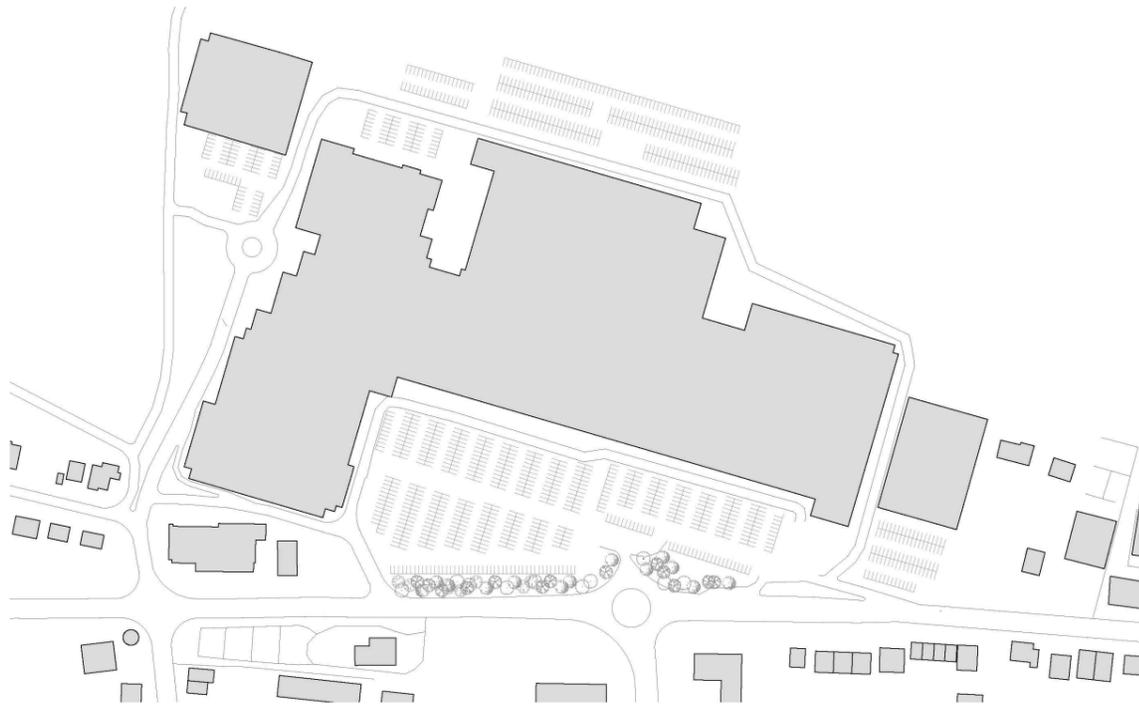


Figure 3.97. Prototype 3—Block typology: Belle Etoile shopping and parking area



Figure 3.98. Prototype 3—Block typology: housing complex/office building situation plan

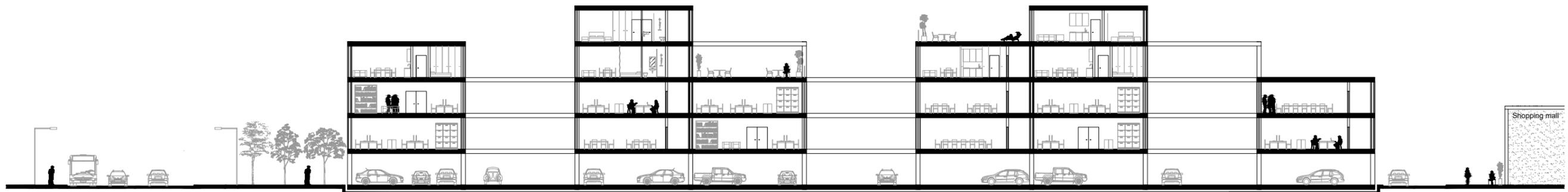


Figure 3.99. Prototype 3—Block typology: section – evolution simulation – parking, coworking, and apartments

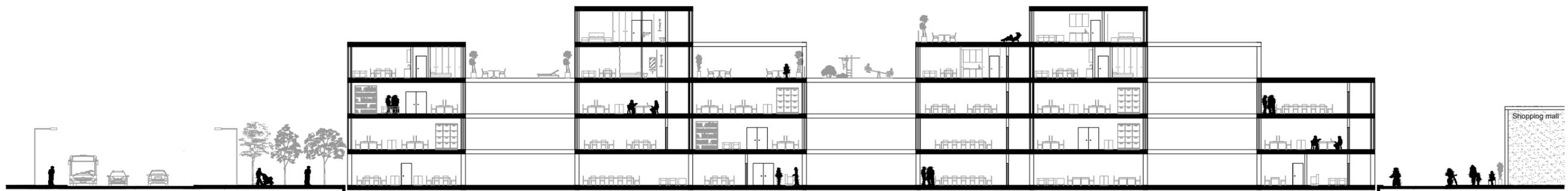


Figure 3.100. Prototype 3—Block typology: section – evolution simulation – commercial, coworking, and apartments

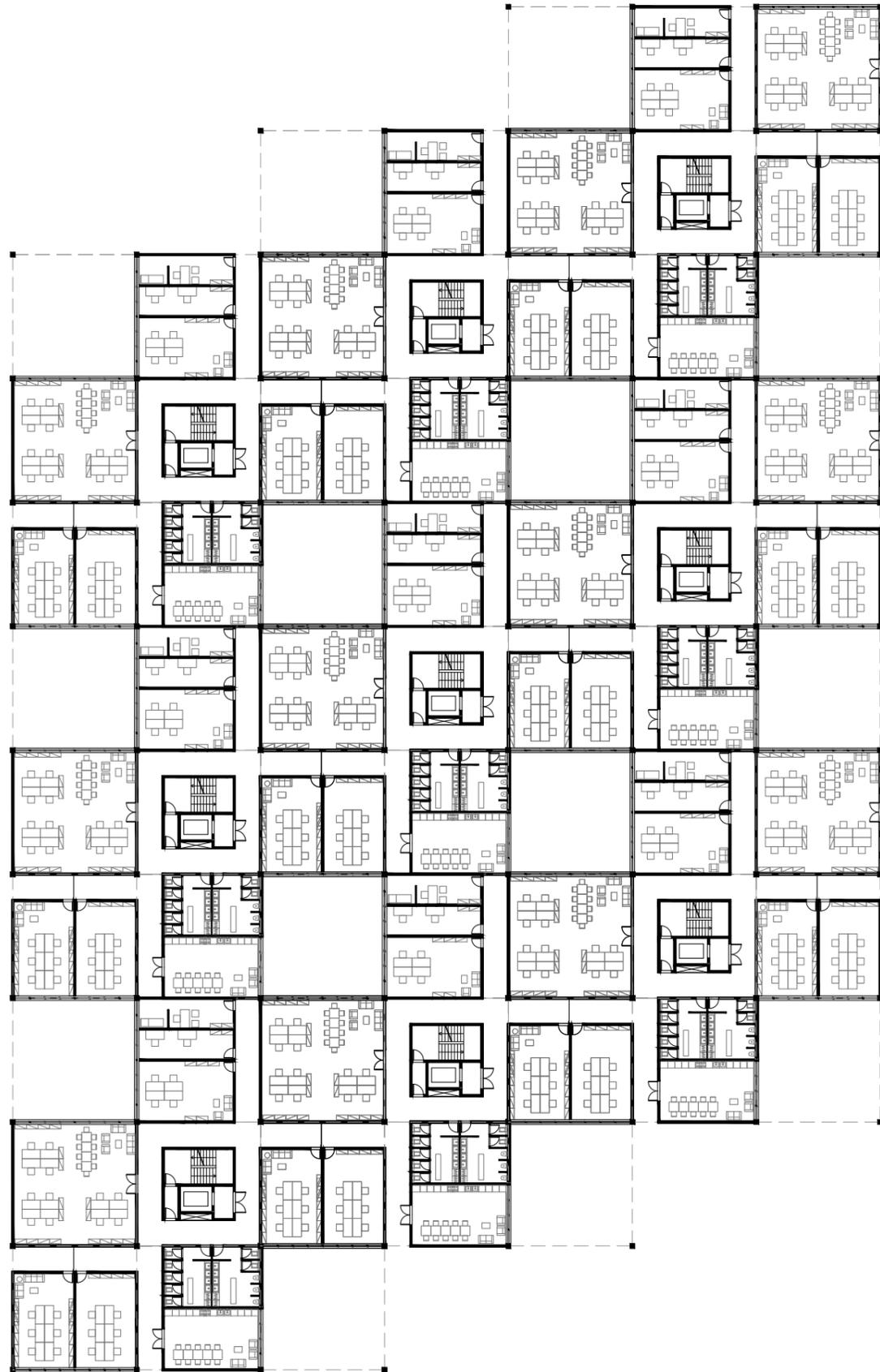


Figure 3.101. Prototype 3—Block typology: office plans

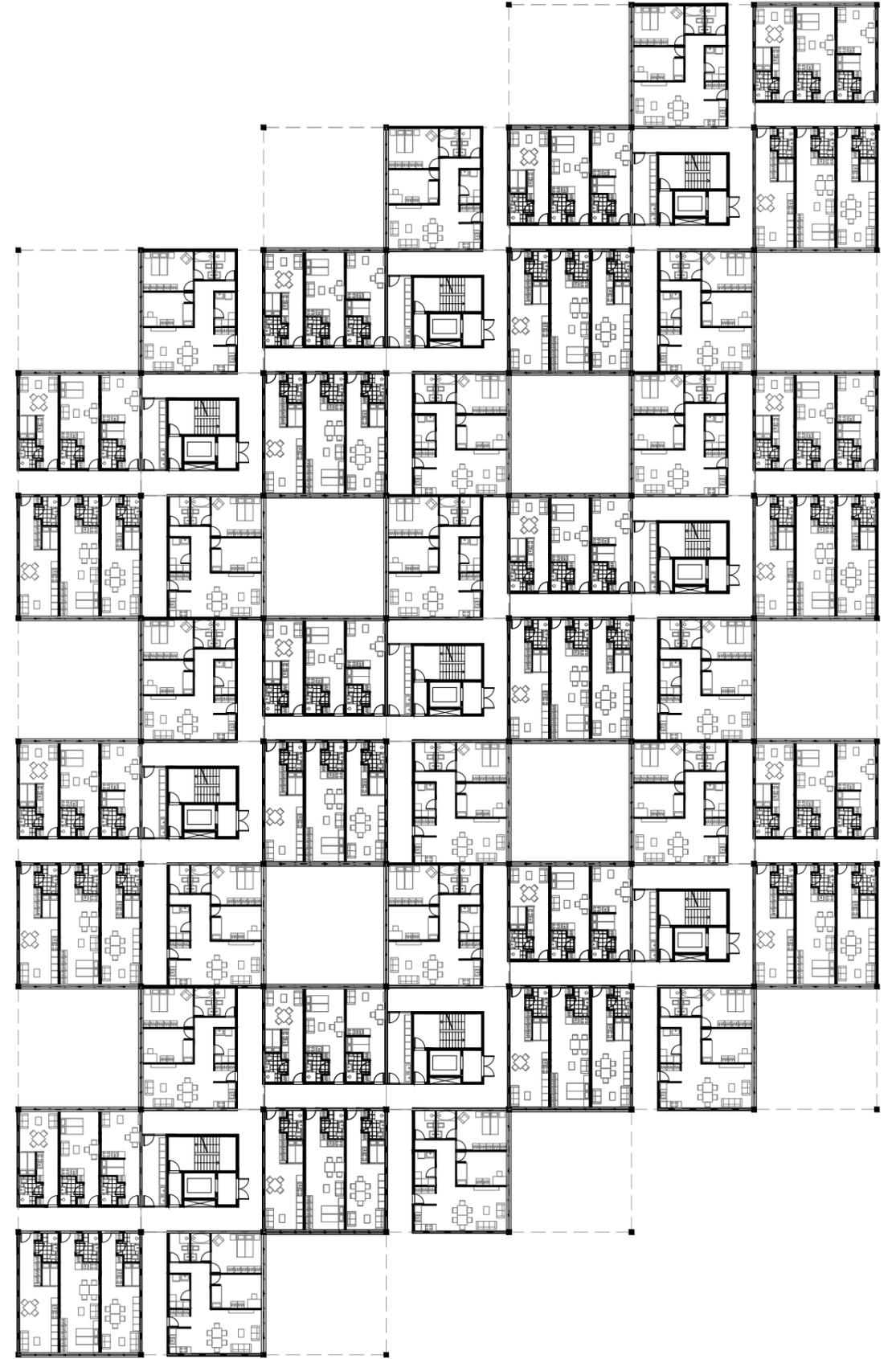


Figure 3.102. Prototype 3—Block typology: housing plans



Figure 3.103. Prototype 3—Block typology: situation plan in Foetz

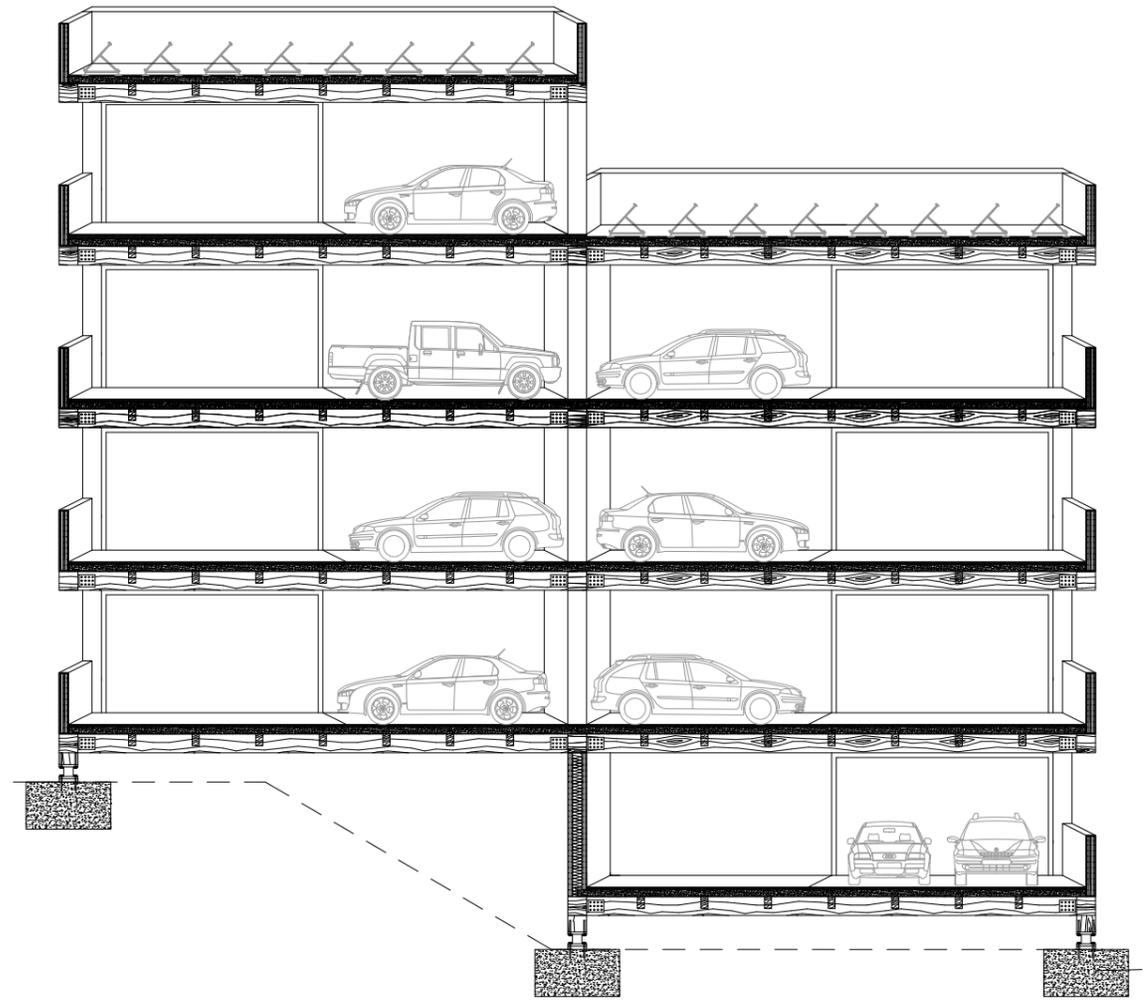


Figure 3.104. Prototype 3—Block typology: Section Foetz 2025

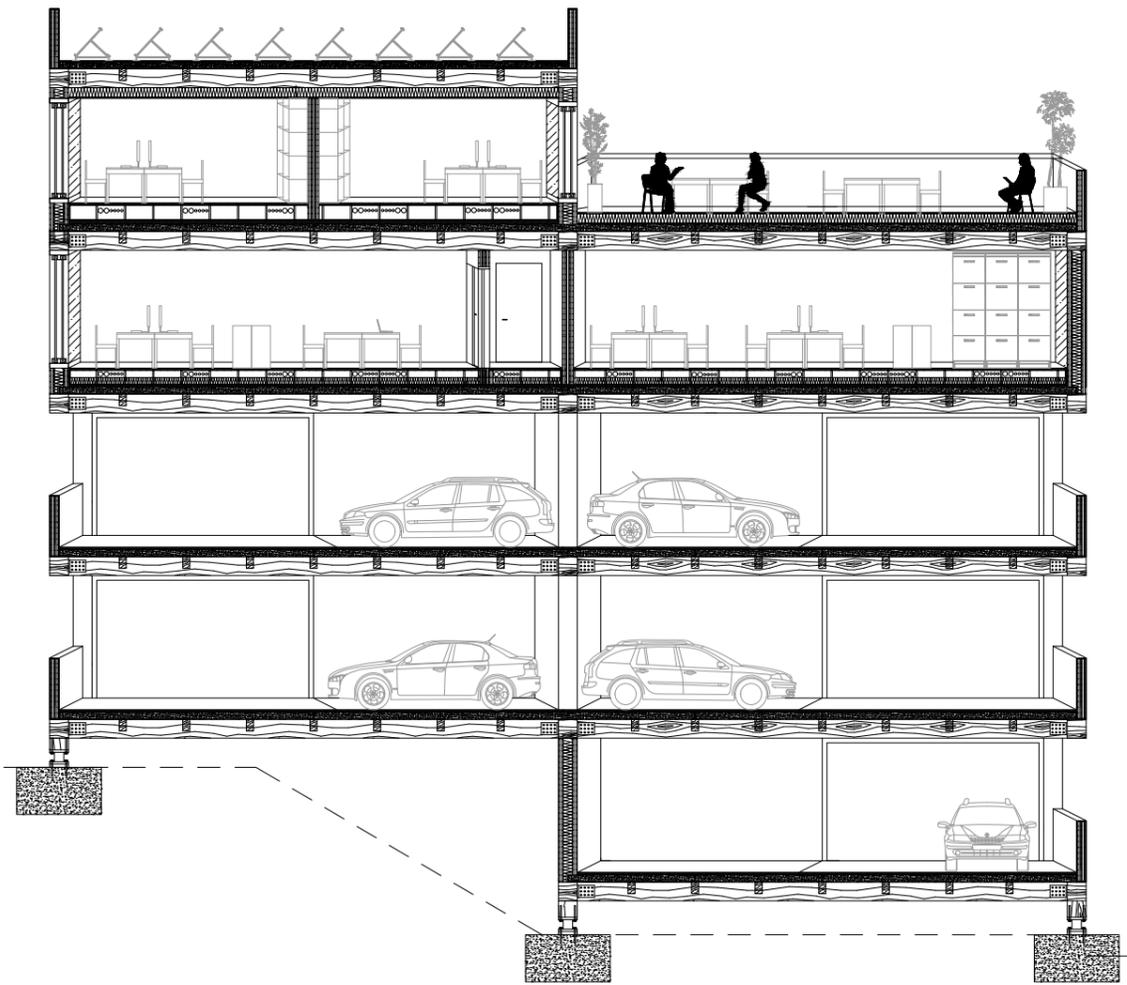


Figure 3.105. Prototype 3—Block typology: Section Foetz 2030

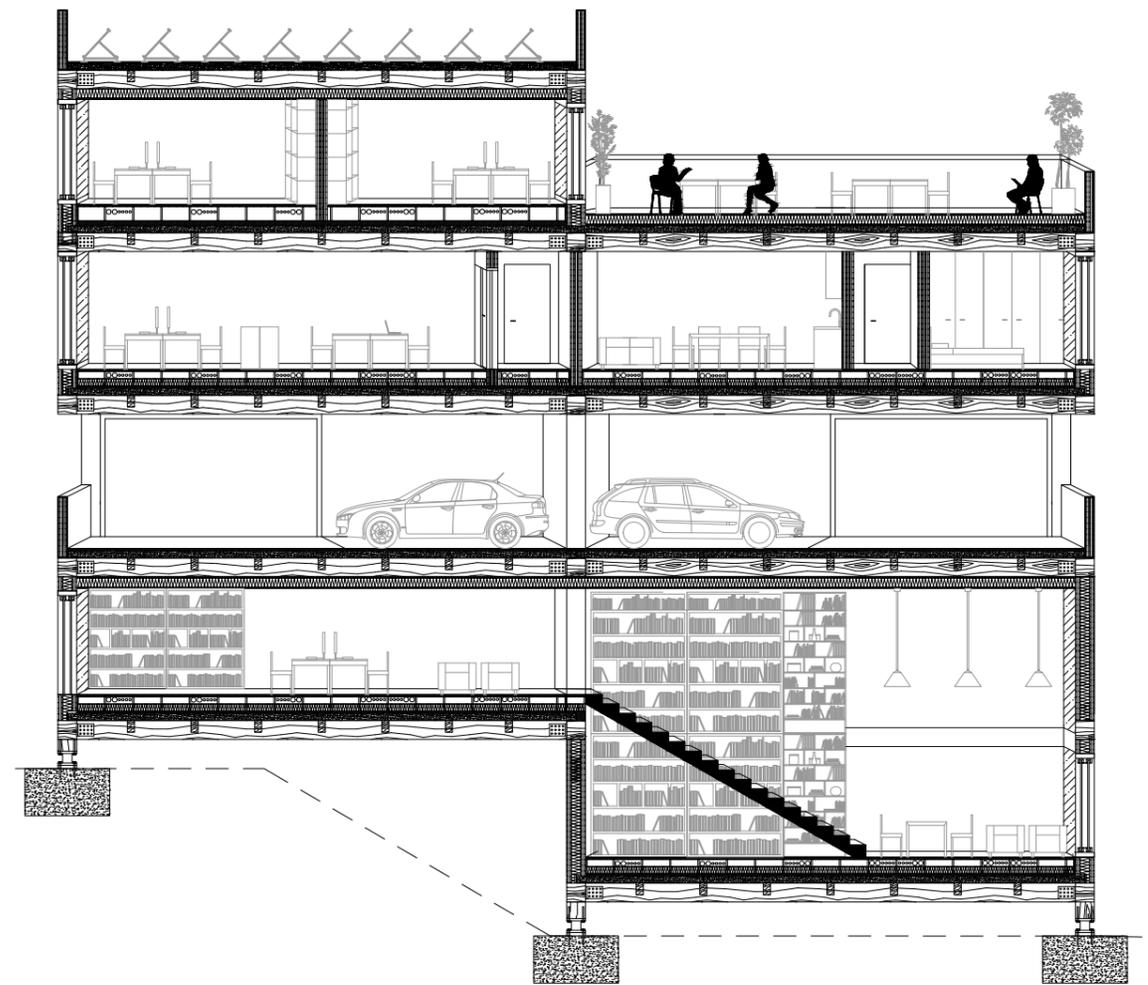


Figure 3.106. Prototype 3—Block typology: Section Foetz 2035

3.4.1. Life Cycle Assessment of Prototype 3 – Block typology

Climate change and CO₂ emission discussions are related to resource efficiency, the life cycle of the materials and consequently, the buildings. Prototype 3 - Dismountable typology has the most characteristics to be analysed since it predicts different uses and forms for more than one life cycle. It was designed to be completely disassembled and recycled and the three applicable structural materials are timber, concrete and steel. For this reason, the subsection presents a short review of LCA with a focus on building and comparing the three different materials for the block proposed in Prototype 3 through the LCA methodology, using existing sources on INIES LCA databases and simplified calculations. However, carbon emission calculations can vary due to boundaries and scale without an internationally accepted method for measuring, reporting and verifying GHG emissions from existing buildings in a consistent and comparable way⁵⁰⁴. The overall objective of this exercise is to understand and assess the importance of resource use, the selection of materials and a buildings environmental impact.

3.4.1.1. Life Cycle Assessment short review

Resource efficiency towards more sustainable buildings aims to reduce the consumption of raw materials and restrict the building's environmental footprint across its life cycle - from the extraction of materials, construction, occupancy and maintenance to the recovery of materials in demolition⁵⁰⁵. One way to evaluate resource efficiency is through LCA, a tool that calculates, evaluates and compares the global environmental impacts of materials, products and structures of a building's life span⁵⁰⁶. The life cycle of a building encompasses the embedded energy impacts of raw material extraction, construction, maintenance, renovation and dismantling operations, eventual reuse of waste, and end-of-life waste disposal⁵⁰⁷.

For buildings, "embodied energy" refers to the energy needed to extract, treat, manufacture, ship and install a specific material related to GHG emissions⁵⁰⁸, which account for about 60% of the global life cycle energy consumption⁵⁰⁹. Each step has an associated environmental impact that produces CO₂, quantified by its total CO₂ equivalent emissions⁵¹⁰. CO₂ from fossil fuels and biomass combustion accounts for 90% of GHG emissions⁵¹¹. It affects ecosystems, human well-being, socio-economic

504 Fenner et al. 2018.

505 Herczeg et al. 2014.

506 Green and Taggart 2017; Potrč Obrecht et al. 2020; Zabalza Bribián, Aranda Usón, and Scarpellini 2009.

507 Adalberth 1997; Green and Taggart 2017; Herczeg et al. 2014.

508 Green and Taggart 2017.

509 Huberman and Pearlmutter 2008.

510 Herczeg et al. 2014; Hillebrandt and Seggewies 2019.

511 OECD 2017.

activities, and the frequency of extreme weather events⁵¹². The increase in CO₂ is considered the leading cause of global warming and a significant indicator in building's material life cycle⁵¹³. Progress towards green growth can be assessed with CO₂ emissions from production and demand perspectives (footprint), the level of decoupling achieved between GHG emissions and economic growth and changes in atmospheric GHG concentrations⁵¹⁴.

Calculations based on the LCA database illustrate resource use and environmental impacts associated with buildings, which can be used to identify which life cycle phases and resources have the most critical environmental impacts⁵¹⁵. The environmental impact of a residential building depends on the different stages of the life cycle of the building and the construction components⁵¹⁶. LCA should be applied in the early design stage in the architecture field, including renovation projects, to compare design options such as geometry, orientation, and technical choices while collaborated with engineers⁵¹⁷. The entire LCA analysis for buildings is complex as they have a relatively long lifetime, often change, can have more than one function, comprise lots of different elements, are made locally, unique, have an impact and are associated with infrastructure where the boundaries of the system are not clear⁵¹⁸. Furthermore, a structure's design life will vary considerably depending on the climate, the structure's use, and its cost of replacement⁵¹⁹. The building's useful life is approximately 50 to 100 years, with renovations scheduled every 10 to 25 years⁵²⁰. Society expects a 50-year minimum life of performance for housing, but some cultures may accept a shorter life span in return for lower cost and portability⁵²¹. However, this prediction is not so simple since parts of the built environment deteriorate at different rates, complicating replacement and repair schedules⁵²². Moreover, materials waste management from buildings is quite uncertain and complicated to treat⁵²³. In a 50-year lifespan, the recycling potential of embodied energy varies between 35% and 40%⁵²⁴.

After the first life cycle of a building, materials can be recycled or reused. Embodied energy can be decreased by using recyclable and reusable components⁵²⁵. Recycled materials impact the environment less than raw materials, which can be accounted for by the CO₂-equivalent greenhouse gas emissions associated with production⁵²⁶.

512 OECD 2017.

513 Hillebrandt and Seggewies 2019.

514 OECD 2017.

515 Herczeg et al. 2014.

516 Priemus 2005.

517 Zabalza Bribián, Aranda Usón, and Scarpellini 2009.

518 Ibid.

519 National Association of Forest Industries 2003.

520 European Committee for Standardization 2010; Hillebrandt and Seggewies 2019; Kibert 2003.

521 National Association of Forest Industries 2003.

522 Kibert 2003.

523 Herczeg et al. 2014.

524 Thormark 2002.

525 Ibid.

526 Herczeg et al. 2014.

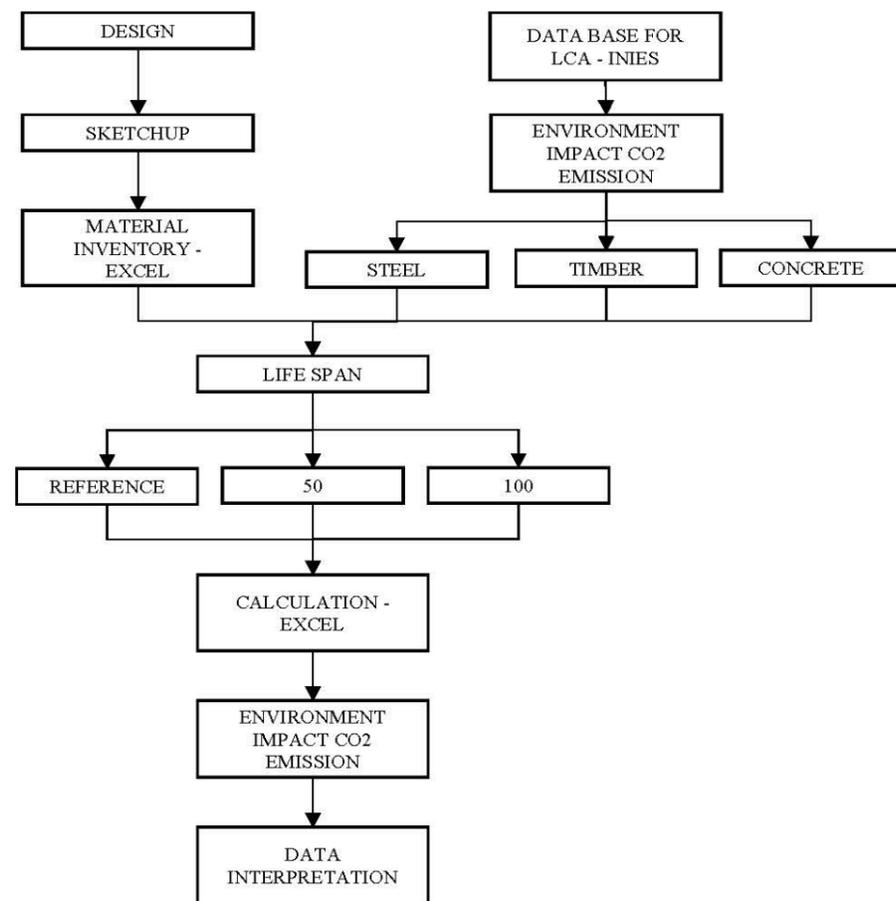


Figure 3.107. Prototype 3 — Demountable typology: LCA methodology

LCA shows wood as the greenest structural material, contributing to climate change mitigation by increasing carbon storage and decreasing GHG emissions by 50-90% compared to concrete or steel⁵²⁷. However, hybrid construction in wood combined with concrete and/or steel is a promising, more practicable, and cost-effective option⁵²⁸. In conjunction with life cycle analysis, energy certification promotes sustainable buildings with low energy consumption and high efficiency in favour of innovation in the building sector⁵²⁹. Beyond that, priority should be given to the passive design in the initial phase using natural and recyclable materials that are available in the surrounding areas.

3.4.1.2. Block typology LCA results

Combining Building Information Modeling (BIM) and LCA is one way to obtain material quantities and allows for electronic material mapping with attached environmental impact factors⁵³⁰. Nevertheless, as a research project, the prototype is in its final phase of architectural design development and not the execution phase and, therefore, there are no detailed structural plans or other elements. Because of that, BIM and LCA software integration became problematic once the integration required a detailed level of information from the execution phase. Thus, the architectural plans were translated into 3D models with SketchUp, and the materials and quantities were determined in an Excel file together for LCA calculations. Although Luxembourg does not have a database for LCA yet, the French INIES database was adopted for the Luxembourg construction sector due to border proximity, country-specific characteristics, and manufacturing processes. The INIES data is an open-source and free of charge, indicating the environmental and sanitary characteristics of construction products and equipment and uses the Environmental standard: NF EN 15804 + NF EN 15804/CN for calculation⁵³¹. The calculations were made using the quantity of each material and combining the data taken from the INIES database. The materials were selected from the database according to the closest match to the architectural design and the better indicator of “Environmental impact.”

Carbon emissions relate to the built environments dominate society’s total carbon footprint⁵³². Accordingly, the focus of the calculation was to evaluate the CO₂ emission for life cycle analysis, so only the Environmental Impact for Climate Change (kg CO₂ eq.) was considered, which included the material production, construction, occupancy, end-of-life stage and beyond. In order to provide results of a similar quality to the comprehensive assessments, some simplifications on LCA studies of buildings were made. The methodology and phases towards LCA for the block of Prototype 3 can be seen in Figure 3.107. The environmental impact was calculated based on material

527 Green and Taggart 2017.

528 Cambiaso and Pietrasanta 2014.

529 Zabalza Bribián, Aranda Usón, and Scarpellini 2009.

530 Bruce-Hyrkäs, Pasanen, and Castro 2018.

531 l’Etat et le Conseil, Supérieur de la Construction et de l’Efficacité Énergétique, and INIES 2016.

532 Fenner et al. 2018.

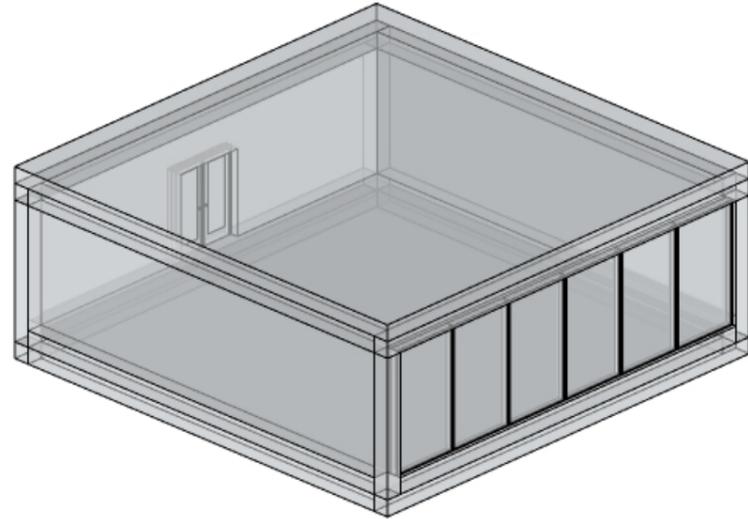


Figure 3.108. Prototype 3 — Demountable typology: 3D Wood Block for LCA calculations

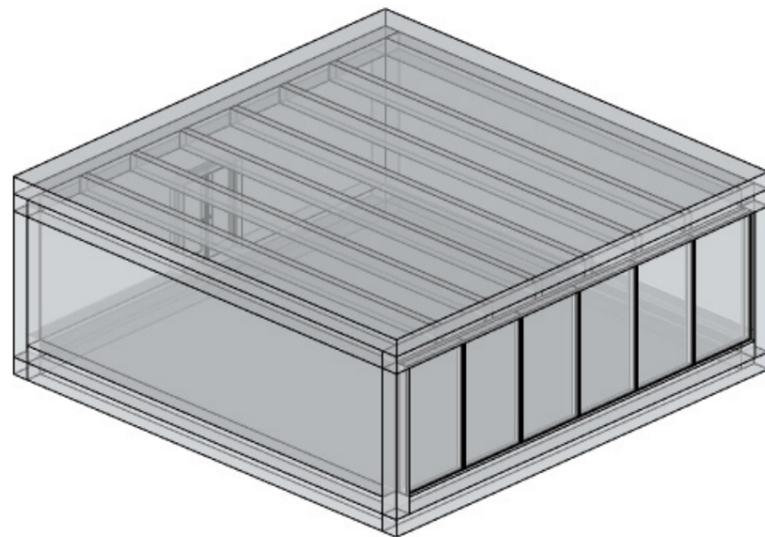


Figure 3.109. Prototype 3 — Demountable typology: 3D Concrete and Steel Blocks for LCA calculations

dimensions or volume according to the database requirement and then added at the inventory level to calculate the carbon footprint for different scenarios. The simplest shape of the structure including the walls, windows, roofs and slabs without extra coverages was considered. Figure 3.108, Figure 3.109 and Table 3.8 present the block dimensions and material quantities of the Dismountable typology block used in the LCA calculations. Three different scenarios of a lifespan were tested – reference of the material scenario, a 50 year scenario, and a 100 year scenario. The LCA calculation considered the environmental indicators of Climate Change (kg CO₂ eq.) for the three structural materials: wood, steel and concrete. INIES inventories include emissions for each material for individual unit processes. The specification of the selected materials and their “Environmental Impact of Climate Change” information extracted from INIES database and LCA calculations are displayed in Annex B. The results are considered an approximation to the environmental impacts of the assessed building materials. The chart in Figure 3.110 shows the final results for the mass of CO₂ eq divided per m² for one module of the Block typology in wood, steel and concrete structures. The results show that the CO₂ emission of a steel structure is higher than for wood and concrete. For 50 years, the steel block emits 1286 kgCO₂eq./m², against 768 kgCO₂eq./m² from wood and 896 kgCO₂eq./m² from concrete. Nevertheless, the steel has a higher potential to be recycled after its lifespan than concrete does. When comparing the CO₂ emissions through the lifetime of the same structural material from the time reference of 100 years, notice that the quantities can be 2 to 4 times higher. This is happening because some materials like the windows, doors and walls need to be changed after 30 and 50 years so the structure can remain longer.

To conclude, the comparison between the three scenarios can provide some information and show the consequences of material selection. Even though the research project is in the final phase of architectural design development and not execution, the LCA is essential to decision making about the quality and quantities of materials. Nevertheless, the research was limited due to the CO₂ emission calculations varying from building type and materials, making the direct comparison with other buildings impossible. Therefore, a clear, approachable, and reliable method for evaluating the carbon emissions of the buildings is needed. This research shows that the design phase can impact the life cycle of the building, which can reduce the environmental impact and supports the development of a simpler method needed to reduce carbon emissions in the architectural phase. In addition, a more qualitative approach should be developed complementary to the general quantitative LCA method to calculate the percentage not only for materials but also for surfaces and spaces of the building that can be reusable for different functions.

Table 3.8. Prototype 3 - Demountable typology – block dimensions and quantities

Dimensions 11.2x11.2x3.8 / Total area 125.44 / Total volume 476.672								
Element	Length	Width	Height	Surface area	Volume	Quantities	Total surface area	Total volume
Pillars	0.4	0.4	3.4	1.36	0.544	4	5.44	2.176
Beams long	11.2	0.4	0.4	4.48	1.792	4	17.92	7.168
Beams short	10.4	0.4	0.4	4.16	1.664	4	16.64	6.656
Support for slab	10.4	0.2	0.4	2.08	0.832	5	10.4	4.16
Floor	11.2	11.2	0.4	125.44	50.176	1	125.44	50.176
Ceiling	11.2	11.2	0.4	125.44	50.176	1	125.44	50.176
Exterior Walls -full	10.4	0.4	3	31.2	12.48	2	62.4	24.96
Exterior Walls - with door	10.4	0.4	3	27.84	11.6736	1	27.84	11.6736
Exterior Walls -full window	10.4	0.4	3	31.2	12.48	1	31.2	12.48
Door	1.6	0.24	2.1	3.36	0.8064	1	3.36	0.8064

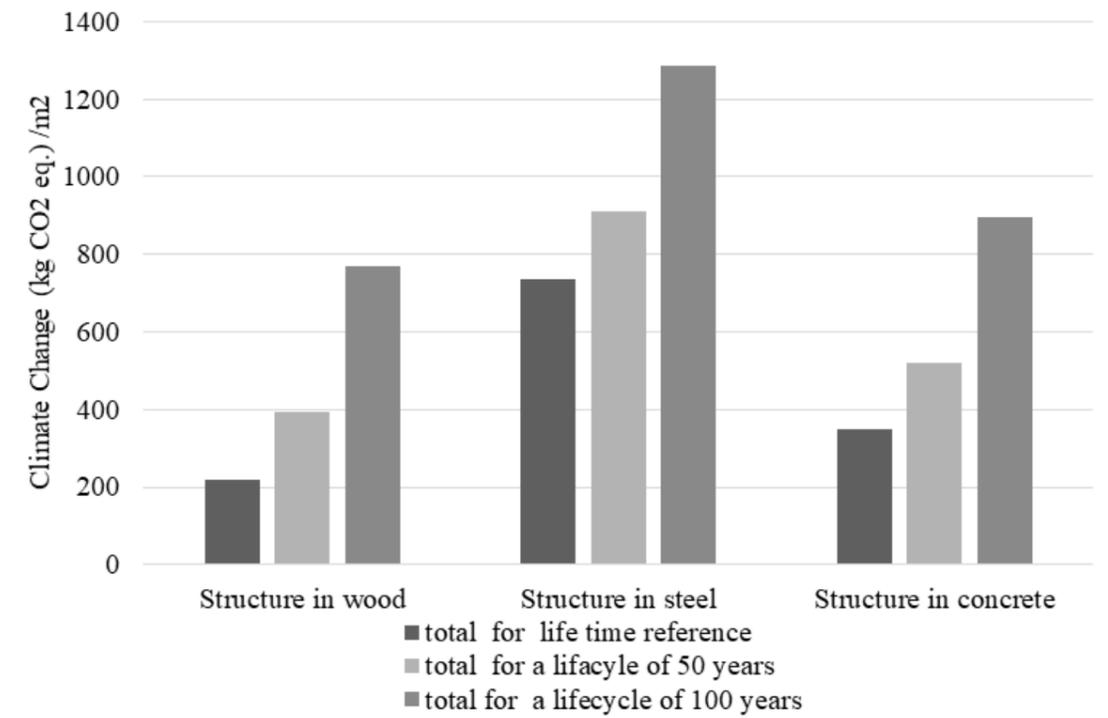


Figure 3.110. Prototype 3—Block typology: LCA results for Climate Change environmental indicator per m²

3.5. The ECON4SD interactions between the architecture WP to other WPs in the design process

The ECON4SD brought together architects and engineers from the University of Luxembourg to discuss how to improve components and design models for energy and resource efficient buildings. Each of the six PhDs, a postdoc and the respective professors had a separate project and hypotheses on how to do it. However, after the first workshop, it was decided that we needed a common project to compare against. The architects proposed the architectural models, while the structure, energy efficiency, concrete ageing, and BIM possibilities were analysed and proposed by the engineers. The project evolved through collaboration, bringing some fields closer than others.

Paper sketches, drawings on AutoCAD and 3D models on SketchUp programs were developed in the first architectural design phase. CAD is a numerical representation of a constructive component, and the knowledge of the product set can be seen as the module itself or a building⁵³³. The plans were exchanged between the WPs through the file format of *dxf*, *dwg*. and *SKP*. In the first moment, the files served as a starting point for the WP6 to develop the object-based model for BIM on Revit, as they were the ones that had worked directly with it. After the architectural conceptual phase, the structural simulation from the engineers' side started, WP2, 3 and 4. The file format of *dxf* was chosen because it could be opened in both structural and architectural software. Then, the structures were developed and exported to Sketchup and CAD for analyses and discussion. The exchange with WP5 was to determine efficient energy strategies and perform analysis through *dwg* and *SKP* formats since the TRNSYS software simulates transient systems' behaviour for the environment.

The ECON4SD project attempted to integrate BIM into the design practice from the early stages of research, but this did not go forward. Only in some moments of development or analysis of the generic models was the BIM application more effective by exchanging data that could be ready for more than one software. This happened because the software programs used during the research and building development were selected by need, understanding and practice of each PhD and postdoc, without constraints of brand or trends, to facilitate their work. Nevertheless, the employment of BIM technologies can make construction more efficient throughout the whole process, from design, construction, and operation to dismantling and reuse of materials and components, contributing to circularity by reducing the generation of construction waste⁵³⁴. Furthermore, data handling and storage could help buildings become more flexible for material reusability and energy efficiency, including micropower generation.

The LCA analysis phase was the moment where the object-based programs were needed to facilitate the process and integrate BIM. BIM can assist the LCA method implementation and simplify steps, including information from materials used and their quantities⁵³⁵. However, as mentioned before, the applications were different due to the demand for a higher project detail level similar to the execution phase and as research

533 Correia 2017.

534 Third Industrial Revolution Consulting Group LLC 2016.

535 Alecrim et al. 2020.

was kept as an architectural concept. Thus, the architectural plans were translated to 3D models in SketchUp, and the materials, quantities, and LCA calculations were gathered in an Excel file. In addition to the high demand for project detail, data is missing for specific materials and local calculations, so adaptations were inevitable. Thus, it is necessary to develop a more specific country lifecycle inventory for building materials, energy and transportation that can be adopted by the different LCA computer programs⁵³⁶. At the same time, LCA programs must be adapted to the different design phases.

In conclusion, the change was achieved through a circular collaboration inside and out of the architectural discipline. To make things work as BIM from the beginning, apart from having a common goal to develop the building, we should have a common understanding on how to use each software and design the components. Even though this is not an easy thing to do at the beginning of research, we could not have such defined goals as the practice market does it.

3.6. Synthesis of the results – Benefits and barriers to designing reusable and recyclable architectural typologies

The prototypes explored the relevant issues of prefabricated and modular building systems and recyclable strategies to increase architectural design flexibility, adaptability and disassembly. Immediate solutions, combinations, and improvements of prefabricated and modular designs and systems from existing projects presented in Atlas - Chapter 2 were brought and translated into the new typologies developed in this research. Although the initial program of the ECON4SD project did not have any specific programs or plots for implementation, the typologies were developed as generic models that considered general society and ecological needs and Luxembourg's challenges, with the possibility of being replicated and adapted to different scenarios. The typologies are a mix of ideas such as rationalisation, modularity, prefabrication, plug-in, reusability and recyclability to reach circularity in construction. The results are innovative tools and approaches to be implemented early in the design process and can be adapted to other buildings. In order to validate the feasibility and highlight the improvement of the three prototypes, a comparison between them were made, which can be seen in Table 3.9.

The main difference is that the three prototypes are high-rise buildings designed to be adaptable through time and disassembled at the end of their lifecycle through prefabrication and modulation, while at the same time providing a large number of housing units combined with more shared and public areas. The Slab typology focused on the housing expansion and plug-in concepts, accommodating 48 portable housing units. This represents 33% of the usable surface, with 41% destined for sharing and public spaces. The floors of the Tower typology are as open as possible to emphasise the internal flexibility and freedom from the structure and façade. At the Timber tower, 9% (5 floors) was destined to be shared spaces, 38% for offices (5 floors and 4 floors mixed with housing), and 32% for housing (10 floors) that can accommodate up to 290 apartments of 27 m² (T1) or less number of apartments and up to 7 rooms. The Block typology was designed to change and adapt to different needs, using a standard block focusing on complete disassembly. In different life cycles, 19% is destined for public and shared activities and can accommodate up to 720 parking spaces, 1,080 working spaces and 54 single housing units per floor (three single housing units in one standard block).

Even though other buildings have integrated modular and prefabrication systems, their focus was on the assembly process rather than the disassembly process, making it more difficult to reuse and recycle. From Durant to nowadays, modular systems are being used and are meant to be rational and universally applicable. From the early nineteenth century, the grid and the rationality were intensely applied in constructing massive buildings, like "*Unité de Habitation*," due to the housing shortage after WWII. The size of the apartments was reduced for social housing to allow for more tenants. In some cases, they had movable partitions, but they could not be expanded to create more space, making the projects not adaptable for future users and needs. As opposed to the new typologies, i.e. the Slab's housing unit can be added or removed, the floors of the Towers can be reconfigured, and the Block building can have more blocks or be

536 Alecrim et al. 2020.

disassembled, and floors may be redesigned. From the 1950s onwards, the concept of a grid and plans changed to more integral modular units. However, it was not until the 1960s that prefabrication was widely implemented in individual homes.

The three prototypes took advantage of this rationalisation and prefabrication on a small scale and translated it to a larger scale. Grids, modules and prefabricated components were used 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. For example, the “Habitat 67” project has a building comprised of concrete blocks, although they were too heavy to be easily installed or relocated. The “Nakagin Tower” also has modules with capsules attached to a core, but the layout was concise for the essential needs without the possibility to combine them into bigger 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. This improved the possibility of extending the residence and connecting it to more than one infrastructure. Since it utilises timber, it also has the benefit of yielding a lighter structure than concrete and steel.

The concept of pilotis, idealised by Mies van de Rohe and Le Corbusier, was brought to the prototypes as an open space at street level but with a public function and adaptable use according to neighbourhood needs where the building is located. The Archigram studies were focused on creating a discussion on architecture with images and propaganda. Added to the opening of the debate on recyclability, the Slab, Tower and Block typologies are realistic and provide more details and concerns about the construction’s feasibility. The ecological examples inspired the integration of nature and lightweight and exposed structures with open slabs in the construction, like Ökohäuser and R50 cohousing, showing that it is possible to propose different internal layouts. Additionally, they open discussion about the use of materials and technologies towards disassembly and make it more environmentally friendly. However, they do not guarantee the environment’s effects on the building by the end of its life. By contrast, the three recyclable architecture typologies are designed from the beginning to reintegrate the materials into the life cycle in other buildings.

The combination of the strategies also brings some limitations. For example, only the housing modules of the Slab typology can be disassembled since a static and robust structure of prestressing concrete is necessary to support it. The module combination and expansion are also limited by a maximum of six. It is a proposed housing expansion with a maximum of 4 modules to have the maximum use with the least space and avoid corridors. Otherwise, the space becomes too big for singular use. Prototype 2, the Tower, is limited by the tree form due to its structural arrangement. Even if the number of the floors can increase, the difference between floor sizes should be kept the same for the stability of the structure. The structure should also be implemented on large or open sites to increase access to natural light on the lower floors, which may suffer due to the tree shape. To have the maximum use of the floor surface, the biggest floors should host mainly offices or commercial facilities due to the deeper width. The availability of natural light is also a limiting factor for the number of blocks from Prototype 3 that can be grouped to host dwellings. Finally, although the research

was collaborative with the engineers, deeper research needs to be done to select the best connection option for the disassembly of each prototype.

Despite their limitations, the Slab, Tower and Dismountable typologies can be built in many neighbourhoods and 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. These projects can be adapted to the regulations of each region while keeping the same typology. To illustrate, the prototypes’ height can be changed by adding or reducing levels. More staircases can be connected to the Block typology. The dimensions of the Tower building can be expanded proportionally. The number of modules of the Block and the Slab building repetition can be related to the terrain dimensions. Moreover, all three prototypes and concepts are intended to guide other building projects. Prefabrication and modularity can be used to increase the building’s flexibility and disassembly. The design of these three prototypes brings several benefits to the construction field, listed below:

- The design brings more value to the construction and to the life of the residents, providing more communal space inside the buildings. In the Tower prototype, the common areas are localised in the upper and lower floors. In the Slab prototype, the rooftop and corridors are the shared spaces. Moreover, the Block prototype have a public access rooftop, and the ground floors of all Prototypes can serve for public and commercial use. These strategies integrate living, working, and leisure all in the same building.
- The open design enables home expansion according to the needs of the resident. The modules are connected to the main core in the Slab building and can be plugged in and out. In the Tower and Block buildings, the open slabs without walls allow for easy adaptations and changes in the layout. As a result, the floors can be adapted to different uses, e.g. the slabs can accommodate offices or the interior layout can be changed to become housing or vice-versa.
- For all three prototypes, the use of primary resources and waste is reduced by proposing in the earliest stages of architectural design the use of recycled materials and by predicting changes and disassembly that may occur over the useful life of the building.
- To complement the above, the transition of a structure reconfiguration, additions and subtractions through time is facilitated because it is separated from the liming. The housing modules are separated from the Slab infrastructure, and the walls are separated from the Tower and Dismountable bolted structure.
- All prototypes serve as material banks for future building construction, considering that from the beginning, all the elements 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, keeping the loop of materials closed. For example, the Slab housing modules can be placed in other buildings and at the end of the life cycle, their wood can be reused in other structures. Secondly, the Tower’s structure separated from the core can be dismantled and reused since it is built entirely in timber or steel. The prefabricated slabs and walls will also be eligible for relocation. Finally, the Block typology was designed to be entirely dismantlable so beams, pillars,

walls, and slabs can be reused in different constructions.

- Parallel disassembly is allowed to minimise time on site, such as removing modules or prefabricated slabs where parts can be detached later.
- Due to the module multiplication and prefabricated systems, materials and processes are reduced, resulting in saving time and money.
- Mechanical, electrical, and plumbing systems are consolidated into core units to minimise runs and unnecessary entanglement.
- Different materials are proposed according to the structural need and possibilities for disassembly and recycling. Considering that the over-harvesting of materials can negatively impact forests and lead to deforestation in some cases, it is important to prioritise the use of materials that can be recyclable and were already exploited. For example, the old steel structures can be easily remanufactured since the wood from reforestation areas are for this specific purpose and the concrete is recycled from the old structure.

The construction sector has been in the midst of evolving to include deconstruction activities in a more circular and sustainable economy. Essential to this transition are pollutants, inventory of materials for reuse, waste utilisation, and reuse platform research. These topics are being investigated, and policies and regulations have been implemented in Europe and Luxembourg, directed by the Green Deal over the years. Even though the models are generic, possibilities for implementation in the actual context of Luxembourg have been made for each prototype. In addition, some regulations that could support the implementation of these theoretically recyclable prototypes.

As a starting point to include the housing in the program of a city in Luxembourg, there is a new law as of 17 April 2018 concerning spatial planning that is intended to cover the spatial planning policy as defined in the Master Plan for Spatial Planning (PDAT, adopted by decision of the Government in Council on 27 March 2003). The Master Plan reserves areas for priority housing projects, which are given a right of preference to the State and municipalities interested in purchasing land which will be used to create new housing, partially or totally built by public promoters, and a high percentage of the buildings supposedly dedicated to rental or low-cost housing. These areas assume an urbanisation density of 40 housing units per gross hectare, which will help reduce the supply shortage in the housing market⁵³⁷. In addition to that, the land once owned by the state can have buildings built for specific periods, which promotes the use of dismountable structures. For the design phase, the general provisions of “*Prescriptions de prévention incendie DISPOSITIONS GENERALES Bâtiments élevés- ITM-SST 1503.4*” establish the minimum conditions that must be met by the design, construction and layout of any building in order to prevent fire, ensure the safety of people and facilitate the intervention of the emergency services in a preventive manner⁵³⁸. After the life cycle of the building, or if the building is not needed anymore at the same place, it can be dismantled and reassembled in another location. For this phase, the Luxembourg amended a law on 21 March 2012 on waste management

537 Aménagement du territoire 2018.

538 Service des établissements soumis à autorisation (ESA) de l'Inspection du travail et des mines 2017.

which requires that the prevention, reuse and recycling of construction and demolition of waste be promoted in accordance with the waste hierarchy⁵³⁹. The following waste hierarchy applies in order of priority in waste prevention and management legislation and policy: prevention; preparing for reuse; recycling; any other recovery, including energy recovery; and disposal⁵⁴⁰. This Act aims to establish measures to protect the environment and human health by preventing or reducing the adverse effects of the generation and management of waste. It is also intended to reduce the overall impact of resource use and improve the efficiency of resource use⁵⁴¹. The legislation also requires that an inventory of building materials be compiled during the dismantling of a building for resource management and presented to the Environmental Administration (AEV) upon request. This promotes the separate collection of building materials and their efficient use as resources in Luxembourg⁵⁴².

To summarise, this study has shown that the total environment matters by considering the fundamental aspect of sustainable living rather than just volume and site. It is possible to develop numerous dwelling types with their corresponding internal space compositions while creating various volumes. The prototypes have the capacities to be in a continuous evolution from one state to another. They are complete but always transitioning to adapt to the users' needs. The design methodology focused on user flexibility and recyclability while improving residential prefabrication to address the housing shortage and ecological issues. It also shows that it is possible to design high quality architecture while being recyclable. So over time, the city can change, piece by piece, transforming individual lands with the new recyclable typologies to give a new perspective of the city.

The circularity in the Slab, Tower and Block typologies can be seen from the first stage of design. The difference between the traditional way of design thinking⁵⁴³ and the improved design process is shown in Figure 3.111 (a)⁵⁴⁴ and (b). The architectural strategies that were combined and worked together in the three prototypes at the same time were: repetition, exposed structure, central core, terrace, open floors, unfinished spaces, prefabrication, area multi-use with private, shared, and public space, combined room activities, have reduced housing unit size, offer different apartment sizes, have retractable/sliding walls, have some level of disassembly and densify the region that is implemented. The goal was to include the disassembly, reuse and recyclable concepts in the design process. From the beginning, the typologies were thought to be entirely recyclable and parts to be disassembled to decrease energy and resource use along its entire life cycle. The infrastructures were designed to be as open as possible, exposed, and with raw materials to minimise the use of primary resources offering different uses on the same site. Accordingly, the main idea of Circular Architecture is achieved by using the proposed typologies. The Circular Architecture concept is defined as modular construction with the ability to be disassembled and allows for functional flexibility

539 LIST 2018.

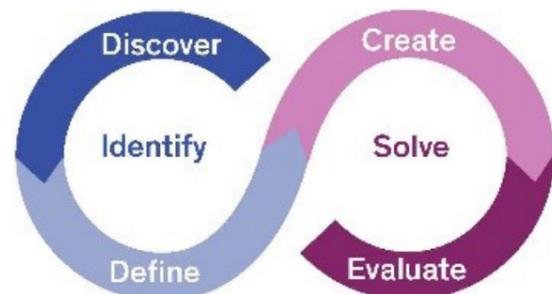
540 Legilux 2012.

541 Ibid.

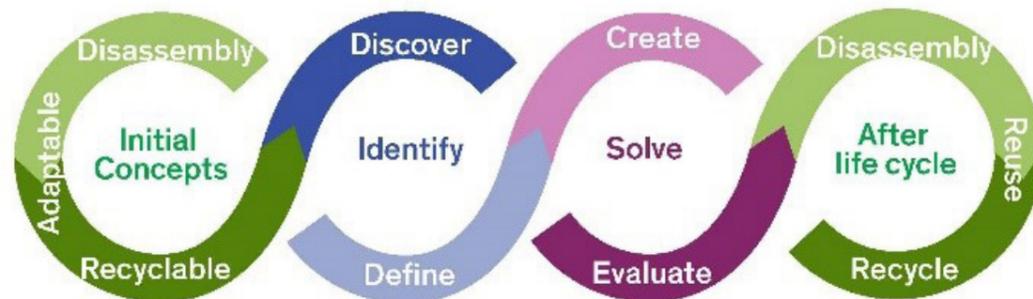
542 LIST 2018.

543 Griffin et al. 2015.

544 Ibid.



A – traditional design thinking ⁷²⁹



B – Updated architectural design process

Figure 3.111: Diagrams of the design process

through time, which also offer reusability and recyclability of materials and space by the end of its life while integrating public and shared spaces according to the needs of society. A circular architecture with reusable and recyclable solutions bring benefits to building product manufacturers, architects, builders, developers, investors, building owners and individual owners/tenants in terms of flexibility of use, harmonisation of systems and structures with other buildings, reduced operating costs, increased asset value and improved building quality. Most importantly, they improve the possibility and facilitation of building deconstruction and reconstruction, recyclability, waste minimisation and energy saving when materials from one building can be reused to build new buildings — reducing environmental impacts throughout the life cycle.

To conclude, despite the challenges of developing generic prototypes proposed by the ECON4SD project, the main research question, “What kind of building design/typology allows architectural cycles?”, was met by developing three different generic architectural typologies, identifying and combining strategies to reuse and recycle buildings, and showing their specific characteristics. In other words, generic models were designed to provide flexibility through time, adaptation for different uses and users, and be easily deconstructed and reconstructed. To ensure the reusability of space and materials, different use scenarios were proposed, and the number of materials and superficies were quantified for future use. During the research process, the results were presented in conferences and exhibitions, and published in multidisciplinary projects, scientific journals and books, as shown in Chapter 4 – Deliverables.

CHAPTER 4. DELIVERABLES

This chapter presents a list of activities, exhibitions and publications of the results during the doctoral period. In addition, the University of Luxembourg required 20 ECTS to fulfil the requirements of the Doctoral Programme in Humanities and Social Sciences (DSHSS). In total, 27 ECTS were validated, the official document can be seen in Appendix C.

4.1. Exhibitions

16 Biennale de Architecture in Venice

Beyond the research, the Slab and Tower Typologies concepts were exposed in the Luxembourg Pavillion during the 16 Biennale de Architecture in Venice, entitled "Freespace." The Luxembourg Pavilion exhibition entitled "The Architecture of the Common Ground" elevated buildings that allow the land to remain open, both physically and symbolically, Figure 4.1. Various projects from the history of ideas engage with contemporary experiments that share the aspiration of making the land accessible to public uses. They are resisting an alleged logic that has led to almost universal privatisation of land in cities, creating isolated enclaves and reducing the public sphere. Freespace, the theme for 2018 Biennale Architettura, has been transformed into Freeland. Thus, architecture's social and political dimension is linked to its creative power. In this context, the new prototypes developed at the core of ECON4SD embrace the same idea once being designed with a reduced structure on the ground floor, giving back the space to the city and the public. Figure 4.2 and Figure 4.3 are the images from the Slab typology, and Figure 4.4 and Figure 4.5 are from the timber Tower during the exposition.

Eise Buedem Exhibition

More detailed models were developed of Prototype 1 Slab typology to be exposed at the Eise Buedem Exhibition with the previous Luxembourg Pavilion from the 2018 Venice Biennale. The question of soil is at the heart of our time's social and ecological challenges. To inaugurate LUCA's new premises, the exhibition was complemented by a panorama of positions on the question of soil in Luxembourg and by the confrontation of more recent architectural experiments carried out by the University of Luxembourg. Figures 4.6 to Figure 4.9 shows the modules exposed on the circular configuration, showing the reusability process from the land, prefabricated components (scale 1/20) used to build housing units (scale 1/20) that can be plugged into the infrastructure (scale 1/100). This infrastructure with the modules is arranged in linear and courtyard configuration (scale 1/200). After that, the process is inverse, and the modules are plugged out of the infrastructure and disassembled. The components and the land remain for future reuse. As seen previously, the concept of the Slab building was developed within the ECON4SD project, and the exposed physical models were made by Marielle Ferreira Silva, Diogo Gomes Costa, Simona Popova, Diana Valentina Zarnescu.

4.2. Scientific journal

A scientific article was written and published in the Special Issue of the Sustainability journal entitled “Recyclable Architecture: Prefabricated and Recyclable Typologies”. The paper briefly examined prefabricated and recyclable buildings in architecture and proposed the three typologies developed during the ECON4SD research project.

Journal Paper - February 2020: MDPI - Ferreira Silva, M.; Jayasinghe, L.B.; Waldmann, D.; Hertweck, F. Recyclable Architecture: Prefabricated and Recyclable Typologies. Sustainability 2020, 12, 1342. - Special Issue “Recent Progresses and New Strategies on Recycled Materials and Reused Components for Sustainable Civil Infrastructures”

4.3. Book Chapter

The scientific article published in the Special Issue of the Sustainability journal entitled “Recyclable Architecture: Prefabricated and Recyclable Typologies” was included as an E-book Chapter at Prime Archives in Sustainability. Hyderabad, India: Vide Leaf. 2020. Ferreira Silva, M.; Jayasinghe, L.B.; Waldmann, D.; Hertweck, F. Recyclable Architecture: Prefabricated and Recyclable Typologies. Sustainability 2020, 12, 1342. <https://doi.org/10.3390/su12041342>.

4.4. Conference presentations

Eco-Architecture 2018

A presentation entitled “Models for Reuse and Recycling of Architecture” was given at the Eco-Architecture 2018 – 7th International Conference on Harmonisation between Architecture and Nature. 2-4 October 2018, New Forest, UK. The Wessex Institute, UK organised the Conference. The first concepts of the three prototypes were presented.

Beyond2020 2020

Two papers were submitted and presented online at Beyond2020 Conference in Gothenburg, Sweden, 9-11 June 2020. Unfortunately, due to the COVID-19 pandemic, the conference was postponed and shifted to online attendance and presentation 2-4 November 2020. The first paper written, entitled “Another way of living: The Prefabrication and modularity towards circularity in the architecture,” presented in more detail the Prototype 1 Slab typology. The second one as a co-author entitled “Designing of the module envelope of a hybrid modular building to meet the passive house standards in Luxembourg” in collaboration with Michael Rakotonjanahary, a member of the ECON4SD project.

Marielle Ferreira Silva. 2020. Another way of living: The Prefabrication and modularity towards circularity in the architecture. IOP Conf. Ser.: Earth Environ. Sci. 588 042048 IOP Conference Series: Earth and Environmental Science - Volume 588, 1.11 – 1.14

Rakotonjanahary, M., Silva, M.F., Scholzen, F., Diederich-Waldmann, D., 2020. Designing of the module envelope of a hybrid modular building to meet the passive house standards in Luxembourg. IOP Conf. Ser.: Earth Environ. Sci.

588, 052026. <https://doi.org/10.1088/1755-1315/588/5/052026>

CiBEn 2021

In cooperation between 3 PhD of ECON4SD, the postdoc and professors, a paper was written, reviewed and selected to present at the “2nd International Conference On Circularity In The Built Environment” on 24-26 November 2021. However, the conference was postponed after our project’s end due to the pandemic situation and finally cancelled.

Marielle Ferreira Silva, Hooman ESLAMI, Jovan FODOR, Daniele Waldmann, Florian Hertweck, Markus Schäfer, Laddu Bhagya Jayasinghe. Demountable Building: Architectural Typology And Structural Floor System. 2nd International Conference On Circularity In The Built Environment, 24-26 November 2021

4.5. Presentation to the Ministry of Housing au Luxembourg

An A4 paper file with more information and diagrams of both prototypes was prepared and presented to the Ministry of Housing au Luxembourg. After that meeting, more information about the Slab building and detailed physical models was prepared and presented to Diane Dupont, head of Fond du Logement au Luxembourg at that time. She was interested in the project, which led us to a third presentation at Fond du Logement with Dirk Kintzinger and Jacques Vandivinit. The physical models and plans of Slab typology were presented.

Slab Prototype Presentation: Fonds du Logement to Diane Dupont at the University of Luxembourg in October 2019.

Slab Prototype Presentation: Fonds du Logement to Dirk Kintzinger and Jacques Vandivinit at Fonds du Logement on 11 February 2020.

4.6. Workshop

Creating Homes for Tomorrow 2020

The participation in the workshop Creating Homes for Tomorrow – Helsinki - 14/09—3/10/2020 and Kyiv 2/11—21/11/2020 was online due to the covid19 pandemic. The workshop was organised by CANactions School. New housing strategies were developed for each city regarding globally relevant questions, considering spatial, economic, social and political measures.

4.7. Participation in Projects

COST Action RESTORE

The participation was made as part of the Management Committee member representing Luxembourg with Antonino MARVUGLIA. The RESTORE Action aimed to discuss the paradigm shift towards restorative sustainability for new and existing buildings across Europe, promoting forward thinking and multidisciplinary knowledge through the design creativity while enhancing users’ experience, comfort, health, well-being, and satisfaction inside and outside buildings, and in harmony with urban and natural ecosystems, reconnecting users to nature. Three chapters for working group

Final Books, and one scientific book chapter was written as co-author. They are listed below:

Haselsteiner, E., Ferreira Silva, M., Kordej-De Villa, Ž. (2021). Climatic, Cultural, Behavioural and Technical Influences on the Indoor Environment Quality and Their Relevance for a Regenerative Future. In: Andreucci, M.B., Marvuglia, A., Baltov, M., Hansen, P. (eds) Rethinking Sustainability Towards a Regenerative Economy . Future City, vol 15. Springer, Cham. https://doi.org/10.1007/978-3-030-71819-0_10

Edeltraud Haselsteiner, Zeljka Kordej-De Villa, Diana Kopeva, Nikolay Sterev, Marielle Ferreira Silva, 2021. The Impact Of Climate And Socio-Cultural Elements On Regenerative Parameters And User Expectations. Cost Action RESTORE. WG4 Final-Book Regenerative technologies for the indoor environment: Inspirational guidelines for practitioners. EDITORS Roberto Lollini, Wilmer Pasut.

Calas, D., Haselsteine, E., Ferreira Silva, M., González, A., Giancola, E., Mihaela, H., KAMROWSKA-ZALUS, D., Soutullo, S., 2021. Small Urban Hacks - Big Impact! Tackling Major Urban Challenges Through Acupunctural Smallness. Cost Action RESTORE. WG5 Final-Book Scale-Jumping.

Clarice BLEIL DE SOUZA, Gulben CALIS, Marielle FERREIRA SILVA, Cristina JIMÉNEZ-PULIDO, Gerald LEINDECKER, Antonino MARVUGLIA, Hanna OBRACHT-PRONDZYŃSKA, Aleksandar PETROVSKI, 2021. Smart Technologies in the Context of Regenerative Design - IoT, (Big) Data, AI, Digital Twin. Cost Action RESTORE. WG5 Final-Book Scale-Jumping.

Luxembourg in transition (LIT) project

The Prototypes were included in the interdisciplinary competition/project Luxembourg in transition (LIT) project – 2020-2022. LiT is a process that encourages multidisciplinary teams from diverse backgrounds to a new transitional and resilient approach to spatial planning. The interdisciplinary team “Luxembourg 2050 – Prospects for a Regenerative City-Landscape”, is composed of researchers, planners and practitioners from the University of Luxembourg (UL), the Luxembourg Institute of Science and Technology (LIST), the Centre for Ecological Learning (CELL), the Institute for Organic Agriculture (IBLA), and the Office for Landscape Morphology (OLM), focused on five most pertinent and closely intertwined topics: agroecology, regenerative energy systems, alternative economies, and governance/participation-processes, in addition to regional planning, urban planning, and design, and architecture. Hypothesis lies in the elaboration of small-scale urban structures and hybrid architectural structures, through which different uses, as well as built and unbuilt areas, could be spatially brought together and designed in such a way that they remain flexible and can be adapted to the changing needs of new forms of cooperation and living together. The Slab, Tower, and Block typologies were presented in the second phase of the LiT project. Figure 4.10 and Figure 4.11 show the Towers implementation and street section in Foetz. Figure 4.12 shows the Slab building section in Route d’Arlon, with the transition throughout the time. Figure 4.13 and Figure 4.14 show the implementation of the Block structure in the parking space

of Belle Etoile in the 2nd phase of the project. The situation plan in Figure 4.15 and sections in Figure 4.16, Figure 4.17 and Figure 4.18 show the transition scenarios for the Demountable structure in Foetz for the 3rd phase of the project. Next to the road, a series of reusable and dismountable structures will be built to concentrate the parked cars of the site and introduce a multimodal sharing car and bike system. When the tram arrives on the site, and the number of cars is significantly reduced, the structure — designed and constructed for a multiuse — will host other activities such as public amenities, working facilities and even housing instead of cars.

4.8. Teaching

Organisation and teaching of the Smart & Circular Cities course with 24 Teaching Units spread across 6 dates offered by the Master of Architecture in the University of Luxembourg, in 2018 and 2020. By teaching, I can improve my knowledge about smart and circular cities and, at the same time, it allows me to put into practice the knowledge acquired during my training and to pass it on to my students.

Course Description: In response to a linear economy, a circular economy aims to dissociate growth from the consumption of finite resources creating the conditions for regeneration by design. A circular city includes a built environment that is shared and flexible design, improving the life quality of the residences, and minimise virgin material use. The large and small districts are proposing a new city model called “the smart city,” in other words, technological, interconnected, sustainable, comfortable, attractive and safe cities. This course aims to introduce students to significant concepts for smart and circular cities, and recyclable buildings, and the analysis and discussion of the solutions adopted in the cities.

Course learning outcomes: the students will learn the concepts of smart and circular cities and find out how technology can be applied. Identify and evaluate cities that already have this concept or development.



Figure 4.1. The Architecture of the Common Ground / Luxembourg Pavilion at the 16th International Architecture Exhibition of La Biennale di Venezia



Figure 4.2. Slab typology in exposition at The Architecture of the Common Ground / Luxembourg Pavilion at the 16th International Architecture Exhibition of La Biennale di Venezia



Figure 4.3. Slab typology exposed at The Architecture of the Common Ground / Luxembourg Pavilion at the 16th International Architecture Exhibition of La Biennale di Venezia



Figure 4.4. Tower typology in exposition at The Architecture of the Common Ground / Luxembourg Pavilion at the 16th International Architecture Exhibition of La Biennale di Venezia



Figure 4.5. The Architecture of the Common Ground / Luxembourg Pavilion at the 16th International Architecture Exhibition of La Biennale di Venezia



Figure 4.6. Prototype 1- Slab typology models at Eise Buedem Exhibition 2022



Figure 4.7. Prototype 1- Slab typology models at Eise Buedem Exhibition 2022



Figure 4.6. Prototype 1- Slab typology models at Eise Buedem Exhibition 2022



Figure 4.6. Prototype 1- Slab typology models at Eise Buedem Exhibition 2022



Figure 4.8. Prototype 1- Slab typology on the left from 2018 Luxembourg Pavillion from Venice Biennial at Eise Buedem Exhibition 2022



Figure 4.9. Prototype 1- Slab typology on the right from 2018 Luxembourg Pavillion from Venice Biennial at Eise Buedem Exhibition 2022



Figure 4.10. LiT project - 2nd phase - Tower placement in Foetz

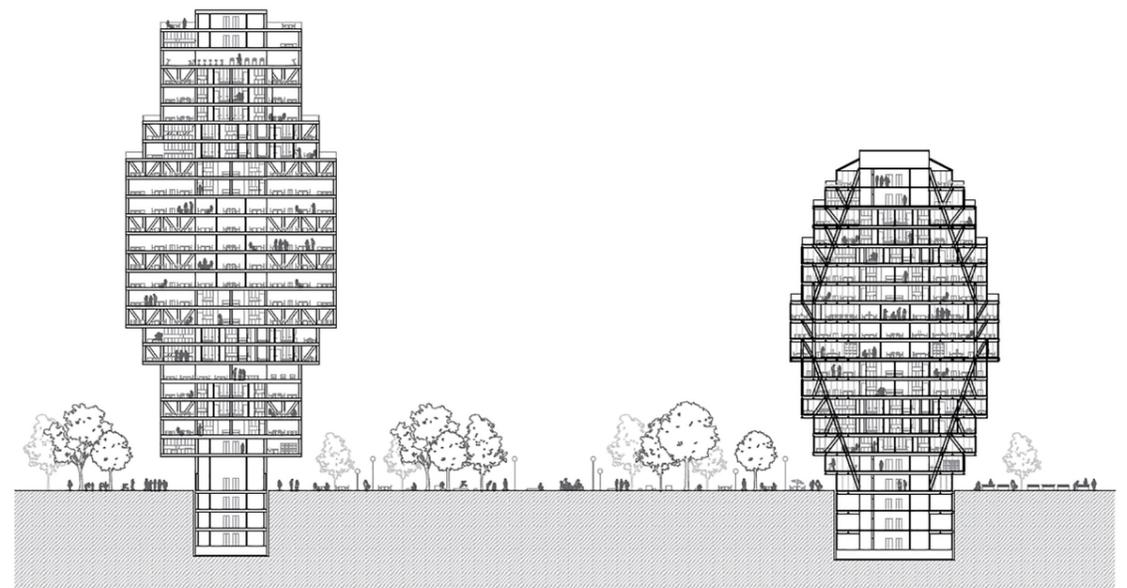


Figure 4.11. LiT project - 2nd phase - Tower section in Foetz

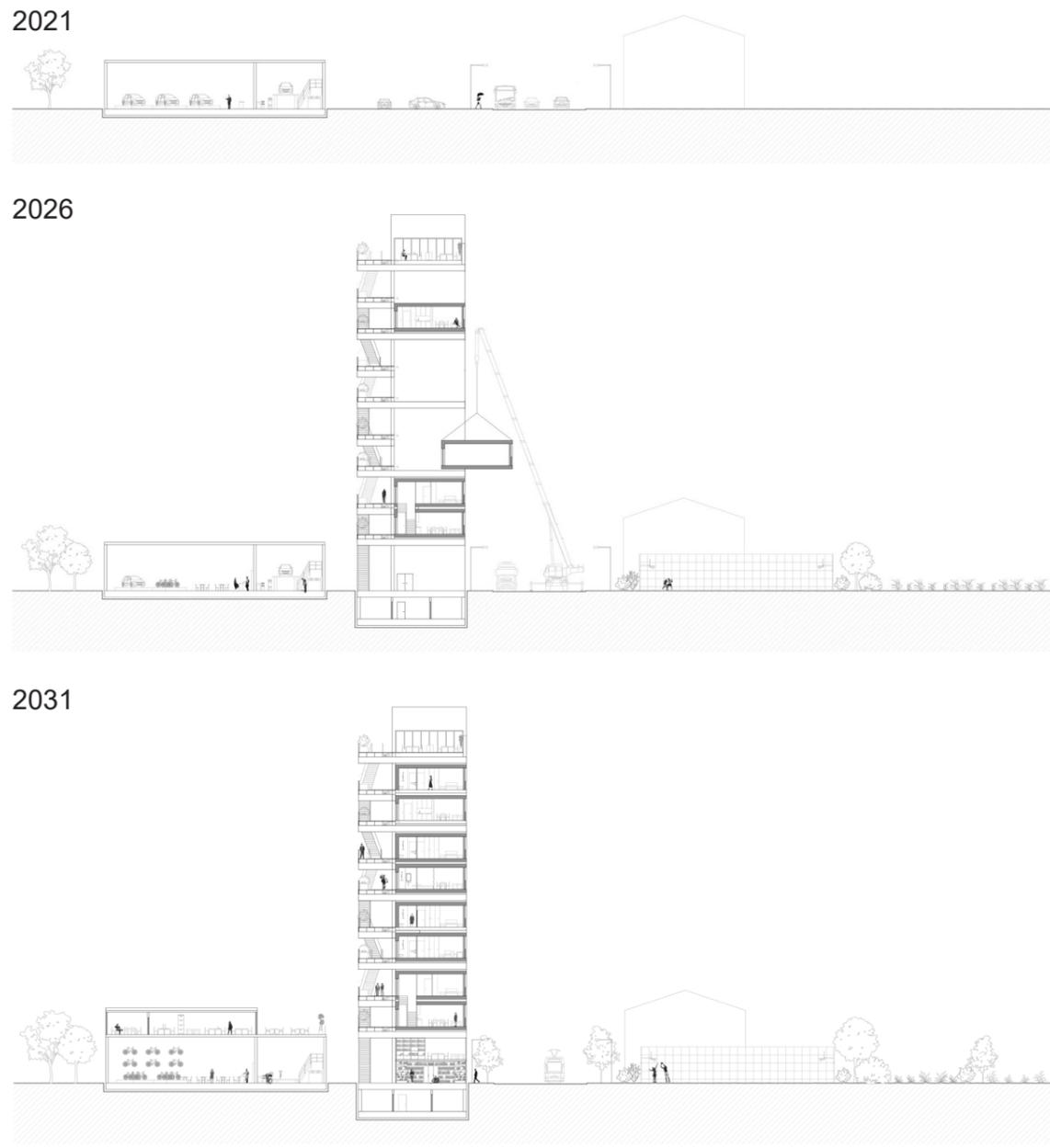


Figure 4.12 . LiT project - 2nd phase - Slab sections in transition Route d'Arlon

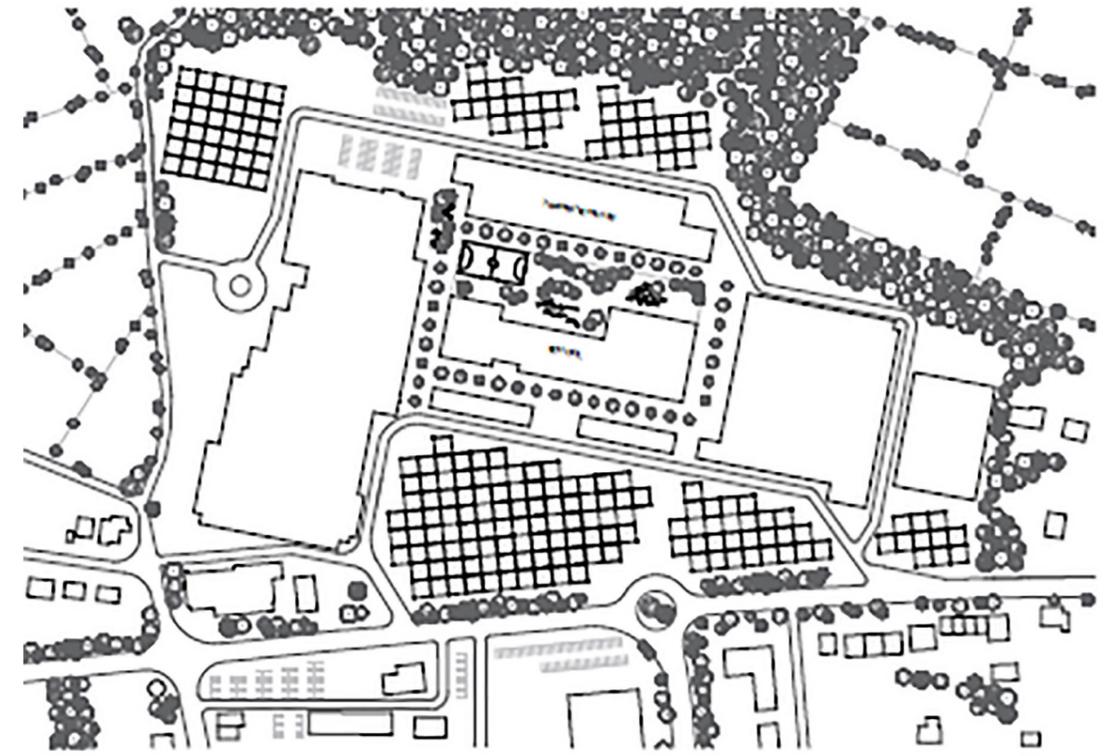


Figure 4.13 . LiT project - 2nd phase - Demountable placement in the car parking of Belle Etoile, Route d'Arlon

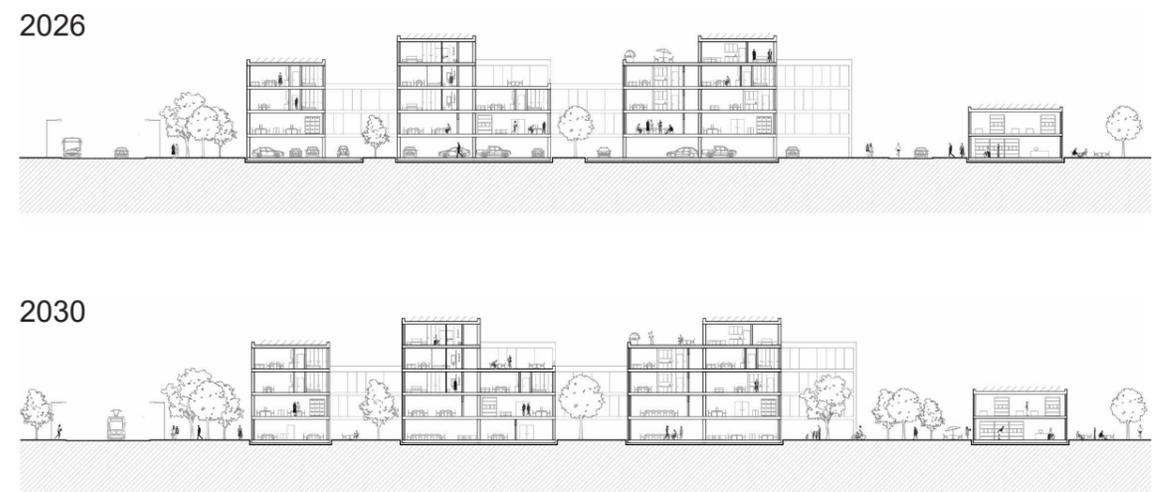


Figure 4.14 . LiT project - 2nd phase - Demountable sections in transition Route d'Arlon



Figure 4.15 . LiT project - 3rd phase - Demountable structures placement in Foezt



Figure 4.17. LiT project - 3rd phase - Demountable typology - prototype 3, parking and offices- Drawings Transition



Figure 4.16. LiT project - 3rd phase - Demountable typology - prototype 3, parking - Drawings Transition

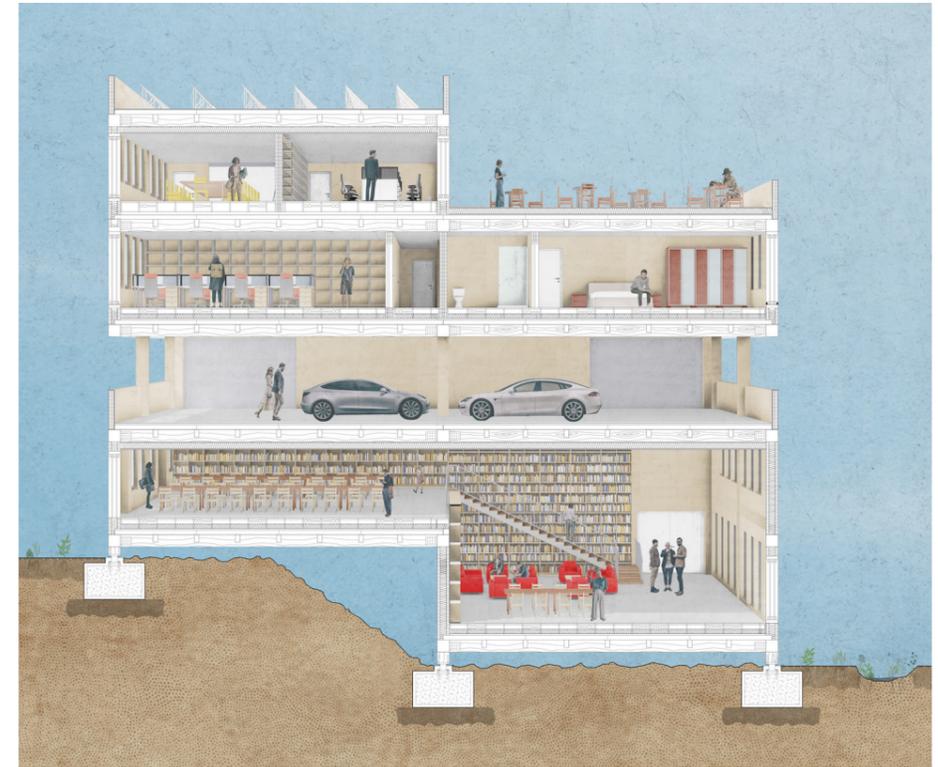


Figure 4.18. LiT project - 3rd phase - Demountable typology - prototype 3, mix uses- Drawings Transition

CHAPTER 5. CONCLUSION

This doctoral thesis was developed during four and a half years in Luxembourg. Over the years, a new perspective on how architecture should be has been created and revised at every research step. This thesis is also a part of the multidisciplinary project ECON4SD. As a project, generical objectives were already predefined, which shaped the whole study and made prototypes' practical development more intense. The collaboration and exchange among the group were essential to constantly receive feedback and align the thesis research questions with the project's objectives while motivating me to push further the boundaries of my knowledge. In addition, the participation in internal and external projects, conferences and workshops was crucial and helped me find my way through so many options and enriched my education. At the same time, the world passed through a pandemic situation where everyone saw themselves locked in their houses. This experience changed and will keep changing the way in which architects design. The housing question beyond the design for today's needs should predict future needs, the interaction between the built environment, people and nature, and ensure the continuation of a healthy world and future for new generations.

This thesis focused on studying the potential of architecture to reconfigure, temporarily and spatially, and produce alternative generic models that reuse and recycle resources. Consequently, the research was complex and non-linear, learning from the past and testing new prototypes. This thesis begins with a broad overview of the world scenario related to resource scarcity, climate change, the social challenges of population growth and housing shortages, ecological trends in architecture, and the challenges of Luxembourg society. This review helped to understand the aspects that can impact the physical world that should be considered when designing a building and that, at the same time, will protect nature and sustain future generations. The way we live our lives, design and build the buildings, the quantity of materials, and how we use them has a massive impact on the environment. Furthermore, the increased demand for affordable housing due to population growth and immigration also impacts nature and challenges Luxembourg society and other countries. Therefore, to reduce the environmental impact, a building should be designed and built to accommodate the future generation only if it is essential and where the population will continue to grow. Therefore, the new buildings should use the minimum quantity of energy and materials, have recycled materials to reduce waste and exposed structure to facilitate the layout rearrangement and disassembling for future reuse, and have a reduced footprint in terms of ground floor area and CO₂ emission. At the same time, offer optimal size and comfortable housing units with public and shared space in the same infrastructure to promote leisure and integration between the users and the city. From this perspective, this research incorporates aspects of circularity, reducing, reusing and recycling materials and spaces from the first design phase of an architectural project.

This research contributes to the current knowledge by providing an insight into modular, prefabricated and ecological typologies and provides a list of architectural strategies that can be combined towards circular, reusable and recyclable architecture. The review and solution are presented in the Atlas. From Durand until today, many architects and designers have offered building solutions for sustainability, modularisation and

prefabrication over time, but not necessarily to be dismantlable and recycled with different life cycles. The modularity can make the construction more rational and bring organisation, facilitating the implementation of prefabricated elements and disassembling. Combining it with ecological strategies can improve the adaptability and reuse of the space while minimising carbon emissions, shaping our future.

The thesis demonstrates how the three new alternative generic prefabricated building typologies were designed that allow architecture cycles through time and how the spaces can be reusable as much as possible before being disassembled for future material reuse and/or recycling, due to social mutation and by answering the research questions. The thesis also presents an optimal size for living space with modular housing units and different arrangements according to the number of family members, combined with public and shared space. Fourteen of the thirty architectural strategies brought from the atlas were combined instantly and worked together in the three different prototypes and can be used in other projects: repetition, exposed structure, central core, terrace, open floors, unfinished spaces, prefabrication, area multi-use with private, shared and public space, combine room activities, have reduced housing unit size, offer different apartment sizes, have retractable/sliding walls, have some level of disassembly, and densify the region that is implemented. The results of this thesis, such as the prototypes, serve as a guideline for further projects and benefit architects, designers, policy makers, clients, developers, and the construction industry in their decision-making or selection of recyclable design strategies.

This research contributes to the change in architectural design thinking as there is a high interest in producing new recyclable materials, waste management processes, and more energy-efficient methods. The new, innovative, reusable and recyclable prototypes evidenced the feasibility of combining architectural design strategies enriching the construction field. Furthermore, the concepts of mutable, reusable and non-permanent architecture to the first architectural design stage were taken into consideration. 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, and offer large-scale structures with flexible and adaptable uses that combine individual housing with community activities and a variety of modular and prefabricated construction types. Since technology is no longer a problem nowadays to provide a wholly dismantlable and recyclable architectural design, the concepts presented can be easily adapted to future requirements. In addition to these new typologies, population density can be increased while maintaining a sense of community in the heart of the city. Their design, modularity and prefabrication can be accounted for building deconstruction and reconstruction, waste minimisation and energy savings during the manufacturing process, recyclability, and materials processed from old buildings for reuse in new buildings. From the beginning, each model considered development with the material bank, a repository, or reserves of materials to be reused. The development of the three new typologies shows that architectural production can be diverse and vary with prefabrication and modularity in the residential high-rise production. This type of design and adaptable architecture have less impact on the environment than the traditional way of design and construction while providing spaces for social integration. As creators, we must accept that the future will have a different way of living in a temporary, recyclable and circular world.

Based on these conclusions, practitioners should consider the execution phase to guarantee the disassembling of the structure. Therefore, further research is needed to determine the specific structure and components connections. In addition, to better understand the implications of LCA and the selection of materials, future studies could address the LCA methodology to have a clearer approach method for evaluating the carbon emissions from the first phase of architecture design.

To finalise, during my doctoral research, I expanded my knowledge and concepts about ecological, sustainable, green, smart and circular architecture, which made me get to know more architects and their projects. I could better understand how the partnership between architecture and engineering should be made and is essential for developing better architecture. I improved my abilities to be more critical of other research and present my ideas to different audiences. I improved my design project process and physical model skills. By teaching the subject “Smart and Circular Cities” for the master in architecture at the University of Luxembourg and worked in the “Luxembourg Pavillion on 16th Bienal of Architecture exposition” and “Luxembourg in Transition” project, I broadened my knowledge about the social and city scenario and problems, and how circular architecture could be part of the solution, testing prototypes implementation in the context of Luxembourg. Accordingly, I gained more confidence and expertise in sustainability, reusability, recycling and circularity in the architectural and construction field.

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- The section was done in a collaboration between Marielle Ferreira Silva, Tahiana Roland Michaél Rakotonjanahary and Laddu Bhagya Jayasinghe - © UL/ECON4SD. 2021.
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APPENDIX A

Table 2.3. Dimensions of the apartments and building from the cases studies presented at the Atlas

Atlas Case studies		Floor / building / apartment	Grid or Module size (m)			Housing/Apartment internal dimensions (m)					Building external dimensions (m)			
			Length	Width	Height	Length	Width	Height	Floor area	Total area	Length	Width	Height	
M o d u l a r b u i l d i n g s	1	Narkomfin, Moisei Ginzburg and Ignatius Milinis, Russia, 1928	1° floor	8	3.75	2.6	9.45	3.45	2.3	32.6	37.92	82.35	10.1	18.75
		2° floor	8	3.75	2.6	1.95	2.3	2.3	5.315					
	2	L'unité d'Habitation, Cité radieuse, Le Corbusier, France, 1945 – 1952	1° floor	4.2	3.66	2.26	23.6	3.36	2.26	79.3	98.11	24	140	56
			2° floor	4.2	3.66	2.26	5.6	3.36	2.26	18.82				
	3	860-880 Lake Shore Drive, Mies van der Rohe, US, 1948-1951	860	6.4	6.4	3.1	16.1	9.7	2.7	156.2	156.2	32.5	19.7	86.6
			880	6.4	6.4	3.1	9.7	6.3	2.7	61.11	61.11	32.5	19.7	86.6
	4	Le Cabanon, Le Courbusier, France, 1951	house	3.66	3.66	2.26	3.66	3.66	2.26	13.4	13.4	4.6	3.9	4.33
	5	The Halen Estate, Atelier 5, Switzerland, 1955-1961 - type 380	1° floor	14.45	5	2.3	11.86	4.8	2.3	56.93	181.8	14.45	5.3	8.8
			2° floor	14.45	5	2.3	14.15	4.8	2.3	67.92				
			3° floor	14.45	5	2.3	11.86	4.8	2.3	56.93				
6	Harumi Apartment House, Kunio Maekawa, Japan, 1956 – 1958	1°/3° floor	5	3.15	-	7	3	-	21	21	78	7.4	-	
		2° floor	5	3.15	-	5	3	-	15	15				
7	Robin Hood Garden, Alison and Peter Smithson, England, 1968-1972	1° floor	11	2.7	2.55	7.2	5.6	2.7	40.32	99.68	160	11	20.45	
		2° floor	11	2.7	2.55	10.6	5.6	2.7	59.36					
8	Nine-Square Grid House, Shigeru Ban, Japan, 1997	house	3.4	3.4	3	10	10	2.4	100	100	11.8	11.8	3	
9	Gifu Kitagata Apartments, Kazuyo Sejima, Ryue Nishizawa, and Koichiro Tokimori, Japan, 1994-2000	one unit x 6	5.9	2.8	2.5	5.7	2.5	2.3	14.25	85.5	130	7.2	25	
10	Quinta Monroy, Alejandro Aravena, ELEMENTAL, Chile, 2001-2004	Type 1	5.9	3	2.6	5.8	8.86	2.2	51.39	51.39	18.14	6	7.46	
		Type 2	5.9	3	2.6	5.8	2.95	2.2	17.11	34.22				
			5.9	3	2.6	5.8	2.95	2.2	17.11					
P r e b u i l d i n g s	11	Pavillon 8x8 Housing packed, Jean Prouvé, 1947	house	8	8	3	7.8	7.8	3	60.84	60.84	8	8	3.6
	12	Habitat 67, Moshe Safdie, Canada, 1967	module	11.7	5.3	2.6	11.4	5	2.27	57	57	306.8	62.4	42
	13	Nakagin Capsule Tower, Kisho Kurokawa, Japan, 1968-1972	module	4	2.5	2.5	3.7	2.2	2.2	8.14	8.14	24	14	54
	14	Yacht House, Richard Horden/ Horden Cherry/ Lee Architects, UK – 1983-1992	house	3.7	3.7	3	18.5	18.5	3	342.3	342.3	18.5	18.5	3
	15	Stars apartments, Michael Maltzan Architecture, US, 2014	apartment	9	3.5	-	8.8	3.3	-	29.04	29.04	51	48.5	-
E c o l o g i c a l b u i l d i n g s	16	Ökohäuser, Frei Otto, Germany, 1987-1990	open floor	7.5	9	6	16	13	2.6	208	208	28	16	18
	17	029 Apartment Building, Herzog & de Meuron, Switzerland, 1987-1988	small apartment	5.4	3	-	10.25	6	-	61.5	61.5	34.1	8.8	-
	18	R128, Werner Sobek, Germany, 1998-2000	one floor x 4	3.85	2.9	2.8	8.7	7.7	2.7	66.99	234.5	9.4	8.4	11.2
	19	M-vironments / M-house, Michael Jantzen, 2000	1° floor x 6	3.6	3.6	3.6	3.4	3.4	3.4	69.36	80.92	18.2	7.4	7.4
			2° floor	3.6	3.6	3.6	3.4	3.4	3.4	11.56				
	20	R50 cohousing, Ifau und Jesko Fezer Heide and Von Beckerath, Germany, 2010–2013	regular apartment	6.15	7.8	3	15.85	7.6	2.6	120.5	120.5	26.8	18	23.2
	21	NEST-Unit Urban Mining & Recycling (UMAR), Werner Sobek, Dirk E. Hebel and Felix Heisel, Switzerland, 2015-2017	module	4.8	3.75	3.53	14.4	4.3	2.5	61.92	61.92	30.8	27.3	20
22	Kajstaden Tall Timber Building, C.F. Møller, Martinsons & Slättö Förvaltning, Sweden 2016 – 2019	small apartment	12.9	4.8	2.9	8.6	4.9	2.4	42.14	42.14	20.45	12.9	31	

APPENDIX B

Table 3.10. INIES data and calculation for wood block

				Climate Change (kg CO2 eq.)											
				Database INIES					Calculation						
				Production	Construction	Use	End-of-life	Total life cycle	Production	Construction	Use	End-of-life	Total life cycle	Lifetime reference	50 years
Element	Material specification	Unit	Lifetime reference	Production	Construction	Use	End-of-life	Total life cycle	Production	Construction	Use	End-of-life	Total life cycle	Total life cycle	Total life cycle
Pilars	Poutre en Douglas lamellé-collé avec aubier, traitée (v.1.4)	m3	100	-660.00	28.50	0.00	683.00	51.90	-1436.16	62.02	0.00	1486.21	112.93	112.93	112.93
Beams long	Poutre en Douglas lamellé-collé avec aubier, traitée (v.1.4)	m3	100	-660.00	28.50	0.00	683.00	51.90	-4730.88	204.29	0.00	4895.74	372.02	372.02	372.02
Beams short	Poutre en Douglas lamellé-collé avec aubier, traitée (v.1.4)	m3	100	-660.00	28.50	0.00	683.00	51.90	-4392.96	189.70	0.00	4546.05	345.45	345.45	345.45
Floor	Panneau contrecollé KLH en bois massif (v.1.1)	m2	100	-82.50	8.33	0.00	79.00	4.84	-10348.80	1044.92	607.13	9909.76	607.13	607.13	607.13
Ceiling	Panneau contrecollé KLH en bois massif (v.1.1)	m2	100	-82.50	8.33	0.00	79.00	4.84	-10348.80	1044.92	607.13	9909.76	607.13	607.13	607.13
Walls exterior -full	Mur à ossature bois Logiwall / Logiskin	m2	50	0.30	3.33	0.00	38.20	41.80	18.91	207.79	0.00	2383.68	2608.32	2608.32	5216.64
Walls exterior - with door	Mur à ossature bois Logiwall / Logiskin	m2	50	0.30	3.33	0.00	38.20	41.80	8.44	92.71	0.00	1063.49	1163.71	1163.71	2327.42
Walls exterior -full window	Mur rideau et verrière mixte bois aluminium [Gestion durable] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.2)	m2	30	632.00	46.10	0.00	15.40	693.00	19718.40	1438.32	0.00	480.48	21621.60	43243.20	86486.40
Door	Bloc-porte isolant sur huisserie bois (v.1.1)	m2	30	20.80	1.09	0.00	1.62	23.50	69.89	3.66	0.00	5.44	78.96	157.92	315.84
Total				-1491.59	156.01	0.00	2300.42	965.48	-11441.97	4288.31	1214.26	34680.61	27517.25	49217.81	96390.96
Total (kg CO2 eq.) Per m2													219.37	392.36	768.42

Table 3.11. INIES data and calculation for steel block

				Climate Change (kg CO2 eq.)											
				Database INIES					Calculation						
				Production	Construction	Use	End-of-life	Total life cycle	Production	Construction	Use	End-of-life	Total life cycle	Lifetime reference	50 years
Element	Material specification	Unit	Lifetime reference	Production	Construction	Use	End-of-life	Total life cycle	Production	Construction	Use	End-of-life	Total life cycle	Total life cycle	Total life cycle
Pilars	Profilé reconstitué soudé en acier utilisé comme élément d'ossature (poteau, poutre, portique ...) (v.1.3)	kg	100	2.71	0.28	0.00	0.04	3.03	5896.96	609.28	0.00	93.57	6593.28	6593.28	6593.28
Beams long	Profilé reconstitué soudé en acier utilisé comme élément d'ossature (poteau, poutre, portique ...) (v.1.3)	kg	100	2.71	0.28	0.00	0.04	3.03	19425.28	2007.04	0.00	308.22	21719.04	21719.04	21719.04
Beams short	Profilé reconstitué soudé en acier utilisé comme élément d'ossature (poteau, poutre, portique ...) (v.1.3)	kg	100	2.71	0.28	0.00	0.04	3.03	18037.76	1863.68	0.00	286.21	20167.68	20167.68	20167.68
Suporte for slab	Poutrelle en acier utilisée comme élément d'ossature (poteau, poutre, lisse, solive, panne ...) (v.1.3)	Kg	100	1.41	0.16	0.00	0.04	1.61	5865.60	665.60	0.00	178.88	6697.60	6697.60	6697.60
Floor	Dalle ou prédalle en béton cellulaire [ép. entre 5 et 20 cm] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.1)	m2	100	38.80	6.97	0.00	1.52	47.30	4867.07	874.32	874.32	190.67	5933.31	5933.31	5933.31
Ceiling	Dalle ou prédalle en béton cellulaire [ép. entre 5 et 20 cm] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.1)	m2	100	38.80	6.97	0.00	1.52	47.30	4867.07	874.32	874.32	190.67	5933.31	5933.31	5933.31
Walls exterior -full	Mur à ossature bois Logiwall / Logiskin	m2	50	0.30	3.33	0.00	38.20	41.80	18.91	207.79	207.79	2383.68	2608.32	2608.32	5216.64
Walls exterior - with door	Mur à ossature bois Logiwall / Logiskin	m2	50	0.30	3.33	0.00	38.20	41.80	8.44	92.71	92.71	1063.49	1163.71	1163.71	2327.42
Walls exterior -full window	Mur rideau et verrière mixte bois aluminium [Gestion durable] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.2)	m2	30	632.00	46.10	0.00	15.40	693.00	19718.40	1438.32	1438.32	480.48	21621.60	43243.20	86486.40
Door	Bloc-porte isolant sur huisserie bois (v.1.1)	m2	30	20.80	1.09	0.00	1.62	23.50	69.89	3.66	3.66	5.44	78.96	157.92	315.84
Total				740.55	68.79	0.00	96.63	905.40	78775.37	8636.72	3491.12	5181.31	92516.82	114217.38	161390.53
Total (kg CO2 eq.) Per m2													737.54	910.53	1286.60

Table 3.12. INIES data and calculation for concrete block

				Climate Change (kg CO2 eq.)											
				Database INIES					Calculation						
				Production	Construction	Use	End-of-life	Total life cycle	Production	Construction	Use	End-of-life	Total life cycle	Lifetime reference	50 years
Element	Material specification	Unit	Lifetime reference	Production	Construction	Use	End-of-life	Total life cycle	Production	Construction	Use	End-of-life	Total life cycle	Total life cycle	Total life cycle
Pilars	Béton armé pour poteau C 35/45 XF1 CEM II/A (v.1.1)	m3	100	239.00	132.00	-20.40	-3.36	348.00	520.06	287.23	-44.39	-7.31	757.25	757.25	757.25
Beams long	Béton armé pour poutre extérieure C25/30 XC3/XC4 CEM II/A (v.1.1)	m3	100	204.00	209.00	-21.00	3.96	396.00	1462.27	1498.11	-150.53	28.39	2838.53	2838.53	2838.53
Beams short	Béton armé pour poutre extérieure C25/30 XC3/XC4 CEM II/A (v.1.1)	m3	100	204.00	209.00	-21.00	3.96	396.00	1357.82	1391.10	-139.78	26.36	2635.78	2635.78	2635.78
Suporte for slab	Poutrelle en béton armé (2,7 kg < masse d'acier ≤ 4,8 kg) (v.1.2)	ml	100	5.38	0.09	-0.30	0.15	5.32	55.95	0.94	-3.10	1.56	55.33	55.33	55.33
Floor	Dalle ou prédalle en béton cellulaire [ép. entre 5 et 20 cm] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.1)	m2	100	38.80	6.97	0.00	1.52	47.30	4867.07	874.32	874.32	190.67	5933.31	5933.31	5933.31
Ceiling	Dalle ou prédalle en béton cellulaire [ép. entre 5 et 20 cm] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.1)	m2	100	38.80	6.97	0.00	1.52	47.30	4867.07	874.32	874.32	190.67	5933.31	5933.31	5933.31
Walls exterior -full	Mur à ossature bois Logiwall / Logiskin	m2	50	0.30	3.33	0.00	38.20	41.80	18.91	207.79	207.79	2383.68	2608.32	2608.32	5216.64
Walls exterior - with door	Mur à ossature bois Logiwall / Logiskin	m2	50	0.30	3.33	0.00	38.20	41.80	8.44	92.71	92.71	1063.49	1163.71	1163.71	2327.42
Walls exterior -full window	Mur rideau et verrière mixte bois aluminium [Gestion durable] - DONNEE ENVIRONNEMENTALE PAR DEFAULT (v.1.2)	m2	30	632.00	46.10	0.00	15.40	693.00	19718.40	1438.32	1438.32	480.48	21621.60	43243.20	86486.40
Door	Bloc-porte isolant sur huisserie bois (v.1.1)	m2	30	20.80	1.09	0.00	1.62	23.50	69.89	3.66	3.66	5.44	78.96	157.92	315.84
Total				1383.39	617.88	-62.70	101.17	2040.02	32945.89	6668.50	3153.32	4363.42	43626.10	65326.66	112499.81
Total (kg CO2 eq.) Per m2													347.78	520.78	896.84

APPENDIX C

Table 4.1. ECTS validated during the PhD training



Marielle FERREIRA SILVA - 1170009221
Examination Board date: 21/02/2022
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Faculty of Humanities, Education and Social Sciences Transcript of records

As of 28/02/2022 this is the only valid transcript. It replaces and annuls all previous records.

Examination session Winter 2021-2022

Last name, First name FERREIRA SILVA, Marielle
Date of birth 07/12/1989
Place of birth Lagoa da Prata, Brazil
Nationality Brazil
Student ID number 1170009221
First registration 12/12/2017
Number of ECTS credits awarded 27 / 0

Doctorat en Architecture

	Grade	ECTS possible	ECTS awarded
Transferable Skills F3_S0C_SCI_DPHum/3	REUSSI	2	2
Advanced Doctoral Thesis Writing for Humanities and Social Sciences_online F3_S0C_SCI_DPHum-281	REUSSI	1	1
Good Scientific Practice - K. Bramstedt (11&12 May 2020) F3_S0C_SCI_DPHum-230	REUSSI	1	1
Interdisciplinary Training F3_S0C_SCI_SocScie/2	REUSSI	4	4
Language Course: Cours d'Allemand A1 F3_S0C_SCI_SocScie-294	REUSSI	1	1
Outreach Activity : participation in Science Communication Basic and Media Training Workshops F3_S0C_SCI_SocScie-297	REUSSI	1	1
School in Building Information Modelling F3_S0C_SCI_SocScie-438	REUSSI	2	2
Interdisciplinary Training F3_S0C_SCI_Psycho/2	REUSSI	1	1
Introduction to user experience evaluation methods - 1 day F3_S0C_SCI_Psycho-81	REUSSI	1	1
Transferable Skills F3_S0C_SCI_SocScie/3	REUSSI	6	6
Developing Writing and reading Skills at Doctoral Level (Introduction) - 29/4 and 2/5/2019 D8-T8-69	REUSSI	1	1
Intermediate Academic English F3_S0C_SCI_SocScie-209	REUSSI	2	2
Introduction to Entrepreneurship D8-T8-34	REUSSI	1	1
Managing your relationship with your thesis Director D8-T8-39	REUSSI	1	1
Reduce your stress and develop more focus (Campus Kirchberg) D8-T8-29	REUSSI	1	1
Disciplinary Training F3_S0C_SCI_SocScie/1	REUSSI	14	14
"Beyond2020 Conference paper - Another way of living: The Prefabrication and modularity toward circularity in the architecture" F3_S0C_SCI_SocScie-382	REUSSI	2	2
Outreach Activity : Participated on the Eco-Construction of Sustainable (ECON4SD) workshops F3_S0C_SCI_SocScie-298	REUSSI	3	3



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Examination Board date: 21/02/2022
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Outreach Activity: Organization and teaching of the Smart & Circular Cities course offered by the Master of Architecture F3_S0C_SCI_SocScie-266	REUSSI	3	3
Participation in the workshop "Creating Homes for Tomorrow" - Helsinki and Kyiv F3_S0C_SCI_SocScie-383	REUSSI	4	4
Scientific Publication: "Recyclable Architecture: Prefabricated and Recyclable Typologies" F3_S0C_SCI_SocScie-299	REUSSI	2	2



Luxembourg, 28/02/2022
Dean of the Faculty of Humanities,
Education and Social Sciences



[Handwritten signature]

Légende
NE: not assessed
EC: course failure
NI: insufficient grade

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ABBREVIATIONS

AEV - Environmental Administration

AIROH - Aircraft Industry Research Organisation on Housing

BIM - Building Information Modeling

CO2 - Carbon dioxide

DfD - design for disassembly

ECON4SD - Eco-Construction for Sustainable Development

EU - European Union

GHG - Greenhouse Gas

ISO - International Organisation for Standardisation

LCA - life cycle assessment

UN - United Nations

UNFCCC - United Nations Framework Convention on Climate Change

US - United States

WP - working packages

WWII - World War II

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