BUILD
MORE
WITH
LESS

BUILD MORE WITH LESS

The potential of building with modular systems to contribute to a more ecological and social sustainable building practice

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ABSTRACT

Considering the growing necessity for a sustainable building practice and the enormous increase of technical possibilities it might seem inexplicable that the way we build has not changed in many aspects in the last years. Most of the buildings are still erected the traditional way on the building site which is very often the reason for time delays or budget overruns. Furthermore, almost every building is a one-off production, requiring specifically developed plans and details.

Even though systems for individual building parts, such as facades or ceilings, have been developed over the years, systems that focus on the construction of entire buildings have not been established on the market yet. However, the application of such "kit-of-parts" systems would bring along many advantages, primarily because they focus on an enhanced integration of prefabricated building elements. This building method leads to a reduction of the project schedule and increases quality. Furthermore is it possible to minimize the use of material and energy consumption and when producing a large series of standardized components costs can be kept very low as well.

Of course it is not sufficient enough to only focus on these technical aspects when establishing such a universally applicable system. Besides the definition of the construction modules further parameters need to be determined which guarantee flexible adaption possibilities. Each user and each site is different and a well-performing modular system needs to be able to adjust to these diverse conditions.

This thesis examines the issue of modular buildings on multiple levels. After a look onto the historical development of building systems, all kinds of technical aspect such as prefabrication, transport and assembly of construction modules will be discussed. Moreover I will take a closer look on the potential benefits that can emerge for the user in terms of flexibility when transferring the principle of modularity onto the floor plan-design as well.

In the practical part of this thesis I will present my own designed modular building system for a multi-unit apartment house that I conceived based on my gained knowledge from my intense research work. Besides the aim of applying prefabricated and standardized elements, the main focus was on the development of a flexible building structure which allows a maximum of choice and individuality for the user.

To make sure that this system does not only work in theory I tested in on a real building site and designed prototypical buildings which will be presented in the very last part of this thesis.

KURZZUSAMMENFASSUNG

Angesichts der steigenden ökologischen Anforderungen an das Bauen und den zunehmenden technischen Möglichkeiten erscheint es mitunter unverständlich, dass sich unsere Baupraxis in den letzten Jahren in vielerlei Hinsicht nur wenig weiterentwickelt hat. Der Großteil der Bauvorhaben wird weiterhin vor Ort auf der Baustelle ausgeführt was immer wieder den Grund für Termin- oder Kostenüberschreitungen darstellt. Auch wird nahezu jedes Gebäude als Sonderanfertigung konzeptioniert, das eigens geplant und konstruiert werden muss.

Zwar haben sich im Laufe der Jahre für einzelne Gebäudeteile, wie etwa für Fassaden oder Decken, Systeme entwickelt, jedoch solche die auf die Errichtung eines ganzen Gebäudes abzielen haben sich bisher noch nicht etabliert. Dabei würde die Anwendung sogenannter „Baukastensysteme" viele Vorzüge mit sich bringen, vor allem weil sie den Einsatz von vorgefertigten Elementen forcieren. Diese Baumethode spart Zeit und erhöht die Qualität der Bauwerke, vor allem auch weil die Gefahr möglicher Fehlerquellen auf der Baustelle minimiert wird. Weiters werden Material- und Energieeinsatz gesenkt und durch die Produktion einer Vielzahl von standardisierten Elementen können zusätzlich auch die Kosten reduziert werden.

Natürlich genügt es bei solch ganzheitlichen Systemen nicht, sich nur auf die technischen Aspekte zu konzentrieren, sondern neben den Baumodulen müssen auch Rahmenbedingungen definiert werden, innerhalb derer eine flexible Anwendung des Systems möglich ist. Denn Nutzer und Grundstücke weisen Unterschiede auf, auf die ein modulares Bausystem reagieren können und flexibel anpassbar sein muss.

Diese Arbeit behandelt das Thema des modularen Bauens auf mehreren Ebenen. Nach einem historischen Rückblick werden einerseits die technischen Aspekte wie Vorfertigung, Transport und Montage von Baumodulen untersucht, andererseits wird beleuchtet inwiefern sich durch eine Umlegung von Modularität auf den Grundriss von Wohnungen Vorzüge hinsichtlich Flexibilität und Anpassbarkeit für den Nutzer ergeben, der ja im Mittelpunkt jeder Bauaufgabe stehen sollte.

Im praktischen Teil wird der Entwurf eines eigenen modularen Bausystems für den mehrgeschossigen Wohnbau präsentiert, welches auf Basis der vorangehenden intensiven Recherchearbeiten entwickelt wurde. Dabei stand neben der Vorfertigbarkeit und Standardisierung der Bauelemente vor allem auch die Entwicklung einer flexiblen Gebäudestruktur im Vordergrund, die einen maximalen Grad an Individualität für den Nutzer zulässt. Im letzten Teil der Arbeit wird die Funktionsfähigkeit dieses Systems auf einem realen Grundstück getestet und das Resultat vorgestellt.

INTRO

There is an explosion in design, an explosion in variation based on standardisation. Many people think that if you adopt a certain form you actually restrict yourself. But if you do it well, you adopt a certain form to buy freedom, which is what you do when you learn to play the piano.

[Bert Mulder]

INTRODUCTION

Discussed topic

Terms such as “building elements” and “building systems” evoke - not only within architects - associations with mass production, uniformity and industrial assembly lines.
Images of typical post-war buildings such as the so-called *“Plattenbauten”* which primarily dominated Eastern Europe and were characterized by monotony, technology and a lack of living quality, come to our minds. This negative perception has not fully faded yet and is one of the main reasons why modular building systems, i.e. systems that are based on a number of combinable pre-selected and usually prefabricated elements, are considered as contradiction to high quality design and “real” architecture.

If we take a closer look on the development of building systems in the past, this attitude is comprehensible, though, only partly justified. Among the ideas of the last century, one will find some functional “living machines” primarily developed to enable assembly line construction with no intention to make a cultural or social improvement. But there are also great examples showing how much effort some architects put into creating modular systems that could be mass-produced but did not sacrifice people’s need for individuality and different personal desires.

The development of bulding systems can be traced back more than 100 years ago. With the advent of the Industrialization new possibilities of production emerged and promised a greater efficiency of the building process in general and a boost for building systems in particular. Prefabrication techniques facilitated standardization of elements which made it possible to use interchangable modules and increase a system’s flexibility. Architects conceived literally hundreds of prototypes throughout the last century, hoping to improve our building practice by applying rationalized, systematic design methods and industrialized production technologies. Especially the architects of the Modern Movement passionately believed in the life-enhancing values of bringing architecture and industrial materials closer together and sensed a way of making design accessible for the masses. Inspired by technological advances, Le Corbusier, Gropius, and other avant-garde architects considered the serial production of elements and their integration into building systems as a necessary further step in the course of construction development. Buildings should be produced in factories, standardized and prefabricated, so that they could be easily assembled on site according to the principles of modular construction. Prefabricated and/or system based houses were seen as a chance to combine mass production with the ideal of contemporary aesthetics to create innovative solutions that still are affordable. It was hoped that these new production methods would help to solve the problems that the housing industry had to face during the turn-of-the-century.

However, despite the broad spectrum of innovative design proposals, most of the developed projects never left the prototype stage or were never realized at all. Ideas did not only fail due to technical boundaries but also due to a lack of acceptance in society based on too radical or industrialized systems. Many people had mixed feelings towards a mass-production of the all-sacred "home" and so in the 20th century there was much theoretical debate going on about the validity of mass-production and associated technologies in relationship to architecture.

An interesting contribution, whose outcome managed to combine architecture and technological advance, came from the Southern Californian *Case Study Program* which was founded by *Arts & Architecture* editor John Entenza. After World War II has come to an end he strongly believed that it was the right time to define a new kind of building design and set new standards in housing construction. Eight contemporary architects conceived thirty-six buildings, among them Case Study House No. 8 - the famous *Eames House*. One of the main reasons for its success was its innovative building structure. Instead of developing a completely new building system, Ray and Charles Eames managed to build their house completely of off-the shelf components. This concept was remarkably advanced in terms of sustainable thinking for that time and has strongly influenced architects until present days.

The big change in the construction industry all these architects were hoping for did not occur, however, and most buildings remained dependent on traditional building methods.

"It was not until the present time – almost a quarter of a century later – that, faced with a growing necessity for resource-conserving techniques and the desire to increase design flexibility continuously, thoughts again began to turn increasingly to the concepts of systems." [1]

Some architects have already realized that it is time to rethink conventional building methods which have proven to be unsustainable in multiple aspects and start taking responsibility for our environment. They are looking for a new way of building that deals with our natural resources in a more responsible manner while providing appropriate living solutions for our diverse society. Especially in terms of flexible structures and environmentally sustainable construction methods modular building systems can offer great opportunities for improvement. Innovative examples show, that the application of a "kit of parts"-method based on various building modules does not necessarily result in uniformity but can provide great possibilities to achieve customized and individual solutions for all kinds of people's needs. *"The trick is to find that magic tipping point where you can use prefabricated materials, components, systems and modules and still create innovative and site-specific buildings."* [2]

In other words, the aim of a modular system-based method is to maximize design possibilities while minimizing the amount of elements to make both, design and construction processes, more efficient and, so to speak, achieve "MORE WITH LESS".

If this approach can in fact contribute to a more ecological and social sustainable building practice will be analyzed in this master thesis - thereby primarily focusing on residential projects. It is argued that the application of a modular system can lower the ecological footprint of a building while increasing the living quality for the people. This supposition is based on the several benefits that come along with a modular building, such as:

- efficient design and production methods
- self-expression through customization possibilities
- adaptability to different personal requirements
- extension of a building's life cycle, etc.

Structure

I will start out by giving an overview on the beginning and the evolution of building systems, illustrated by significant architectural examples of the past and current applications.

Chapter 2 and 3 will explain the theorectical background of modular systems, their benefits and how they are used in today's planning and construction processes.

Chapter 4 deals with the potential flexibility a modular structure can offer to architects and dwellers in terms of initial customization and later on transformation possibilities . The adaptability of buildings to dynamic changes in modern life has become a powerful variable and has great potential to increase the social sustainability of a building.

The next chapter focuses entirely on the ecological sustainability of a modular building. While time and cost-saving aspects might have dominated the interest in building systems in the past, today the ecological benefits of modular buildings get increasingly relevant.

Chapter 6 gives an overview on the variety of possibilities in terms of module choice and illustrates the lastest architectural trends in this field.

Practical part

After having pointed out all the positive aspects of modular systems in theory, I will present my own concept for a modular building system. Based on my gained knowledge I integrated the most important benefits of modularity in terms of improving environmental and social issues into my design. The result is a building system which primarily consists of standardized and prefabricated elements which can be arragned to form a great variety of living units. Under some simple rules the user can combine them accroding to his own and the building site's requirements. The main focus however, was not only on the most efficient application of industrially produced modules but also on providing a high level of customization possibilities for the user - thereby maximizing the technological and social potential of modularity in the field of architecture.

The proposed system is primarily intended to be applied for multi-story residential buildings and is therefore not to be confused with the ordinary prefabricated houses we all know because their concepts are only limited to the construction of single-family houses. Since this type of building brings many negative effects primarily for the environment but also for society with it, it was very important to me to offer a more sustainable living concept. Especially due to the many customization possibilities in terms of unit layout and size and the reduction of costs which can be acieved once the construction elements get standardized, the proposed modular system could result in an attractive, sustainable alternative to single-family houses. The system is also simplified to such an extent that it can be understood and used by a layman in order to make it applicable for a larger target group.

To ensure that the designed system does not only work in theory I applied it on an empty building site in my home town in Carinthia. The results of this prototype will be presented in the very last part of this thesis.

NOTES:

[1] Staib, Gerald/ Dörrhöfer, Andreas/ Rosenthal, Markus: *Components and Systems* - Modular Construction. Munich: Birkäuser Verlag AG 2008 p. 5

[2] Interview by Arieff, Allison: *Carlos Martin on the PATH Concept House.* In: Dwell Magazine (April/May 2005) p. 128-132

EVOLUTION

“

Construction systems have been employed in architecture almost as long as mankind has been building structures; based on a minimum of identical units, they have been used in efforts to erect, alter and dismantle buildings as quickly, efficiently and economically as possible.

[Staib, Dörrhöfer, Rosenthal]

”

CHAPTER

EVOLUTION of BUILDING SYSTEMS

“System building”, “industrialized building”, “modular system”, “prefabrication”, “unitized building” etc. – there is a long list of terminologies which describe the approaches aiming for a more efficient production in the construction sector. Many different terms have developed throughout the last century, showing that viewpoints have changed over the years, but basically they are all based on the same conceptional goal to optimize the way we design and build by making use of rationalization and technology. Some architects rather focused on an efficient construction phase making use of prefabricated elements, others tried to rationalize the design process with the creation of a modular planning system, but usually these approaches are linked and depend on each other in order to realize the most efficient solution. Whichever approach is used they all suggest to replace the traditional way of building on site with system-based methods in order to achieve a more efficient and therefore more sustainable building practice:

“Building System is a set of parts and rules where the details are resolved so as to generate many different and customized buildings. Therefore, the construction method is not re-invented each time a building is planned, as it is still the case with the traditional set of working drawings.” [1]

This chapter focuses on the evolution of industrialised building systems from the introduction of prefabrication, through the concept of interchangeable components and developments toward customization, to today’s goals to achieve highly sustainable buildings with incorporating a flexible building system based on interchangeable modules. It also shows that the application of modular building systems can be extremely relevant in future because besides increasing efficiency they also allow for transformation and adaptations - key features which are getting more and more important in our ever-changing society.

1. PREFABRICATION | First Attempts

Nomads and settlers

Prototypes of prefabricated and unitised buildings were firstly developed many thousand years ago. During that time nomadic peoples were constantly on the move, searching for new habitats and food, but also needing shelters wherever they would go. To avoid having to search for the required building materials after every change of their location, the nomads started to collect building materials which were easy to assemble, but also easy to dismantle so that they could just take them with them to their next location. In order to make these materials transportable, they had to be lightweight, easy to handle, and not to consist of too many individual pieces. Each element already had a specific function and was roughly worked and shaped to do so.

Once humankind managed to settle down and erect permanent dwellings, they improved their handwork skills and tools. Over a period of many centuries they developed a tradition of brickwork, stonework and timber constructions. Very impressive examples of buildings using prefabricated materials and systems can be found in Greek and Roman temples, where individual finished blocks could be put together with razor-sharp accuracy, or in Gothic cathedrals. [2]

The introduction of prefabrication

In the 19th century unitised building systems for houses got more and more important due to two specific reasons: the military and the colonial expansion. Soldiers in distant field operations and settlers immigrating to European colonies, such as Australia or Africa which were lacking of civilization and infrastructure, as well as fortune seekers in the California Gold Rush were in need of quick shelter. So called "kit houses" - off-site produced timber constructions consisting of pre-cut elements - promised easy, fast, and inexpensive housing for those purposes. The first documented prefabricated house which can be considered as the beginning of mass-produced housing was built in the 1830s by London carpenter H. Manning. His son was immigrating to Australia and he wanted him to have a comfortable place to live in the new land, but didn't know what materials and supplies his son would find there. So he constructed a house which could be broken down into elements that were small enough to be stowed for shipping.

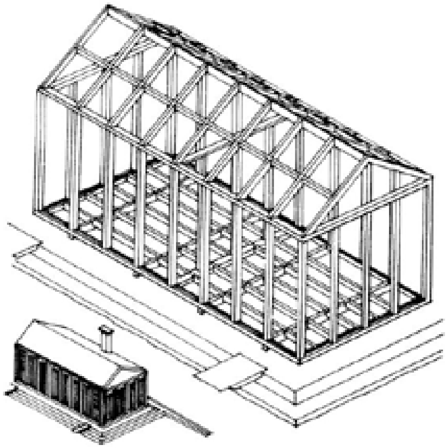

Fig. 1: Manning Portable Colonial Cottage, H. Manning, 1833

The different wooden pieces were fabricated entirely in the carpenter's shop, requiring no site work except the assembly of the elements on a simple foundation. No joints, cutting, or even nailing were necessary. He standardized dimension so that every panel, post and plate had exactly the same length, breadth and thickness in order to avoid mistakes or time loss during the assembly. The cottage became a commercial success and Manning developed several models varying in size and cost and shipped them to the new land.

"This transfer from ad hoc building to planned multiple production is one of the fascinating break points in the curve of architectural evolution." [3]

Catalogue Homes

The most successful prefabricated houses were the kit-houses introduced by *Sears, Roebuck and Co*. in 1908. The Chicago-based company was the most productive designer and manufacturer of prefabricated housing anywhere in the world. Between 1908 and 1940 they sold around 100.000 homes which were advertised and ordered by catalogue. Customers could choose between more than 400 different models and even had the possibility to customize numerous aspects of each house. Almost every Sears model used the balloon frame technique, making this construction method even more popular across the United States.

Fig. 2: Catalogue Home No. 102, Sears, Roebuck and Co.,

The average kit-house arrived in 30.000 pieces, each of them number-keyed to a blueprint and ready to assemble. It took months to build it but was by far the most inexpensive alternative to a site-built home. Mass production of the parts reduced their associated costs, which was passed on to the homeowner. Even though the Sears homes were produced en masse, systematically, efficiently and affordably the designers tried to cover these qualities and made them look like a normal home – in contrast to the constructive aesthetics of industrialized buildings fostered by the architects of the avant-garde. [4]

The advent of new materials

Iron frame constructions

While wood was the perfect material to erect structures in an easy, fast, and lightweight manner, iron gained more and more impotence as its availability increased during the industrial revolution. Especially larger structures benefited because the dimension of the buildings could be increased, and the sections of structural elements reduced. Furthermore, the features of iron and later steel were very suitable for industrialized building systems, such as the possibility to manufacture the elements in factories, standardize their dimensions and forms to achieve serial production, easy assembly and even disassembly. [5]

The first important developments on the path towards pure iron frame structures occurred in the construction of greenhouses. Constructors could focus on a rational solution to structural, technical and climate problems since architectural design was of marginal importance and so they created the first unitised systems – later transferred to other buildings. One of the first buildings that can be considered as unitised is the Crystal Palace by Joseph Paxton built for the World Exhibition of 1851 in London. It is a perfect building system, both architecturally and technically, consisting of different standardized elements that were connected to create a frame based upon the principles of modular arrangements. Even though the Crystal Palace measured 564 m by 124 m with an overall height of 40 m, it only took 6 months to build it due to the use of this modular system. Unlike its predecessors, every item of the building’s construction was carefully planned for reuse in the new structure, even the temporary timber fencing was reused as floorboards inside. [6]

”The system was successful in its inner logic and economy, which allowed for rapid assembly and re-assembly, and could be erected in locations remote from its manufactory. The extent to which the Crystal Palace succeeded in revolutionizing the building industry or engendered a new way of building is debatable; its novelty, however, is indisputable.” [7]

Fig. 3: Crystal Palace, Joseph Paxton, 1851

Prefabricated concrete construction

Besides iron and timber, a completely new building material appeared at this time. Joseph Monier experimented with cement and discovered reinforced concrete, a material that turned out to be very suitable for monolithic constructions which required great stability. Prefabricated concrete elements were used in 1891 by French businessman E. Coignet for the first time. Only five years later another businessman and constructor, Francois Hennebique, developed the first concrete modular units used as gatekeeper lodges for the French railways. [8]

From materials to systems

By the turn of the 20th century, architects and inventors had developed prefabricated houses of nearly every material – timber, concrete, sheet metal, and cast iron. All meant to be produced in great numbers based on faster and more efficient building methods resulting from the industrial revolution. Products were no longer the individual results of manual labor but were manufactured in large series by machines. It was believed that architecture should be renewed similar to the changes in other technical fields like ocean liners or automobiles.

“Buildings should be produced in series in factories, standardized and prefabricated, so that they could be assembled on site according to the principles of modular construction.” [9]

It was hoped that these new production methods would help to satisfy the severe housing problem in European cities which was caused by the high rate of migration into cities throughout the 19th century. People were hoping for work and better living condition but the cities were simply not designed for such a big amount of inhabitants. The result was an increasing house shortage and miserable living conditions especially for the poorer working-class who were mainly accommodated in ghettos. Industrially manufactured building elements and faster assembly techniques seemed to be the right answer to that issue.

2. THE DREAM of MASS-CUSTOMIZATION | The Modern Movement

Mass production, rationalization and standardization

"The prefabricated house is an important theme, perhaps the most important, in the conventional, canonical history of the twentieth-century architecture. […] Modernist rejected the elitism, historicism and anti-industrialism that had characterized their profession in the nineteenth century. They wanted to bring architecture to the masses and to face up to the realities of an industrial society. What better way to achieve this goal than to design houses that would be mass-produced in factories just like Model T Fords?" [10]

The advantages of a prefabricated system were becoming increasingly appealing: They promised greater economy, speed of erection, reduction in need for skilled labor on site, and a higher quality product due to factory manufacture. Also many avant-garde architects were impressed by these features and started to get involved in this promising movement. While preceding attempts had rather focused on functionality and profitability, architects and designer like Walter Gropius, Le Corbusier or Frank Lloyd Wright recognized a possibility to define a new design culture. They passionately believed in the life-enhancing values of prefabrication and sensed a way to bring design to the masses. Combining prefabricated, mass-produced homes with the ideal of contemporary aesthetics that are still affordable can be seen as one of the core themes of modernist architectural discourse. The industrial revolution - they reasoned - had proven that you could build cars, clothing and furniture more cheaply and efficiently on an assembly line. Couldn't the techniques of mass production be harnessed to make inexpensive, attractive houses for the masses?

There were multiple ideas already how to make use of the new technologies and mass-produce houses. Multiple companies offered ready-cut and ready-made houses which could be ordered from a catalogue and arrived in prefabricated elements ready to assemble at the new owner's building site. It was not until the modern movement, however, that architects began to raise the question of how to combine efficient building methods with contemporary aesthetics. Inspired by technological advances and challenged by social and economic realities they have developed quite an impressive number of different conceptions. Taking a closer look at some of the conceptions created in the last century one will find functional "living machines" primarily developed enabling assembly line construction and meeting functional requirements. However, there are also great examples showing how much effort some architects put into creating systems that could be mass-produced but do not sacrificing people's need for individuality and different personal desires as a consequence.

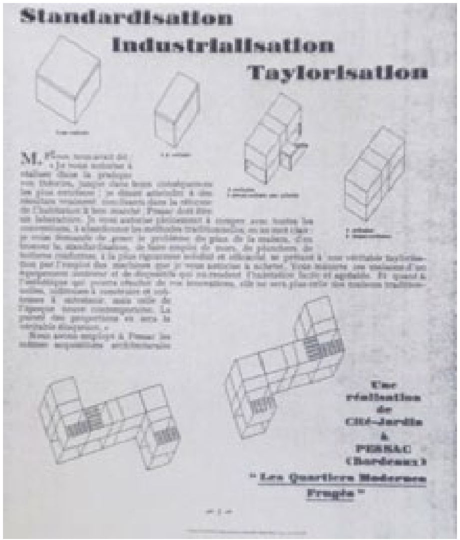

Fig. 4: Illustration from "Standardization, industrialization, taylorization", Le Corbusier, 1928

The hope for at least limited customization within a set of established types generated all kinds of modular construction systems which seemed to combine efficiency with variety. Even though most of those concepts had limited commercial success and none of them reached the ultimate goal of getting mass-produced, they influenced the prefabrication and system-based movement in architecture significantly.

Machines for living

Especially Le Corbusier dreamed of the modern house as a kind of “machine for living” and believed that building houses should follow the modern production logic of automobiles, airplanes, and ships. He quickly incorporated techniques and formal developments from industry, thereby influencing a great number of architects. In “Vers une architecture”, his famous collection of essays published in 1923, he called for a new era of architecture:

“We must create the mass-production spirit. The spirit of constructing mass-production houses. The spirit of living in mass-production houses. The spirit of conceiving mass-production houses. If we eliminate from our hearts and minds all dead concepts in regard to the house, and look at the question from a critical and objective point of view, we shall arrive at the “House-Machine”, the mass-production house, healthy (and morally so too) and beautiful.” [11]

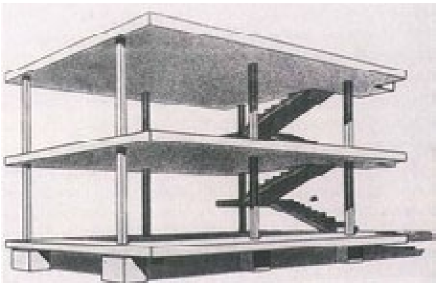

Fig. 5: System Dom-ino, Le Corbusier, 1914

In 1914 he developed the “Dom-ino House Project” which was based on a new framework that eliminated the need for load-bearing walls. This distincition between a supporting structure and non-loadbearing infill elements can be seen as a decisive step towards flexible building structures. The modular system consisted of three flat floor slabs supported by six concrete columns and was linked by a cantilevered concrete stair. Serially, mass-produced walls, windows and doors could be put together individually by the owner to create cheap, flexible dwellings. Le Corbusier tried to realize a building system aligned to standards of industry, technique and production, but which would also be the framework for invention and allow for individuality.

The Prefab Pioneer

Modular building systems at Bauhaus

Inspired by the rationalization and industrialization taking place in America, Walter Gropius also addressed the issue of standardization of building elements. He was not less determined than Le Corbusier to find a way how to combine the means of production while achieving aesthetic designs and possibilities for personal expression. He saw the answer in applying modular building systems:

“The idea of industrializing house construction can be realized by repetition of the same component parts in every building project. By this means the mass production can be made both profitable for the manufacturer and inexpensive for the customer.” [12]

He suggested that the factory-produced house would leave open not just a terrain for artistic invention but also for personal desire of the future owner. The hope for at least limited customization within a set of established types accompanied his dream of prefabrication from the very beginning. He had long been fascinated by the possibilities of applying innovative techniques to create mass-produced housing kits that allow for efficiency without forgetting about personal desires. This was also the idea behind the “***Baukasten-System”*** which Gropius developed with Adolf Meyer at the Weimar Bauhaus in 1923. It was a large construction kit consisting of variable standardized, industrially produced elements that could be combined and joined together according to the number of occupants and their personal needs.

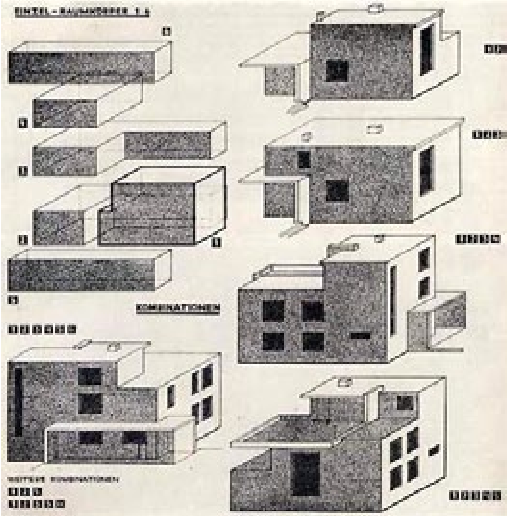

Fig. 6: “Baukasten”, Walter Gropius, 1922. A system allowing for a great range of variations

“Gropius and Meyer envisioned that architects would guide the client through the system employing a scale model to illustrate possible configurations.” [13] In order to avoid monotony his approach was to only *“typify components while leaving the larger building volumes subject to variety.”* [14] Even though it was never realized, this system highly influenced the concrete-panel, industrially produced housing blocks built a few years later after the Bauhaus had moved to the industrialized city of Dessau.

Exile years in the United States

During World War II Gropius, as many other European architects, emigrated to the United States. He was hoping to find new construction methods in the New World based on the fact that America had pioneered off-site fabrication – first in the balloon frame and then from the 1890s with precut timber kit-houses sold by specialized companies.

Together with Konrad Wachsmann, also living in exile in the U.S. by that time, he developed the “Packaged House System”, which was based on Wachsmann’s earlier work on load-bearing construction systems with Christoph & Unmarck. It was further developed in 1943/44 to the so-called General Panel System with fewer elements and improved construction methods. It consisted of standardized load-bearing timber panels which could be flat packed on a truck and transported from a factory to the building site. The panels already included the electric wiring and were connected by hooks and cotters. The most unique feature of that system was that the same panels could be used for floors and ceilings as well as for walls. For Wachsmann and Gropius a great step forward, since this limited the numbers of parts that were needed for the construction while increasing the possibilities for design flexibility – so that ironically the smaller the deck the greater the freedom in employing it.

Fig. 7: General Panel System, Walter Gropius and Konrad Wachsmann, 1943

But because of financial difficulties, ideological differences between Wachsmann and Gropius and a conservative market no more than 150 were built. [15]

Despite the failure of the system to make money Gropius still believed in the promise of mass-produced housing: A reporter from the NY Times asked him in 1947 if it wasn't a good thing that at least the house would stay a refuge from standardization and industrialization. Gropius answered that between 1913 and 1937 the average cost of a house in America had increased 193 %, while the average cost of the car had fallen by 60 % and concluded:

"The coming generation will certainly blame us if we should fail to overcome those understandable though sentimental reactions against prefabrication." [16]

More prefabrication icons

Buckminster Fuller – Dymaxion House

Another significant contribution came not from an architect but an engineer. Buckminster Fuller understood the necessity to focus on the production of lightweight building materials and systems in order to address the problem of transport and assembly.

"Buckminster Fuller believed in efficiency: the most efficient use of time, space, resources, and energy. Nothing should be wasted, nothing underestimated or overlooked. […] More than anything else, Fuller believed that it was possible to do more with less." [17]

His Dymaxion House, a circular, prefabricated housing unit machined from aluminum panels he constructed in 1927 realized his philosophy probably best. The house weighed only 2.722 kg, consisted of various easily fabricated elements and could be packed onto a single truck. Once delivered to the building site it could be erected by six people in a single day. The geodesic dome of the house covers the maximum amount of space with the smallest amount of material possible. From a profit-based point of view this project failed miserably, unable to win investors because it appeared far too strange and futuristic. But as a prototype for mass housing assembled of prefabricated elements and universally available at a low cost the Fuller's Dymaxion House remains an icon. [18]

Fig. 8: The Wichita House, Buckminster Fuller, 1944. A descendant of the Dymaxion House

Jean Prouvé

Meanwhile in Europe the French engineer and designer Jean Prouvé, who had played a key role in industrial fabrication from the 1930s on, continued to work on the development of simple and flexible building systems. Around 1950 he produced a design entirely consisting of metal components in which the rigid pole of the house provided the basic spatial envelope and a series of panels were used for enclosure and rigidity. This system could be adapted to different sizes trough modular expansion or pavilion additions. Everything was designed to a 1-meter grid and no element was more than 4 meters long or weighed more than 100 kilograms to ease the assembly. The design was based on Prouvé's dictum of only using the smallest possible number of parts. His "Tropicale" house was originally designed to provide housing and civic buildings in some of the French colonies in Africa. Besides the fact that the elements were prefabricated and easy to assemble another specialty about it were the incorporated “green” features. Natural cooling and ventilation was used, there was movable shading to control sunlight and the elements were flat for easy packing and transport. *“This small building would be a perfect answer in today’s energy-conscious world, with its low consumption of energy in use, and perhaps more important, minimum use of energy consuming materials in manufacturing and construction.”* [19] However, only three were built in the Republic in Congo and a cluster model of 14 houses which Prouvè designed based on the system used for the “Maison Tropicale” was built at Meudon, near Versailles.

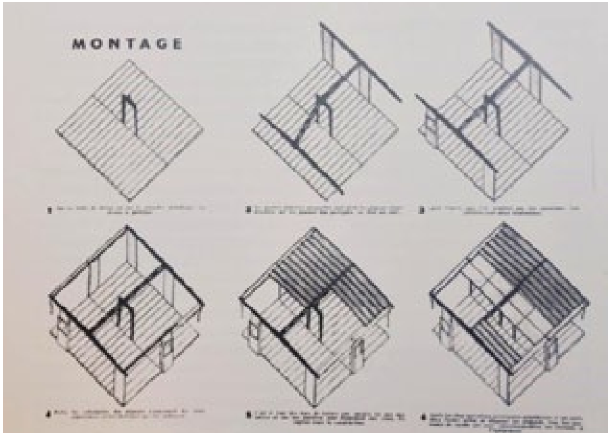

Fig. 9: Central column system used for Maison Tropicale, Jean Prouvé

Frank Lloyd Wright - American System-Built Houses and Usonian Houses

Frank Lloyd Wright also devoted parts of his lifework to the design of standardized housing systems. In 1911 he developed his American System-Built Houses, an architectural answer to the catalogue houses sold by companies like Sears, Roebuck and Co. In contrast to these companies, he didn’t only focus on costs: *“Simply selling houses at less cost means nothing at all to me. To sell beautiful houses at less cost means everything.”* [20] The American System-Built Houses consisted of various lumber elements which were all precisely cut in the factory and required no on-site carpentry. The true novelty about his approach was, however, his attempt to produce infinite variations instead of defined models to ensure that the home meets the owner’s needs. Like many modern architects, he combined both the benefits of the rationalized standardization and the desire for individual expression. Wright explicitly insisted that it was only the elements that were to be prefabricated, not the overall forms. An untold number of System-Built Houses were built, none of them looking alike. [21]

About 25 years later Frank Lloyd Wright started another attempt to create affordable houses. This time he simplified the building process not by using prefabrication but by developing a system to make the design process easier. He didn’t want to sacrifice the traditional architect-client relationship and with it the possibility to design homes specifically for the owners, but he was aware that not everybody could afford his work. So he needed some kind of system that would allow him to design quickly and delegate the details to one of his employee, a method he applyied for his popular Usonian Houses. They were not standardized or mass produced, but neither entire one-offs. Whereas most architects invent their building almost completely from scratch, Wright conceived a system which he used as foundation for every Usonian House. The most important manifestation of the system was a 1200 by 600 mm planning grid. He also worked out a vertical grid that was conform to brick as well as standard timber sizes. The materials he used were not prefabricated; site work was only minimized by rationalization of the design, a principle still applied today. [22]

3. THE OFF-THE-SHELF HOUSE | The California Manifesto

California Modern

The idea of the post-war house

As World War II was about to come to an end the dream of the industrially manufactured houses again caught architects attention. John Entenza, the editor of the California-based journal *Arts & Architecture*, made great effort to promote the idea of the new technologies of production, in particular prefabrication, and their benefit to architecture and housing. He and his editorial assistances, Charles and Ray Eames among them, were fully aware of the demand of new housing that awaited the end of the war and believed in the necessity of applying new technologies to solve this issue. Furthermore they were trying to link the technical possibilities of prefabricating new materials and assemblies to the idea of defining the “modern home” and a new way of designing houses.

War had created new construction techniques, new materials and industrial expertise that could be used in order to rationalize the construction of the post-war house. It seemed that for the first time industry, research and materials existed in the right relationship to each other. As the war was about to come to an end it became clear that the American housing industry would begin to erect wide-scale projects again. The question was: who would define the post-war house? [23]

The pre-war modern California house

John Entenza had the vision that California-based architects were in charge especially because there was already a tradition of experimentation with new materials and construction among architects in the Southern California region. This was evident in the early work of Austrian émigrés Rudolph Schindler and Richard Neutra who arrived in Los Angeles in the early 1920s exercising a powerful influence on the development of a specifically Californian modernist architecture. Schindler’s House on Kings Road (1921-22) was a groundbreaking work of modern architecture, whose innovations included the use of a tilt-slab wall system (an on-site prefabricated concrete panel system that Schindler had learned from local architect Irving Gill) and a new timber framing assembly to allow for large wall openings. Schindler would continue to develop the concept of modular building in later projects. His spatial and material experimentations had a specific influence on modern California architecture and many subsequent architects would follow his example. Richard Neutra, in his first major work in Los Angeles, the Lovell Health House (1927-29), introduced lightweight steel framing arranged in a modular frame, allowing the use of standardized window/wall units. He was committed to the use of steel for structure and other off-the-shelf components as means of making high quality but affordable buildings; but he was ahead of his time. [24]

Fig. 10: Lovell Health House, Richard Neutra, 1927

The Case Study Program

Re-defining the Modern house

Based on these influential examples of the past and the strong believe in the possibility to define a new kind of architecture Entenza initiated the “Case Study House

Program" in 1945, which looked for designs of the post-war house. He commissioned eight architects, including Charles and Ray Eames, Eero Saarinen, Pierre Koenig and Richard Neutra. As a result of this program, 36 buildings were completed that set new standards in housing construction.

They can be characterized by the incorporation of new technologies (materials, assemblies, factory-based mass production), the modular arrangement of space, structure, and cladding, in combination with the architectural characteristics of the pre-war modern California house conceived of by Schindler, Neutra, Ain, Soriano and others: simple in plan, modulated in structure, classically ordered in aesthetics. [25]

The Eames House: Case Study House No. 8

The most successful example of creating a completely innovative system made entirely of off-the-shelf elements was Case Study House No. 8, designed by the couple Charles and Ray Eames as their own residence in Santa Monica near LA. Every single element they used was ordered by catalogue or purchased from an industrial manufacturer, including the steel beams and trusses and the façade elements of various materials and colors. The dimensions were based on a grid to ensure a more efficient planning and assembly process.

Basically, the Eames House consists of two steel framed rectangular boxes, connected by an open court. Each of the buildings is two stories high and taken together the two components comprise about 230 m² of space. The construction is based on a modular system, using a vertical geometric grid that measures 2.35 m. The residential part is made up of 8 modules, the studio is made up of 5 and the central court consists of 4 modules. Charles saw the many benefits of a modular system, including symmetry, inherent strength, the absence of waste, and the speed of construction.

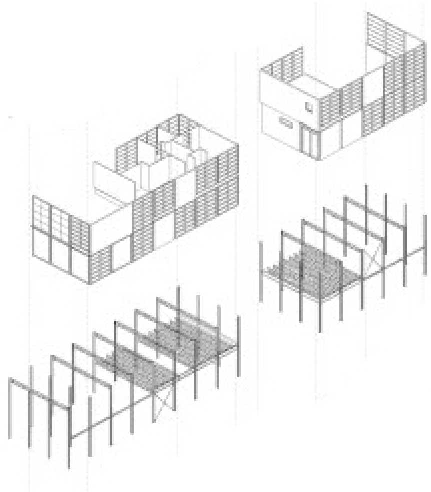

Fig. 11: Eames House, Ray and Charles Eames, 1944. Modular frame structur

The façade is defined by steel columns which are positioned according to the 2.35 m grid. The in-betweens are filled with transparent and translucent glazing panels in addition to opening elements and colored panels.

Fig. 12: Eames House. The frame structure is exposed in the facade

Since all building parts were prefabricated, the assembly process was extremely short; five men erected the structural shell in only sixteen hours. But Charles and Ray Eames did not only succeed in fusion new technologies with lightweight materials, they also focused on the integration of the landscape, the course of the sun and the relation between the outside and the inside to guarantee living qualities – all together making it to one of the most iconic houses of the 20th century. [26]

Fig. 13: Eames House. Interior view of the studio

Fig. 14: Eames House. Exterior view

Influence of the Case Study House No. 8

The influence of the Eames House has been remarkable; it is certainly one of the most often mentioned examples when it comes to prefabricated and modular houses. One of the main reasons for its success is the fact that it was one of the first houses that were completely built of off-the shelf components. The Eames ordered those elements from steel manufacturer catalogues and they arrived ready for assembly on site. This was a completely new building method that was remarkably advanced in terms of sustainable thinking for that time. It made it possible to simplify the assembly process, save time, money and waste and even provided the possibility for disassembly.

Besides the fact that it only made use of factory-produced materials, it is also a demonstration piece showing a system that holds the potential to be copied and modulated in various configurations. Even though neither a replication nor a disassembly was ever carried out, the pioneering approach to the topic of sustainability, industrialization and modularity regarding housing is out of question. Therefore it is not surprising that it had several descendants.

The idea of using factory-produced components in metal or plastic that could be rapidly assembled on site got further developed, especially by British architects like Richard Rogers and Norman Foster, who initiated a new style that came to be known as British High Tech Architecture.

In 1968 Richard Rogers conceived the Zip-up House, a house consisting of several identical-sized segments which could be combined according to the owner's spatial needs. The floor, walls, and roof components were to be fabricated off-site in separate pieces and attached on the site to form a structural ring. Each of the ring's four sides could be customized, including colors, textures and windows and the rings could be zipped-up allowing many different sizes and configurations.

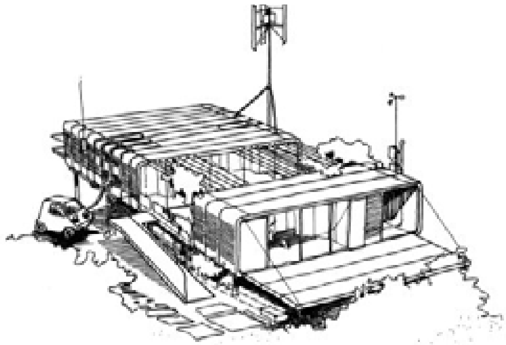

Fig. 15: Zip-Up House, Richard Rogers, 1968

In 1975 Michael Hopkins, an ex-partner of Norman Foster, built himself a version of the Eames house and a few years later Richard Horden, another offspring of the Foster office designed another example of a "High Tech"-house, based on the principles used by Charles and Ray Eames. The Yacht House was a simple assembly of a few standard factory components consisting of a single-story frame, filled with roof, wall and screen panels.

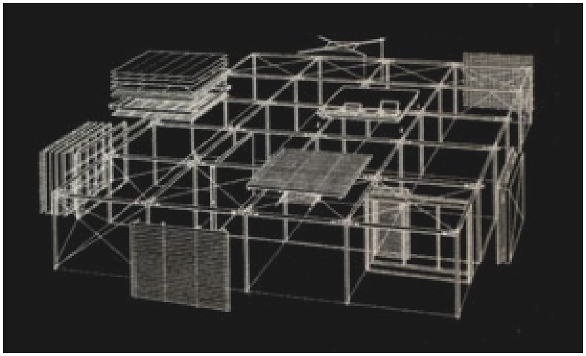

Fig. 16: Yacht House, Richard Horden, 1983

Even though these High Tech houses were, in a sense, specifically designed to be mass-produced, they remained one-offs, similar to the Eames House. In general, Colin Davis argues in his book *The Prefabricated Home*, that this tendency of creating "one-off mass-produced houses" without raising the actual effort of replicating the house in a factory can be noticed in several examples created after World War II. [27]

"Architects – or at least the sort of architects that history celebrates - seemed to lose their will to change the world by direct interventions and instead put their faith in influence and example." [28]

4. PLATTENBAU | The Post-war Era in Europe

"Better, cheaper, and faster"

After World War II many countries, especially Germany, were badly damaged which resulted in a high demand for housing. For that reason most projects developed during that time tried to realize affordable housing on a large scale. The Eastern Bloc saw the solution to handle the housing shortage in focusing on technical rather than aesthetic aspects and realized under the motto "better, cheaper and faster" very simplified, industrially produced housing programs. Prefabricated reinforced concrete was declared to be the true spirit of the times and under Khrushcev this attitude was elevated to a continent-wide scale. This building technique was exported to many parts of Europe, in particular to the German Democratic Republic. At first they used large block constructions, later large-format concrete panels, a building technique commonly known as "Plattenbau" and most popular during the 1960s. Basic modular units of 120 cm were laid down for all "housing and social buildings" and the large panel construction was based on standardized room-sized elements. In most cases the Housing Construction Series 70 (WBS 70) was used which consisted of elements with finished surfaces and built-in windows. The result of this unified building method was an environment lacking of variety and living quality. [29]

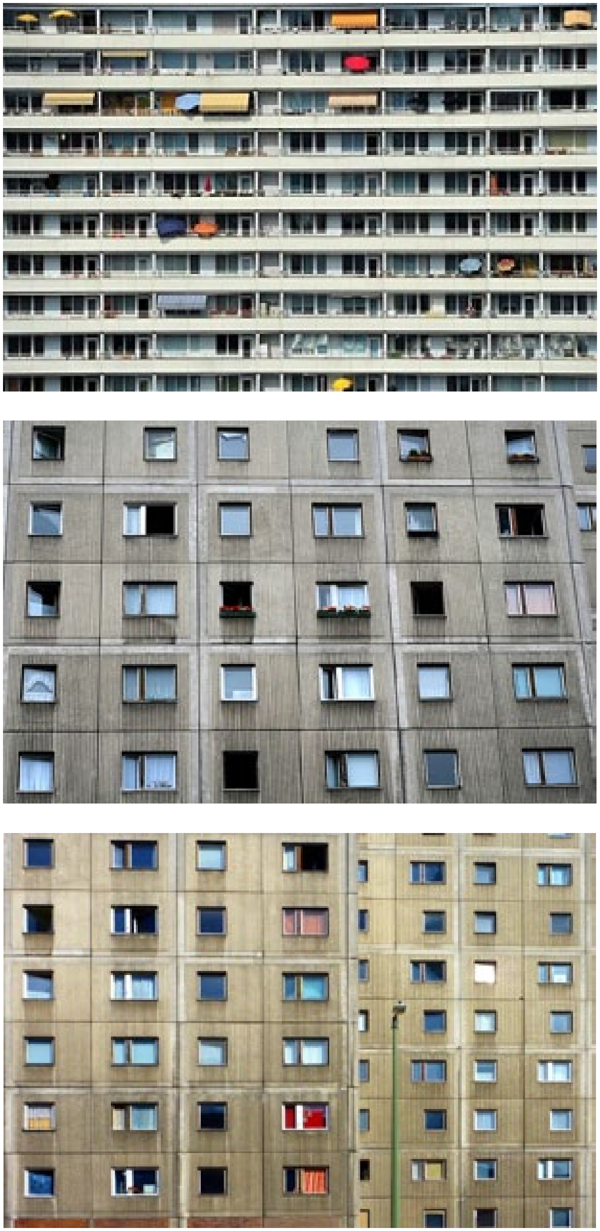

Fig. 17: Facades of different “Plattenbauten” in East Berlin showing uniformity and monotony

“By the time the Berlin Wall came down in 1989, the entrenched panel construction system, or plattenbau, had become synonymous with the monotony of daily life and the suppression of individual aspiration throughout the former Soviet Bloc and in the former Soviet Republics.” [30]

5. MEGA-STRUCTURES | Visions and Utopias

Ever-changing systems

Meanwhile in the West architects also put the search for the modernist ideal of living on a bigger scale but with a lot more visionary and creative impetus. The expected increase of population and all the associated problems of expanding cities led to the design of new, futuristic habitats.

“The goal was that flexible construction systems, which could grow to become enormous, high-density spatial living structures with exchangeable and variable elements, cells and capsules, should offer an alternative concept to the conventional, traditional urban housing model. The city as a process: nothing is fixed, everything could be changed.” [31]

Nagakin Capsule Tower

In Japan architects and designers founded the Metabolist Movement in 1960 that fused ideas about architectural mega-structures with those of organic biological growth. One of the most popular examples generated during that movement is the Nagakin Capsule Tower in Tokyo completed in 1972. Architect Kisho Kurokawa created a tower which consisted of a load-bearing primary structure and prefabricated capsules that were put in that frame. The capsules were designed to accommodate individuals in an apartment or studio space or, by interconnecting modules, families in larger units. [32] The capsules could be exchanged as desired and are fixed with only eight screws at four points. [33] The module was created with the intention of providing housing for travelling businessmen that worked in central Tokyo during the week. It is a prototype for architecture of sustainability and recyclability, as each module can be plugged in to the central core and replaced or exchanged when necessary. In the architect's idea, capsules were to be replaced every 10 years, in order to keep the building up to date and fully functional. Capsules would eventually be transferable from one capsule tower to another, anywhere in the world. However the capsules were actually never replaced, and the building was set for destruction in 2007.

Fig. 18: Nagakin Capsule Tower, Kisho Kurokawa, 1968. Delivery of the concrete units

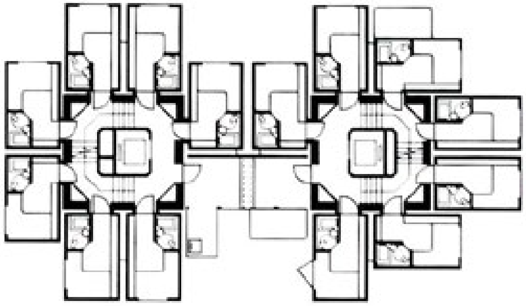

Fig. 19: Nagakin Capsule Tower. Floor plan

Habitat '67

Moshe Safdie, Israeli-born architect, designed as part of the World Expo in Montreal in 1967 another impressive modular housing project called Habitat '67.

The project is based on a basic concrete module measuring 12 x 5.33 x 3 m or 56 m². The modules, or 'boxes' as they are known, are connected in varying combinations to create 158 residences ranging from 56 m² to 158 m². Each unit has access to a spacious private terrace located on top of the underlying unit and furthermore has harbor and city view exposure at least on three sides. Habitat's modules were all constructed of precast concrete panels which were produced by a small on-site factory.
Even though Safdie also applied precast concrete modules, his construction system was significantly different from the Metabolist work. For the Habitat '67 no mega-structure was needed - rather than "plugged-in" prefabricated units, modules were interlocked and woven primarily horizontally. Besides the necessary vertical cores, he focused entirely upon the unit rather than the global structure. Another difference is that the units couldn't get exchanged; they have their fixed spot and are an absolutely irreplaceable part of a greater whole. [34]

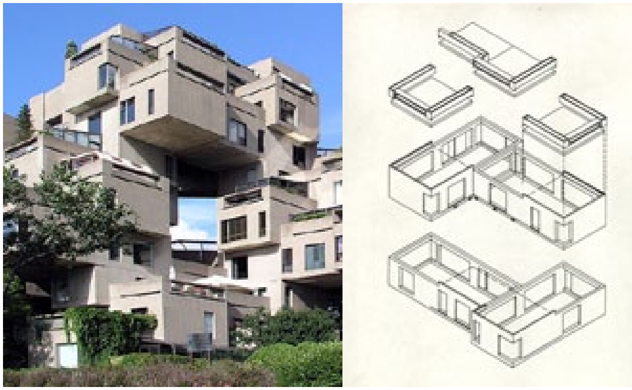

Fig. 20: Habitat '67, Moshe Safdie. Exterior view and assembly of concrete elements

6. OPEN SYSTEM MOVEMENT | Technical and ideological approaches

Steps towards open structures

The desire to create improved architectural systems which allowed for adaptions to personal needs and requirements continued on smaller-scale as well. Buildings with closed systems where nothing can be added or removed were not accepted anymore, *"instead what was needed was the chance to combine the existing/unchangeable with the individual flexible/changeable, order with freedom."* [35]

A technical approach

Ezra Ehrenkrantz founded the SCSD program in California in 1961 which focused on building new types of schools. The system wasn't based on a specific material or design, it only determined the requirements and rules the individual subsystems should provide. The most important novelty that this program was aiming for was the possibility to combine elements from different manufacturers within one system. Construction parts were produced by different companies that could be combined to create new building systems. Some of them were soon released onto the market as industrially mass-produced elements, which ensured the success of this system. *"This cooperation of different manufacturing companies was one of the first truly convincing demonstrations of the efficiency of open building systems."* [36]

In the 1970s Helmut C. Schulitz continued in California this idea of an open market and aimed to develope a system that *"does not start out from the development of new building systems, but rather represents a coordination system that for elements already available in the market."* [37] He wanted to find a system that allows the combination of elements which were already in mass production.

An ideological approach

Whereas this was a rather technical approach to improving buildings systems in terms of flexibility, Aldo van Eyck and Hermann Hetzberger rather saw the solution in a structure that was open to different uses. Between 1967 and 1971 they built the "Diagoon" houses in Delft, implementing their idea of adaptable housing which should be based on an empty framework that can be completed by the residents according to their needs. [38]

Another Dutch architect who was less concerned with the technical system, and more with the possibilities to allow users a maximum of participation on the organization and design of the floor plan was Nicolaas Habraken. He founded the *S.A.R. Stiftung Architekten Research* (Foundations for Architects' Research) in order to find solutions how to achieve such highly flexible structures. His research lead to the "support-infill theory" which was very influential to many projects associated with flexible housing. It is based on the idea of dividing buildings into a loadbearing structure (support) and internal infill elements.

One excellent project based on this theory is Otto Steidle's experimental housing in the Genter Strasse in Munich. Residents could use and alter their housing individually. The primary structure was provided by concrete columns and floor slabs, in which the prefabricated partition and façade modules could be inserted in multiple ways within the structure and adjusted after some time.

Fig. 21: Housing experiment Genter Strasse, Otto Steidle, 1972

7. REVIVAL of BUILDING SYSTEMS | Conclusion

System building after Postmodernism

Despite the development of all these innovative examples of building systems, their realization was rather an exception and many architects turned their back on industrialized buildings during the 1980s. Limited success, the oil crisis and the persistent association with the monotonous postwar designs reduced the former euphoria for technology and standardization. It was once again believed that architecture should be a product of place, materials and function.

"It was not until the present time – almost a quarter of a century later – that, faced with a growing necessity for resource-conserving techniques and the desire to increase design flexibility continuously, thoughts again began to turn increasingly to the concepts of systems." [39]

"Do more with less"

There are very many different ways how modular systems have been used in the past and how they are today. Taking into consideration all the various examples that have been developed over the past century, basically two different ways of making use of a modular system can be defined: a conceptional and a constructional approach. Their focus might be a little different but they both have more or less the same two goals of (1) rationalizing the planning and construction phase to save money, time and energy and (2) giving customers a wide range of different configuration choices for their homes. In order to achieve these goals, some designers break with our traditional way of building houses and apply systems that are based on the principle of only using a limited number of specific elements. Buckminster Fuller already realized half a century ago that "it was possible to do more with less". It increases efficiency in the planning as well as in the construction stage, but also enhances design flexibility because the pre-selected components are standardized and compatible with each other which means they can be combined and exchanged according to different needs.

Conceptional principle

Modular systems can be used in a conceptional sense - in this case the architect has a kit of pre-selected planning modules which to be dimensional defined (two- or three-dimensional). Then they can be combined with each other to configure a living unit or an entire building. This approach doesn't necessarily simplify the building process because it is not bound to a certain material or construction method. Efficiency is achieved by rationalizing the design process. Examples are Frank Lloyd Wright's Usonian

Houses or the concept of “Additive Architecture” by Jorn Utzon. Utzon was inspired by the Case Study Houses in America and the traditional Japanese dwellings when he developed his concept of “Additive Architecture”. It was based on the idea of creating a single family house of unitised modules, which were designed as room types and could be freely combined. This concept didn’t only allow adaption during the design phase - modules could also be added and removed in future to allow flexibility for unpredictable happenings. In his opinion a house that cannot be changed is a waste of space and money.

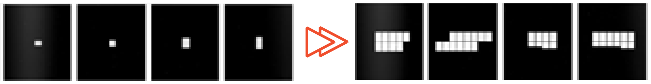

Fig. 22: “Additive Architecture”, Jorn Utzon. A set of pre-selected modules can be combined to various configurations

Constructional principle

But there are also many, probably even more, modular systems which are based on a pre-selection of construction elements. That means that the architect can use certain construction modules to design a building, like wall/window/door panels with specific dimensions or a 3-dimensional box with an explicit size. Materials and construction methods would be defined first and determine the structural framework within the architect can design the building. In other words the building elements define the structure.

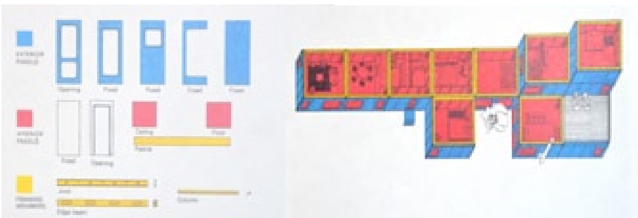

Fig. 23: Stelco Catalogue Housing, 1968. A set of building elements can create different homes

The Stelco Catalogue Housing system by the Canadian firm Barton Myers Associates perfectly illustrates this principle; even though it never passed the prototype-stage. It consisted of a kit of steel columns, beams and a number of different panels for vertical and horizontal surfaces. [40]

Lesson from history

This element-based approach has also been used in the postwar years in Eastern Europe, but in that case the only focus was on the creation of cheap and fast housing. Having learned from mistakes in the past, today’s architects aim to develop smart building systems that are not only money- and time-wise efficient but sustainable in multiple ways. It is very important that the incorporation of standardized and prefabricated elements is not only seen as an end in itself, but more as an instrument capable of enhancing comprehensive design concepts. So in the best case the conceptional and constructional use of modular system would be combined in order to realize the full potential of modular systems.

Considering how many systems, even the ones developed by well known architects such as Walter Gropius, Frank Lloyd Wright, Le Corbusier, etc. have failed and were never fully realized, there is something else we can memorize:

“One of the lessons that can be learned from the many previous attempts at prefabricated housing production is that uniquely proprietary systems of single-sorce components are too costly to develop and have almost always ended in econmic failure, even when excellent in design, detailing, and production concept.” [41]

Meaning, that closed systems which only function with specially designed and produced elements from a certain manufacturer, probably won’t lead to a sustainable building practice in future. It is much more promising to develop building systems which are based on industrially already available materials and elements that can be used by anyone to a reasonable price.

Different approaches today

Today, facing the growing necessity for resource-conserving techniques and the desire to increase design flexibility, modular building systems are promising instruments for realizing sustainable buildings. Many architects have realized that in order to do so they don't have to reinvent the wheel but make use of existing conditions which have been developed since the postwar years. New digital technologies give enormous boost to the further industrialization of building and system development. Computer design has opened up new possibilities for prefabrication, enabling architects to customize houses to different tastes, without sacrificing the speed and efficiency of the production. Particularly younger architects, who already think of design as something that happens in a computer and possess the required knowledge in CAD/CAM technology, are willing to take up on building systems in order to contribute to a more sustainable building practice. Architects use different strategies to reach this goal; some concepts are based on basic and repetitive applied modules during the design stage, some consist of a kit-of-parts that include pre-selected and/or prefabricated modules which can be combined individually, others use entirely finished modular units that only need to get joined together on the building site.

The following chapter gives an overview on building systems and modular building systems and explains the different options how they can be applied.

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[26] *Components and Systems* p. 29

[27] cf. *Home Delivery* p. 38

[28] *Home Delivery* p. 35

[29] *Components and Systems* p. 34

[30] *Home Delivery* p. 23

[31] *Components and Systems* p. 31

[32] cf. *Components and Systems* p. 192

[33] cf. *Components and Systems* p. 32

[34] *Home Delivery* pp. 124ff

[35] *Components and Systems* p. 34

[36] *Components and Systems* p. 37

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THEORY

Modularity is a strategy for organizing complex products and processes efficiently.

(Carliss Y. Clark)

CHAPTER ■■

THEORETICAL BACKGROUND of MODULAR SYSTEMS

As seen in chapter I the application of building systems in general and modular building systems in particular has a long history. Architects have created hundreds of prototypes hoping to change the conventional building industry towards a more efficient and rationalized way of building. Even though none of them succeeded in causing a revolutionary change, their innovative designs aiming to bring better-designed, more affordable, easier to produce housing to the public have influenced architects all over the years and still do. However, most buildings are still constructed in the traditional way, designed individually for each project and carried out on site with the same techniques that have been used for many years. By doing so we don't only unnecessarily waste time, resources and energy but also create buildings with permanent structures, unable to keep up with the quickly changing needs of our society. To avoid this issue, we finally need to start thinking in systems and not in single projects and make use of the technological possibilities of our time.

This chapter defines the basic principles of system buildings and the different types that can be used, including closed, open and modular systems. Its emphasis, however, is on modular building systems, their main features, advantages and disadvantages and questions their impacts on the built environment in terms of uniformity.

1. DEFINITIONS

Building System - System Building

“Building System is a set of parts and rules, where the details are solved so as to generate many different and customized buildings.”[1]

A building system doesn’t aim on creating one particular building, the idea is rather to apply it to the design of many other buildings in different configurations. This makes planning and construction more efficient, because the construction-method is not re-invented each time a building is planned, as it is still the case in many projects. Systems are by no means neutral but should be seen as specialized ways of allowing for more freedom to create. [2] A building system is not a material and fixed entity; it is a conceptual approach to construction. It defines the relationship between the individual elements within a geometrical organizational principle. Building components usually don’t only have one specific location in a building; they can be combined in various ways. To achieve this compatibility of elements standardisation and dimensional coordination are necessary. Therefore it is reasonable to make use of industrialized and prefabricated elements.

Closed vs. open systems

The main parts of a building system are its sub-systems, which generally respond to the main functions of a building. It is usually composed of five sub-systems: STRUCTUE, ENVELOPE, PARTITIONS, SERVICES and EQUIPMENT. The relationship between these sub-systems is decisive whether a system is considered as “closed” or “open” system. Most conventional systems are designed in form of closed systems which means that a limited range of parts are used to simplify assembly; flexibility and disassembly remain problematic. Usually closed systems are developed for a specific building, like a particular multi-family house, a school, an office building, etc. All individuals elements are coordinated and harmonized with one another and can only be exchanged, altered or extended within their own system. Elements of a closed system are fabricated by one single manufacturer and are usually not compatible with elements from other manufacturers. Closed systems can be developed for either an entire building or only for one sub-system. If the system is designed for an entire building it includes all kinds of subsystems which are needed to form a building; elements for the structure, the façade, partition walls, service, and equipment are produced by one manufacturer. This ensures increased clarity and order but also implicates limitations in terms of design options and flexibility. [3]

If an open system is applied, a building is composed of various sub-systems which work and are produced completely independent from each other but can still be matched. Compared to closed systems which are usually designed for a specific type of building an open system allows the formation of various buildings by combining various prefabricated parts. It offers the possibility of mixing and interchanging components from different manufacturers. There is an opportunity for many manufacturers to participate to the system, as long as their dimensions and their interfacing details are compatible. In an open system it must be possible to add, exchange and vary type standardized elements. Interchangeable parts, components and sub-systems form the foundation of an open system. Open systems will most likely become increasingly important in future, because they offer more choice to the user and permit continuous adaption over time. To make that work, a building needs to be separated into independent sub-assemblies which have the same functional and technical life-cycle; then parts of the building can be independently assembled, changed and disassembled. [4]

Closed systems, for example the load-bearing structure, can be coordinated with open systems, for example the internal fit-out.

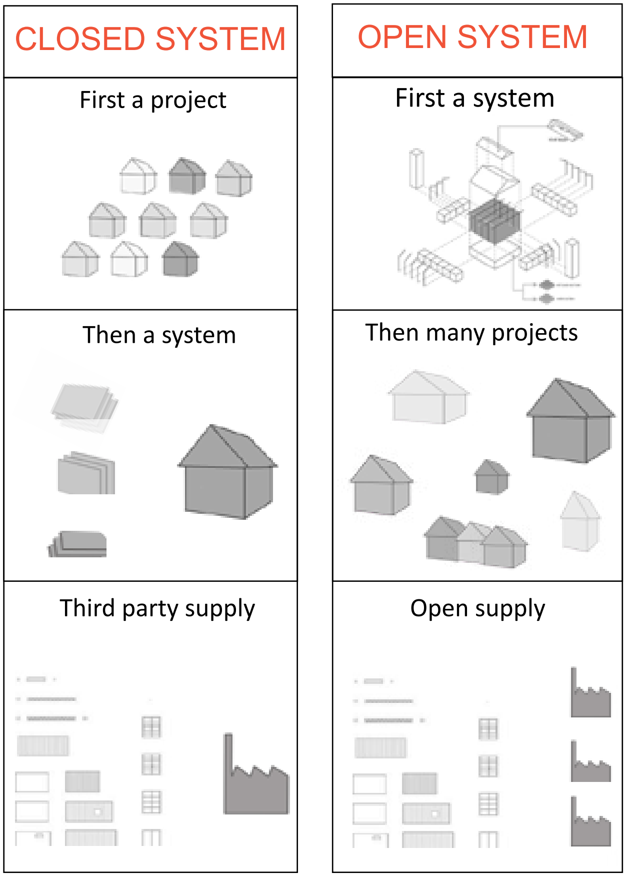


Fig. 24: Main differences between closed and open systems

Modular systems

Modular building systems are a combination of closed and open systems. The biggest difference to open systems is that not every generally available building element can be used, but only a particular number of pre-determined ones. The organization and assembly of these elements must be carried out according to geometrical rules. However, modular systems offer by far more possibilities than closed system do, because they are not designed for a particular building. The elements or modules can be organized into a wide range of various configurations and form all kinds of different buildings. Another big difference to closed systems is the interchangeability of its modules which creates a flexible and adaptable building structure. [5]

Modularity

General meaning

In general, modularity means the division of a whole into a number of components which are called “modules”. These components or modules may be mixed and matched in a variety of configurations. The possibility to combine the modules in various ways is an important feature of a modular system. Metaphorically a modular system can be compared to a kit of building blocks whose components can be connected in many different ways. The opposite would be a puzzle with components that can only function in a certain location and their combination leads to only one specific result (closed system).

Possible benefits of modularity are:

> inexpensive production due to identical constructed series
> low development costs and fast product cycles
> easy assembly and reparation through exchange of the broken component
> realization of a variety of different configurations
> high level of flexibility because modules can be exchanged, removed and added to adapt the system to changed conditions .[6]

Etymology of Modularity

Originally the term “module” comes from the Latin *modulus*, meaning “a small measure”. Today, modularity in a general sense stands for confronting and managing complexity in a dynamic and systematic context. Based on that feature modularity has in recent decades become a common strategy for the organization of information within

and across a number of professions and disciplines, including computer, biology, management, etc.
The Oxford English Dictionary (OED) provides therefore a wide range of various definitions for the noun "module". One of the definitions - also relevant in terms of modular building systems - describes a module as "*a length chosen as the basis for the dimensions of the parts of a building, especially one to be constructed from prefabricated components, all the dimensions being integral multiples of it*". [7]

The OED identifies the origin of this particular usage in a book from 1936, *The Evolving House*, *Vol. III,* by the American industrialist and housing reformer Albert Farwell Bemis. Bemis introduced a new concept to rationalize building methods at the beginning of the 20th century: **modular coordination.**

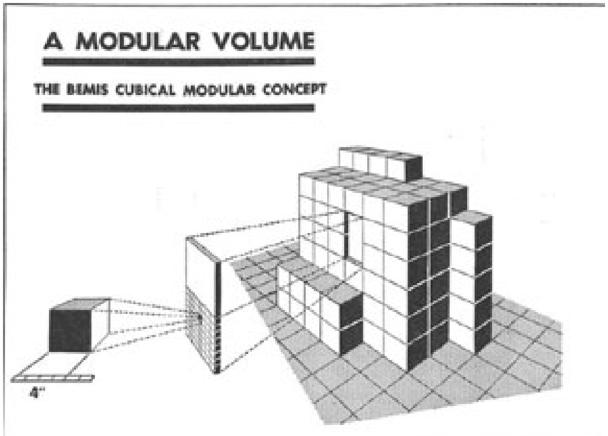


Fig. 25: The Bemis cubical modular concept based on four-inch cubes

His main intention was not only to simply provide a system based of a specific unit of measure, like it was carried out by other contemporary architects such as Frank Lloyd Wright, but to initialize a fundamental reorganization of the US building industry and American society. *"Bemis called for cooperation among architects, manufacturers, and laborers to adhere to a common standard for the dimensions (thickness, length, and height) of building materials. His solution was a theory developed around what he called a four-inch cubical module."* [8] In his belief an industry-wide shift in structural design would lower costs, reduce waste, and increase efficiency.

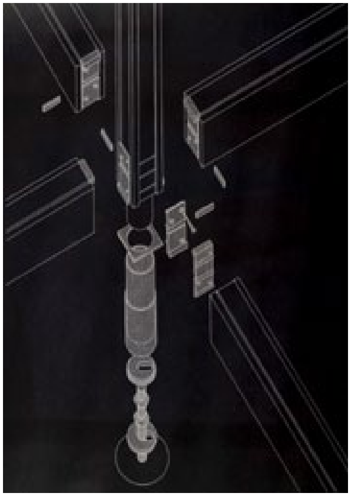
After he died in 1936, his colleagues and heirs, moved by his commitment, developed practical applications of his modular theory but nevertheless in the 1970s, *modular housing* had become little more than a synonym for prefabrication that did not necessarily use a four-inch module. Since builders were under no legal obligation to design on an "open system" basis using a standard four-inch cubical module, many sought to capture higher profits by making proprietary, prefabricated, "closed system" buildings. Since the mid-1970s, the single term "modular construction" has been used to refer either to (1) low cost, prefabricated houses where the requirements of a tight budget overshadow aesthetic requirements or (2) high end, modern, environmentally friendly designs. This indicates that discourses of modularity continue to be fluid. [9]

In the English language, especially in the United States modular construction is primarily identified with buildings which are constructed of three-dimensional boxes.

2. MODULAR BUILDING SYSTEMS

Functional principle

A modular building system consists of a particular number of predetermined elements which can be combined in many different ways to form various configurations. Modularized constructions are usually based on an underlying system, for example a certain grid, to achieve clarity and order. The individual elements can only be placed according to the geometric and construction rules defined by this system but within this framework the building com-



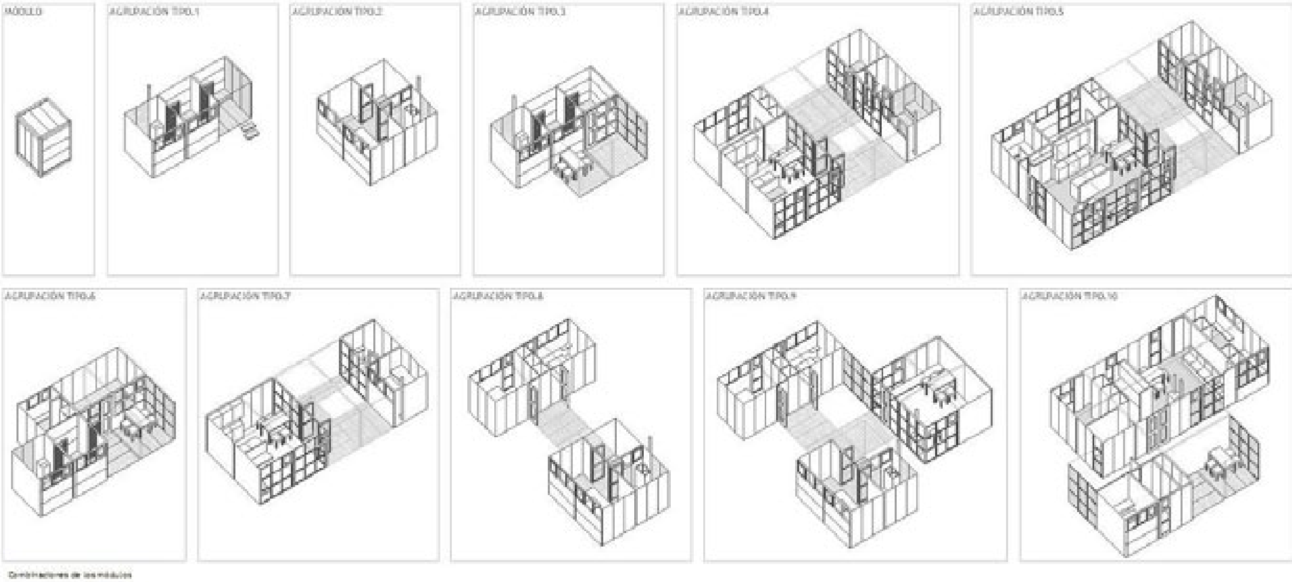


Fig. 26: Gullichsen and Juhani, Moduli 225 house, 1968. Example for a modular building system

ponents should be variable and exchangeable in order to allow future changes. [10] Some people refer to it as "Baukasten", a kit of building blocks, which children usually play with – the most popular one amongst them probably being "LEGO". Lego as well as a modular system in general is based on the idea of providing a kit of different but limited components which are repeatedly used and can be combined to form an almost endlessly seeming variation of construction possibilities.

"Systems in which a user can initially choose a set of modules to match his or her needs are called "configurable". If a user can also subsequently add or subtract modules as or her needs change, the system is "reconfigurable", or modular in use. Reconfiguration may take the form of substitution (e.g. upgrades of existing modules), augmentation (the user adds a module to give the system some new type of functionality), or exclusion (the user gets rid of a module no longer needed)." [11]

The principle that components can potentially be arranged and (rearranged) in an infinite number of ways guarantees flexibility and the use of standardized components would allow adaption over time, with the possibility of elements being replaced or added with the minimum of effort. In its best case this means a high flexibility in terms of spatial arrangements, size and materials. In order to achieve this flexibility in terms of assembly and exchangeability the modules have to be standardized and have matching interfaces. Therefore industrialized methods of production are applied which are associated to a greater or lesser extent with the notion of prefabrication. The result is an even higher rate of efficiency and other benefits related to prefabrication such as a shorter construction period, less costs, higher quality and less waste. [12]

Components of a modular system

Modules

Modules build the foundation of a modular building system. These are standardized, independent and in a repetitive manner used elements of a building. In general modules should be wisely chosen because they determine the extent of design possibilities, flexibility and adaptability. What is considered as module may vary from system to system and from the project stage:

(1) Design phase: During the planning phase modules don't necessarily need to be associated with construction elements yet. They can also be used in a conceptional manner to ease the design process. In this sense modules can be entire living units, rooms with specific functions, or two- or three dimensonal components with certain dimensions, etc. Their use gives the design of a building a structural framework, which makes planning more organized and efficient.

When applying a modular system the architect doesn't start off at the scratch, pre-designed modules build the foundation for the design. That also means that possibilities are not infinite, there are some limitations defined by the system and the chosen modules, but this is not necessarily a negative aspect - it can also make the design process easier and clearer. Depending on the kind of module chosen as basis for the system, the combination and configuration possibilities vary – the use of a smaller module leads to more possible variations, whereas using entire living units doesn't implicate much design freedom.

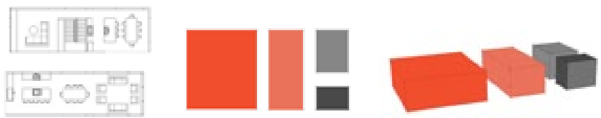


Fig 27: Different examples for possible planning modules: (a) room, (b) 2-dimesional modules and (c) 3-dimensional modules

(2) Construction phase: Modules can also be used for actually constructing a building. In this sense a module would be a linear, a planar or a volumetric actual construction element; i.e. frame elements, panels or prefabricated room units. In building industry usually these three building methods don't appear in isolation but get combined with each. Frame structures are usually combined with panels or room-modules. Regarding the level of flexibility of these three building methods it can be said that *"the frame is the most flexible, followed by the panel system and the modular building methods, while the level of prefabrication follows the reverse order – modular units are the most highly prefabricated."* [13]

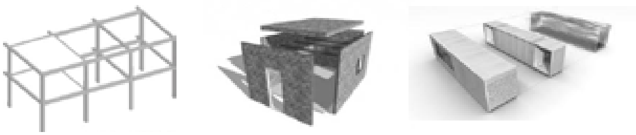


Fig. 28: Different examples for possible construction modules: (a) linear, (b) planar and (c) volumetric modules

Grid

The grid is a geometrical system that determines the position and dimensions of modular building elements. The basis is provided by a network of dimensional lines generally based on a square or rectangular system. Planes, lines and points of reference, whose distance apart is based on the primary module or multiples of it, are required to define the relationship of the individual building elements to each other. [14]

Key features

As already mentioned there is not one specific way of making use of a modular system but lots of different approaches, depending on the project's requirements, the architect's taste, the construction company's preference, etc. In many cases the stakeholders who are involved in the projects develop their own modular system accustomed to their needs. Whichever system is applied it should fulfill at least the following three criteria in order to be considered as a well-perfomring modular system:

1. Limitation of elements:
One of the main characteristics is the limitation of usable elements. Certain components – also called modules – are pre-selected and provide the basis for the systems. In order to design a building, possibilities are not unlimited because only those specific modules can be used in a repetitive manner. The application of such a "kit of parts" enhances efficiency and fastens processes in the design as well as in the construction stage of the project. This may also lower costs and make the buildings affordable for people with different income levels.

2. Variation of configurations:
Despite this restricted kit of parts, modular systems still provide a great variety of possible configurations in terms of size, layout and design of a building. While the elements which can be used are limited, the way they can be combined is not. The customer can mix and match the pre-selected elements as he wishes in order to create a building which exactly meets his individual requirements and personal taste. This ensures that the end-user has influence on the design of his future dwelling - a feature which is especially missing in mass-housing projects.

3. Transformation of spaces:
But not only can living units be customized in the planning stage, modular systems should also provide the possibility to make changes when buildings are already in use. If the user's spatial needs change, new modules can be added or existing ones removed, or if a module is old it can simply be exchanged by a new one without causing the system to become non-functioning. In order to achieve this compatibility the modules need to be standardized, technically exchangeable, and must have appropriate interfaces. *"As its best modularity embeds the principle of exchangeability*

and so it represents an acknowledgement of life-cycles as a direct expression of an integration of the dynamic process of living into the building process: some things simply last longer than others and therefore have to be modified, remodeled, retrofitted or completely exchanged." [15]

Advantages

The application of a modular system brings multiple advantages with it - for the user as well as for the environment:

Advantages for the user

(1) Customization: Everybody has different ideas about how his dwelling should look like. The most obvious difference between homes is the variation in size. Different types of households require different spatial needs which are reflected in the building size. But people have many other individual wishes regarding their homes: Some dwellers want lots of glass in their exterior walls, or would rather admit less sun or light; some prefer living-kitchens to living-dining room; some children need bedrooms in which they can study, while other will do their homework in the living room. [16] These individual preferences differ from person to person and buildings should be able to fulfill these personal wishes. Modular systems make this customization of living spaces possible, not only in detached houses and expensive high-rise buildings but also in public housing projects. The "end-user" gets involved during the planning stage and has an influential role. By combining the modules with each other the user determines the layout of his own personal dwelling and doesn't need to adapt to any given floor plan designed by any architect who might not even know the dweller or his preferences. Besides varying visions regarding size and layout, people's income level differs as well. While some wish high quality and luxurious finishes other dwellers would rather prefer laminate to parquet floors in order to afford some extra square meters living space. Especially in large housing projects where everything is as standardized as possible this might not be practical. But the use of modular systems makes the differentiation in quality and finish easier and ensures that people of different social classes can live in the same building.

(2) Adaptability: Many buildings, especially mass housing projects, are defined by a rigid structure in which it is difficult to change any individual part. This makes them difficult to change under the impact of life. We never know what circumstances we are confronted with in future and we can't always plan ahead. Life situations change constantly; families grow or shrink, a new job might require the establishment of a home office and our income levels rise and fall. All these factors affect our needs and requirements in terms of size, layout and quality of our living units. Since most are not adaptable, people need to move to different apartments or houses which can fulfill their needs. One of the main advantages of a modular system is its flexibility – buildings can be constantly adapted. [17]

(3) Affordability: In most cases, modular building systems make use of industrial production methods in order to achieve standardizes dimensions and interfaces. Prefabrication of elements goes along with an increase in production efficiency, because a certain number of elements are produced over and over again. This makes use of the principle of economy of scale and results in a shorter construction time, higher quality and an easier and faster assembly process on site which most likely leads to a reduction of costs and makes it affordable to people with different income levels. [18]

Advantages for the environment

(4) Energy reduction: In modular systems the same construction elements are used over and over again. They have standardized dimensions and appropriate interfaces in order to achieve compatibility of the components. This standardization allows machine production and prefabrication to be applied to a high extend which means that the

production processes get more efficient (i.e. shorter construction period and higher quality) and therefore require less energy in general. The factory working conditions also minimize waste and increase recycling. Any material or element that is left over can be used for another project or at least get recycled properly. It also reduces waste on the site itself because the materials arrive specifically sized for the project. [19]

(5) Lifecycle extension: The interchangeability of building parts leads to ecological benefits regarding the entire life cycle of a building. Because modular systems provide the possibility of adaptions to unpredictable requirements in future, the life span of a building extends automatically. If the demographic structure changes dramatically and different living units are needed or if a component doesn't function anymore, buildings based on a modular system can adapt to these changed conditions more easily. Only components would be exchanged, added or removed in order to re-organize living units; the structure of the building would remain the same. This flexibility reduces energy-consumption of new production and demolition. But not only the life span of the building itself extends; also the different modules or building parts can be used for a longer time. Once windows, walls panels, doors, etc. aren't needed anymore in their original position, they can just be dismantled and re-used on a different spot or in a different building.

Disadvantages

Of course not all modular systems that are developed bring only advantages with them. Some buildings are not able to realize the most important features of a modular system, but downsides differ from system to system and it is therefore difficult to generalize disadvantages. However, problems that hinder a modular system to be successful are usually based on an inappropriate choice of modules in terms of size, layout, dimension, and design.

Another reason is that the guaranteed flexibility and exchangeability of elements is affiliated with an unproportional high technical effort and therefore never gets carried out. Customers also have to accept that opportunities are not endless - design possibilities are bound to the use of certain elements. So if a customer wishes a round dwelling it will not be possible with only straight building elements. Sometimes the realization of building systems fails because people have negative associations with it and fear its application would result in uniformity. They also might argue that it is not real architecture because the design is not entirely specific to a site.

Standardization and uniformity

Because the use of building systems involves at least to some extent systematization and prefabrication, some people fear that their application would result in uniformity of the built environment. This attitude is mainly based on the prefabricated houses that were built after World War II, having their focus rather on speed and cost reduction than on aesthetics. But this is not necessarily true. If we make use of standardized building elements wisely and let potential homeowners customize their dwelling to their taste, a high range of differentiation will be achieved. Carlos Martin of the U.S. Department of Housing and Urban Development (HUD) explains in an interview in the DWELL Magazine:

"Too often we equate standard building components with sterile and uniform design. But we all had the same box of Lincoln Logs [Note: a children's toy consisting of miniature logs to build houses] as kids, and I never knew one kid who built the house on the box cover, or who would built the same structure every time they emptied the components. This myth of prefab's banality couldn't be further from the truth. […] The trick is to find that magic tipping point where you can use prefabricated materials, components, systems and modules and still cre-

ate innovative and site-specific buildings." [20]

Also John Habraken argues that the reason for uniformity is *"not due to the action of the machine, but to the non-action of the man".* [21] That means that as long we involve individual people in the planning process and give them a reasonable variety of customization choices the outcome can't be uniform since we all have very different expectations and needs in terms of our living environment.

Fields of application

Ordinary vs. extraordinary buildings

Modular systems are usually used for housing projects, hotels, hospitals, or office buildings. These fields of application provide the biggest potential to realize the benefits of modular systems, because each of these building types can be constructed of many similar parts and modules. This means that the economy of scale can be applied. Every other type of building, which has a high cultural or public importance, for example a museum, should be unique and therefore designed entirely specific for a site using appropriate construction methods.

Single vs. universal use

Most modular systems only look at single projects. Architects and construction companies worldwide develop modular system for their own projects: every series is a new design, made up from several new details and elements. However, there are some attempts by different groups to develop systems which would be applied nationwide or even internationally - known as the "Open Building" movement. Open Building is *"a way to reorganize the housing industry toward a more consumer-oriented and efficient industry. It also represents a new view linking technical issues to social and equity issues that are also important components in any consideration of sustainability."* [22]

Their idea can be compared to the production of the modern kitchen: Different manufacturers market kitchen consisting of elements which, by means of dimensional standardization, can be fitted together in innumerable variations. Sink units of different lengths and widths, different cupboards which can be placed beside or above them, systems which allow the inclusion of dishwashers, cookers, washing machines, refrigerators - independent from the manufacturer can be combined with each other; the principle is as wide and complete as one may wish. And due to the different taste of each dweller this standardization wouldn't result in uniform solutions. [23] This principle could also be applied to some kinds of buildings, especially when it comes to housing projects. This would mean a big change in the building practice as we know it today.

NOTES:

[1] Richard, Roger Bruno: *Looking for an Optimal Urban Residential System?* In: International Journal or Construction Management (2005 Vol. 5, No 2) p. 93-104

[2] cf. Durmisevic, Elma: *Transformable Building Structures*. [Diss. Delft 2006] Delft: Cedris M&CC 2006 p. 152

[3] cf. Staib, Gerald/ Dörrhöfer, Andreas/ Rosenthal, Markus: *Components and Systems* - Modular Construction. Munich: Birkäuser Verlag AG 2008 pp. 42f

[4] cf. *Transformable Building Structures* p. 153

[5] cf. *Components and Systems* p. 43

[6] cf. http://de.wikipedia.org/wiki/Modularit%C3%A4t

[7] Russell, Andrew L.: *Modularity - An Interdisciplinary History of an Ordering Concept*. In: Information & Culture: A Journal of History (Volume 47, Number 3, 2012) pp. 257-287. Published by University of Texas Press p. 261

[8] ibid. p. 264

[9] cf. ibid. p. 269

[10] cf. Schneider, Tatjana/ Till, Jeremy: *Flexible Housing.* Oxford: Elsevier Inc/Ltd. 2007 pp. 175f

[11] Baldwin, Carliss Y./Clark, Kim B.: Design Rules - The Power of Modularity. MIT Press 2000 p. 136

[12] cf. ibid. pp. 23f

[13] *Components and Systems* p. 42

[14] cf. *Components and Systems* p. 44

[15] *Flexible Housing* p. 175

[16] Habraken, N. John: *Supports* - An Alternative to Mass Housing. 2nd edition, U.K.: The Urban International Press 1999 p. 88

[17] cf. *Flexible Housing* p. 175

[18] cf. *Flexible Housing* pp. 21ff

[19] cf. Bernstein, Harvey: *Prefabrication and Modularization - Increasing Productivity in the Construction Industry.* In: SmarkMarket Report, edited by McGraw-Hill Construction: National Institute of Standards and Technology. 2011

[20] Interview by Arieff, Allison: *Carlos Martin on the PATH Concept House.* In: Dwell Magazine (April/ May 2005) p. 128-132

[21] cf. *Supports* p. 25

[22] Kendall, Stephen: *Open Building - An Approach to Sustainable Architecture.* In: Journal of Urban Technology (Dec. 1999, Vol. 6, Issue 3) p. 1-16

[23] cf. *Supports* p. 76

STRATEGY

“

A building is not something you finish.
A building is something you start.

(Stewart Brand)

”

CHAPTER

STRATEGIES and METHODS of MODULAR SYSTEMS

After having defined the main characteristics of a modular building system, this chapter will specify on how it can be incorporated into an architectural project. The first part describes the different design strategies that can be applied and illustrates them by means of contemporary architectural examples. Even though they all fulfill the requirements for a modular system, they are quite different, depending on the kind of modules the architect has chosen to use.

The second part deals with the technical requirements that need to be considered in order to guarantee that a modular system also functions in reality. Building modules need to have matching dimensions and interfaces; otherwise they can't be mixed and matched with each other and fail to achieve one of the main characteristics of modularity. To simplify this standardization process, many modular systems implicate industrialized production methods and prefabrication of their building elements. This extends the efficiency of modular systems from the design- to the construction stage, because the use of prefabrication has great potential in reducing time, costs, resources and energy.

Not every building material and construction is suitable to achieve these advantages however, and therefore it is important to know what options are reasonable and how they can be applied. The last part of this chapter will give an overview on the most commonly used construction principles and materials in terms of building systems.

1. DESIGN STRATEGIES

There is not one specific way to make use of a modular system when it comes to designing a building. Since this term allows a broad range of interpretations, there are several different design approaches. They all have in common that they are composed of a number of modules that may be mixed and matched to achieve a variety of configuration. But what architects consider as “module” may differ from project to project as long as it is the basic foundation for a system. A module could be an entire living unit, a defined part of a living unit or even wall or window panels with a certain dimension which can be combined to form a living unit.

One can say that a modular system can be used in either a conceptional or a constructional sense. Either way, it brings a limitation of selectable elements with itself – based on the idea to enhance possibilities by restricting yourself and “do more with less”.

In best case those two approaches are combined within one project to maximize the potential and benefits of modular building systems. That means that the dimensions of the modules used in the design stage should be harmonized with construction components and vice versa.

Conceptional principle

A modular system can be used in a conceptional sense. In this case the architect has a kit of pre-selected planning modules that he can use to create a building according to specific needs. The architect is not restricted by building element sizes (yet), only by the dimensions of the modules he had chosen. That means that the elements used for construction will be adjusted to the dimensions of the design modules. However, it is reasonable also to consider the construction method or material when choosing a module’s dimension in order to simplify the production and building process.

Characteristics:

- > planning gets easier and more efficient because the designer is limited to some specific modules which he, however, can determine himself
- > modules are compatible with each other and can be mixed and matched in many different configurations which provides a certain extent of design freedom and customization possibilities
- > dimension of modules don’t necessarily depend on certain construction elements; modules are understood as a practical unit
- > customer can actively participate in the design process because it is usually very simplified

Option I: SPECIFIC MODULES

The modules are particular parts of a living unit with already determined functions (kitchen, bathroom, bedroom, etc.). The architect/client can choose form a certain selection of pre-planned elements and combine them according to his specific needs. A variety of building configurations and sizes are possible.

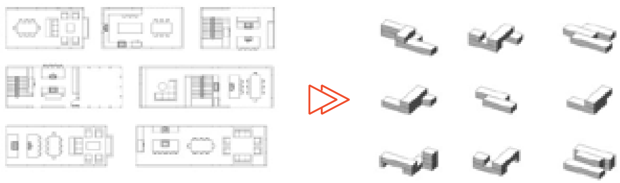


Fig. 29: Pre-planned rooms can be combined to lots of different living units (Resolution 4 Architecture)

▶ Example: Resolution 4 Architecture - Modern Modular

This New York based architectural firm is dedicated to addressing 21st century conditions through intelligent architecture and design. Their system of design, called the

"Modern Modular", started out as a study on how modern home design can be transformed to take advantage of the economical, environmental, and structural benefits of standardized modules and is now being realized quite successfully.

"Modern Modular homes are designed with a focus on creating a wide range of living solutions capable of being adapted to meet the varying needs of a broad and diverse audience. Through extensive research and design, Modern Modular provides a full line of houses to fit different uses, be it a solitary residence, weekend home, or full-family house. Through a focus on modular living units, houses are fully customizable to meet functional requirements of different locations and climates, and the specific needs of different households. Homes are easily expandable and transformed, allowing Modern Modular homes to grow and adapt to its residents." [1]

Functional principle: It consists of a series of predefined modules which can be combined by the homebuyer to create a home which exactly meets his requirements and needs regarding size, layout and design visions. The predetermined line is divided into 7 typologies which illustrate potential concepts in organization of layouts including the single wide, the double wide, the triple wide, the courtyard, the T, the L, and the Z-series.
The homebuyer chooses one of these series depending on his taste and the requirements of the building site and can then customize his home by selecting the number and type of modules.

The modules are divided into:
> communal modules of use: kitchen, dining and living space
> private modules of use: bed- and bathrooms and storage space, and
> accessory modules of use: staircases or an additional home-office.

These modules can be combined horizontally as well as vertically to allow for a unique response to each client, site and budget. [2]

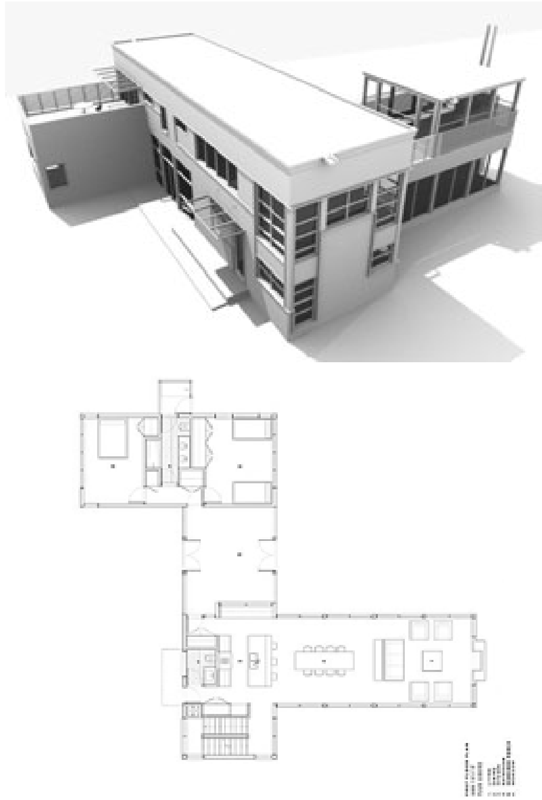


Fig. 30: Example of a *Modern Modular* house - Summer Retreat in East Hampton NY, 2006: Z-series, 4 modules

Option II: BASIC MODULE
Another possibility is that there is only one basic module with certain dimensions but no specific function. It can be connected horizontally or vertically to create different sized and formed units. The architect/client can choose as many modules as he wants to create a living unit depending on the client's spatial needs.

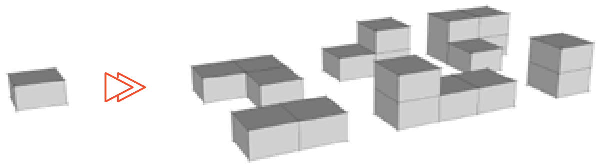


Fig. 31: The basic module approach offers many option, even though minimized to only one module

▶ Example: KFN Kaufmann product gmbh - KFN Modul System

The Austrian architects Oskar Leo and Johannes Kaufmann have spezialized themselves on building systems made of timber elements. One of their systems they have developed is the KFN Modulsystem, which focuses on a high rate of efficieny and flexibility in terms of form and materials.

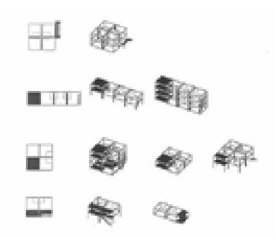


Fig. 32: Left: different configuration possibilities of the system, right: 2-family-house in Andelsbuch as prototype, 1997

Functional principle: This construction system offers a variety of different configurations. It is based on a 5.0 x 5.0 m module which can be connected horizontally or stacked vertically as desired, thus permitting flexible layout and dimensioning of the individual spaces. The structural timber frame is filled with prefabricated wall and floor elements. The wall units include both, external and internal cladding, isolation, windows and glazing, sunscreens and service runs. The building envelope is completely separated from the interior partition which allows for flexibility and convertibility of the building design. The dimensions of the basic module were also considered in the construction phase: The wall units measure 5.0 x 5.0 x 2.7 m and match exactly with the basic module used for planning the building. [3]

Constructional principle

There are also modular systems which are based on a pre-selection of construction elements. In these systems the modules are pre-selected wall, window, and door panels with certain dimensions which are usually based on a planning grid. So if the planning grid measures 1.0 x 1.0 m, the modules also have a width of 1.0 m (or a multiple of it) or vice versa. The architect/client can combine the different modules in a random order and can create a variety of units, different sized and different shaped – as long as his designs are aligned to the planning grid.

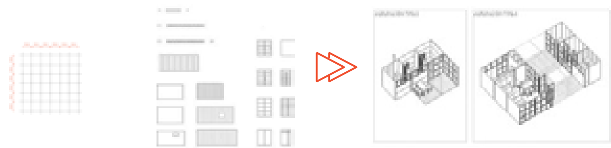


Fig. 33: Pre-selected construction elements (walls, windows, doors, etc) can be combined to different buildings

Characteristics:

> allows the use of industrialized off-the-shelf elements which reduces costs and time

> due to lower costs houses get affordable for a broader audience and therefore more socially sustainable

> the modules or construction elements are industrially standardized and should be designed to be exchangeable which extends the overall lifecycle of a building

> the design is based on building elements and not the other way around

▶ Example: Charlie Lazor - FlatPak

“FlatPak is a design game that even a kid can play,” says Charlie Lazor, the architect of FlatPak. *“It is designed to be easy understood and manipulated by a layman.”* [4] The FlatPak system is highly adaptable, easy to use and gives the customer a great choice of customization according to his and the site’s unique needs.

Functional principle: The system is based on an 8-foot grid (ca. 2.45 m) and consists of prefabricated external wall panels which can be combined in a variety of configurations. The flexible kit can be broken down to three basic components: concrete wall panels, wood-framed panels filled with wood, metal or cement and wood-framed panels filled with glass. Together with the FlatPak designer the homebuyer can design his own special floor-plans as long as they are aligned to the 8-foot grid. After the layout is determined he can choose between the various types of claddings to respond to the site and to his and his family’s needs. The FlatPak system is also designed to be as wide and long as you like, so it could even be used for a multi-unit dwelling. The maximum height is 4 stories.

The way the house is constructed is very simple, the static system is based on a post-and-beam construction and the elements are held together by bolts. This simplifies assembly, which only takes about 15 days, but also disassembly. Not because Lazor subscribed to the idea that his buildings would get reassembled somewhere else, but rather to handle the ultimate disposal in a greener manner and make parts reusable.

Inspired by architectural icons like the Eames house, Lazor used off-the-shelf construction elements and buys them from multiple manufacturers to avoid dependency. [5]

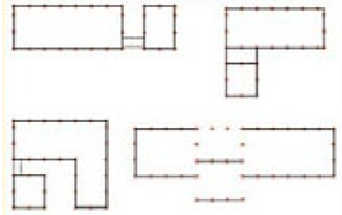


Fig. 34-36: Top left: choice of facade panels, top right: some possible floor plans, bottom: built FlatPak

Mega-structures

A modular system can also be applied in order to design projects in a larger scale, such as multi-family houses or buildings with mixed functions. In this case the architect can define a basic module – usually a living unit – which can be extended by combining it horizontally or vertically. This allows dwellers to customize their home and generate some extra room for a further child or a working space. If their spatial needs change after some time, they can drop additional modules and minimize the living area again. Small units can be transformed in bigger ones and vice versa. This principle counts for offices or stores as well.

▶ Example: MVRDV - RØDOVRE SKYVILLAGE

One recent example for a mixed use building whose design is based on a modular system is the RØDOVRE SKYVILLAGE or “Pixel Tower” in Copenhagen by MVRDV. It won the first prize in a competition carried out in 2008 but has not been realized yet. However, it perfectly illustrates the potential of modular buildings regarding flexibility and sustainability. The architects wanted to create a new building concept for the unstable market in Copenhagen. “*Where offices can easily be transformed into housing – and vice versa. Where smaller units can be transformed into bigger ones – and vice versa. How to realize this flexibility?*” [6]

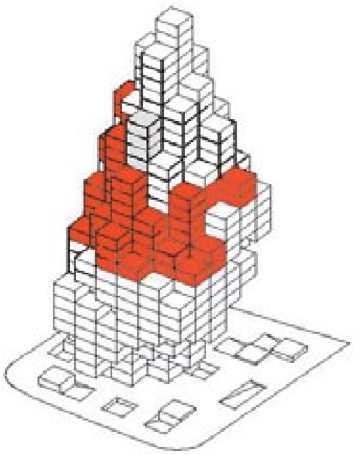


Fig. 37: Pixel Tower, MVRDV, 2008. In this project the chosen modules are entire (living-) units

The result is a tower based on a grid structure with a basic module (or pixel) size of 7.8 x 7.8 m. Any configuration can be filled in within these dimensions. According to the architects the grid-size of 7.8 x 7.8 m combines a good parking grid, a proper housing unit and office type (a unit of 7.8 x 7,8 x 4 m, equals approx. 60 m² or 240 m³), that can easily accommodate a large variety of tenants, e.g. young people who want to live close to the city and starters in the office market. *Small offices and home offices... a vertical SOHO! The units, or pixels, can also be joined together to form larger spaces to accommodate larger apartments, hotel rooms or offices. A sustainable structure arises. As well as a mixed use building!*” [7]

2. TECHNICAL STRATEGIES

Industrialized production

Using a modular system implies the limitation of parts a building is made of, because the same elements are applied over and over again - just in a different configuration. To make modules interchangeable with each other not only on plan but in reality, construction components need to be standardized and have matching interfaces. Since only a certain number of construction elements are used in a repetitive manner to set up the building, this allows machine production to be applied to a high extent. Of course a building which has been designed based on a modular principle could be realized in bricks and mortar as well, but that would mean that the potential of a modular system is not fully exploited.

The fact that dimensions and elements are limited anyways offers a perfect opportunity to improve the production process by involving industrializatial production. This term basically means the automation of building construction utilizing advanced equipment and technology to minimize human involvement.

There are some advantages the industrial production of building elements brings with it which are especially beneficial when using a modular system:

> Standardization: Standardization is the process of developing and implementing technical standards. The standardization of components means reducing the number of part types in order to make production more

efficient. Benefits include savings in costs and time, enhanced quality and a lower environmental footprint. [8]

> Dimensional coordination: The dimensional coordination of a building system determines the spacing, function and location of the building elements as well as their relationship to each other by using a standard dimensional unit in association with planar and spatial grids.
> Matching interfaces: In order to realize that modules can be mixed and matched as desired they need to have the same interfaces. This simplifies the connection process. By using machine production the identical interfaces can be easily produced over and over again. [9]

Prefabrication

With the development of prefabrication techniques the possibilities of using interchangeable building units emerged. Industrial prefabrication of building elements has been possible since the beginning of the 19th century, with the advent of industrialization. Prefabrication is simply a process of making a series of pieces in one location (factory), delivering them to another location (building site), and joining the pieces into a larger whole. The vast majority of buildings constructed today use some form of prefabrication, because this method certainly brings advantages with it. In general, benefits related to prefabrication compared to traditional on-site construction are a shorter construction period, less costs, higher quality and less waste. It can be carried out to different extents, which determine how much work is left on the actual building site. For a long time prefabricated buildings had a bad reputation, associated with "*Plattenbauten*" in Europe or mobile homes in the U.S. But as people realize the advantages of prefabrication this stigma slowly fades away and currently - especially in the U.S - a big revival of applying prefabrication is taking place. Prefab houses are no longer cheap, temporary buildings, but have become high-quality, up-market buildings. Computer design has opened up new possibilities for prefab, enabling architects to customize houses to different tastes, without sacrificing the speed and efficiency of the production.

Advantages

(1) Project schedule: The most significant benefit is the increase of productivity, which primarily means a reduction of the construction schedule. This is based on the fact that on-site work which often leads to delays and loss of quality is transferred into a sheltered facility, where building elements can be manufactured independently of the weather and under optimal production conditions. Another timesaving factor is the possibility to work simultaneously on the site preparing the foundation and in the factory manufacturing and pre-assembling the elements. [10]

(2) Quality: A major advantage of building with prefabricated elements compared to traditional construction techniques is the constant quality level achieved by production in plants. [11]

(3) Costs: Costs can be reduced primarily due to a shorter construction time but also through less labor and less material costs. However, it is important to find a reasonable way of transporting the elements from the factory to the building site; otherwise these cost savings are off-set through transportation costs.

(4) Predictability: Even if costs can't be minimized decisively, the customers appreciate the value of having guaranteed, fixed costs. In traditional construction projects costs often increase significantly due to weather delays or other unforeseen circumstances. But when producing building elements in sheltered plants it is much easier to stick to the budgeted costs.

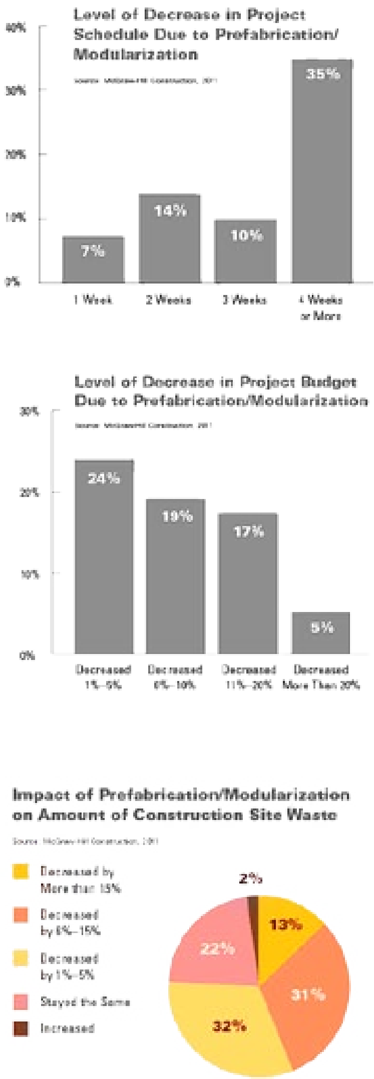


Fig. 38: Results of a study carried out by McGraw-Hill Construction in the United States in 2011. 809 contractors, architects and engineers were asked about their experiences with prefabrication

But cost and time savings are not the only driving forces for prefabrication today. In times of increased ecological awareness the "green" benefits of prefabrication are getting more and more significant:

(4) Waste/Materials: According to the industry, factory working conditions minimize waste and increase recycling. Any material or element that is left over can be used for another project or at least get recycled properly. It also reduces waste on the site itself because the materials arrive specifically sized for the project. Once the lifecycle of a building is over it could get disassembled instead of demolished and its components could be reused for a different project.

(5) Site impact: Prefabrication means a minimal environmental impact of the construction process on the site, both in terms of duration and affected areas.

(6) Tighter Envelope: Large prefabricated panels have fewer joints that need to be sealed on site and are usually "tighter". The tightness is especially important for an efficient energy performance of a building.

Constraints of prefabrication

(1) Acceptance: Because of the prefabrication building techniques applied during the post-war era in Europe and the negative reputation of mobile or manufactured homes in the U.S, prefabrication has developed a stigma of "cheapness" and "poorness", which is still not completely abandoned yet. People also fear that prefabrication goes along with uniformity; this belief is also based on mistakes that had been made in the past.

(2) Design: Especially in the past industry was lacking of technologies for mass-customization; everything mass-produced was identical. If architects did customize prefabricated buildings to different tastes, they had to give up on speed and efficiency of production. Today modern, computerized planning and production techniques are capable of developing, producing and assembling distinct

elements.

(3) Transportation: The transport of larger building elements has always been and still is problematic. Particularly the transport of entire room-modules implicates high costs as well as restrictions of size, weight and design.

(4) Preparatory work: In order to guarantee smooth processes and matching components a high level of detail and time commitment is required during the planning stage.

Classification of prefabrication methods

There are several ways to integrate prefabrication in a construction process. Whereas the use of simple elements such as precast concrete slabs or timber frame panels is widely spread, the incorporation of entire structures or finished room-modules is still not very common in Europe. However, in the U.S. the use of highly prefabricated room-modules is getting more and more popular.

1.

2.

3.

Fig. 39: Different degrees of prefabricatin. 1. simple components, 2. panelized structures, 3. modular room-units

1. Processed materials/simple components: Building elements such as panels, floor-slabs or columns that are fabricated off-site represent the lowest level of prefabrication and are commonly used in construction today.

2. Panelized structures: Panelized structures are assemblies of a series of prefabricated elements, for example wall panels that already include windows and doors, which shortens the construction time on site and enhances the quality compared to traditional construction methods. It basically means that a home gets cut into a series of two-dimensional pieces that could then be flat packed on a truck for transportation from the factory to the building site.

3. Modular room-units: When prefabrication is taken to its logical conclusion, one ends up with three-dimensional, volumetric elements which only need to be lifted into place once they arrive on site. They are almost entirely complete (up to 95%) including finished interior and exterior surfaces. While this method has some considerable advantages, the shipment of the modules implicates high costs and dimensional restrictions. [12]

Transport

Since the key element to this type of construction is its production “off-site”, it is very important to be familiar with the possibilities and restrictions the transportation industry provides.

To enable the transport from the factory to the site, a building gets broken down into its individual components. This fact has caused problems ever since, because the transport, usually carried out by trucks, implicates limitations to the design as well as high costs. The monetary aspect is especially evident when it comes to the shipping of three-dimensional units where the cost savings in construction are typically offset by the transport costs of these large elements. This is why many architects prefer using two-dimensional elements such as panels or post-and-beam-constructions which require more work on site, but allow

a higher design freedom and a smaller budget.
The height, width, length and weight of the elements are restricted by the physical limitations of the truck and the road itself. Every state has its own transportation rules which make it even more difficult because a module must not only be aligned to the state rules where it is produced but to each along its path of travel. The authorized dimensions for a truck in Austria are 2.55 x 4.0 x 12.0-16.0 m. In special cases oversize loads are allowed but require a special permit. [13] When it comes to distances, the economical transport radius is determined by the value of the building element and the costs of transporting it. Transport by road is standard procedure for distances up to 1000 km and avoids repeated and costly load transfers.

type, weight and value of building element	economic transport radius
heavy, raw building materials e.g. prefabricated reinforced concrete elements	up to approx. 100 km
middle-weight, raw building materials e.g. prefabricated steel elements	up to approx. 300 km
light, highly-refined building elements e.g. external and internal walling	up to approx. 600 km
completely finished elements e.g. sanitary blocks, mobile homes	up to approx. 1000 km

Fig. 40: Economic transport radius of various building elements

In the United States the transportation of modules or entire houses has a long tradition because it is much easier due to the wider roads and bigger trucks. However, dimensional restrictions vary from state to state which makes it important to plan the path of transport in advance. Transportation can also be carried out by ship or railway, even helicopter delivery is possible but due to the exorbitant costs, only for extremely inaccessible sites.

In order to reduce the dimension of modules and with it the transportation costs but still achieve a high level of pre-assembly designers have come up with quite a number of creative ideas. The most obvious solution which is especially widely spread in the U.S. is to erect the house on a wheeled chassis and tow it to the building site. This chassis is permanently attached and gives the owner the possibility to move without much effort – for this reason this kind of housing is commonly known as “mobile home” or “manufactured home”.

Fig. 41: The “mobile” or “manufactured home” in the U.S. is built on a wheeled chassis which also remains part of the building once the building is delivered to its site

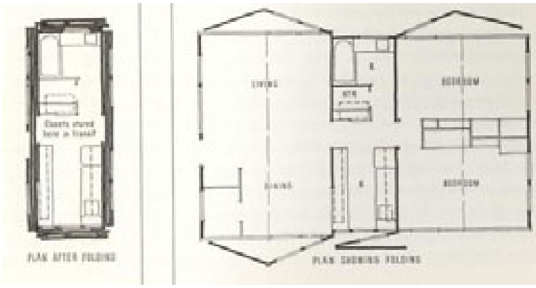


Fig. 42: Acorn House by Carl Koch: ships as one volumetic module with a hinged panelized system to save on transportation costs (1958

Carl Koch tried to improve this concept by applying the principle of fold-out elements in the year 1958. The central utility of his Acorn House was built on a steel chassis and would be transported to the site on the flatbed of a truck. Attached to the core was a panelized skin that rotated on hinges, allowing the exterior walls, floors, and roof system to fold out and create bedroom, dining room and living room. [14]

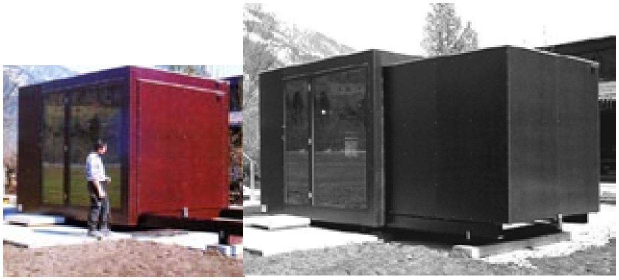


Fig. 43: *Fred*, Leo and Johannes Kaufmann, 2001; making use of the principle of expandability

Another way to make the transport of three-dimensional units more feasible has been adopted by Austrian architects Leo and Johannes Kaufmann. *Fred* is one of the few projects that explore the idea of building in expandability. It consists of two boxes; one is slightly smaller and slides inside the bigger one during transportation.

Assembly

The erection of a building based on prefabricated elements typically requires only a fraction of time compared to erecting a stick-built house. Elements arrive in the right size and partly pre-assembled so that all that needs to be carried out at the building site is assembling and fitting. This includes hoisting, positioning, adjusting, connecting and waterproofing. Whether this is a matter of hours or of weeks depends on the chosen extent of prefabrication and pre-assembly. Logically, the assembly of room-modules which only need to be jointed together is less time consuming than setting up a system of panels, even though with the help of a crane this doesn't take very long either. As already described above, minimizing the amount and the complexity of work that needs to be done on-site has several benefits. The controlled environment of a fabric and the independency of weather conditions provide a far more ideal construction surrounding which results in higher quality and a shorter time period. Another time-saving factor is the possibility to work simultaneously on the site preparing the foundation and off-site manufacturing and pre-assembling the elements. The most important requirements to guarantee an easy assembly on site and the possibility to change the system on a later date are dimensional coordination, matching interfaces as well as efficient connection techniques. [15]

Disassembly

Many modern buildings today are made of prefabricated components designed for an easy assembly, but not for disassembly. If buildings reach the end of their life cycle or simply can't adapt to changed conditions and requirements, they get demolished in most cases. In doing so, materials and energy brought into our system are often thrown away, together with tons of non-recycled materials, which go into landfills. Buildings which can be disassembled make it possible to divert the flow of materials from disposal and save the energy embodied in them by avoiding the demolition process.

To make a building demountable it requires a lot of consideration in the planning stage in terms of choosing the right of materials, structures and connections. Only by naming a few requirements for disassembly one can see that this is a quite complex topic:

> materials need to have a high quality to be feasible for reuse and recycling

> connections need to be demountable and accessible; if possible no chemical connections should be used - only bolted, screwed and nailed connections

> a building has to be separated into different subsystems (constructional system, internal fit-outs, mechanical, electrical and plumbing (MEP) systems) in order to make the parts independently accessible, replaceable and demountable.

Construction principles

When designing with prefabricated building elements, there are three kinds of elements the architect can choose from: linear, planar and spatial elements. *"These determine the construction principles characteristic of system building: the frame, the panel and the room module. These three building methods are frequently combined in the building industry and rarely appear in isolation. Frame structures are often combined in a system with panels or room-modules. As regards the level of flexibility of these three building methods the frame is the most flexible, followed by the panel systems and then modular building methods, while the level of prefabrication follows the reverse order – modular units are the most highly prefabricated."* [16]

Fig. 44: The three main construction principles which can incorporate modular construction elements: (a) the frame system, (b) the panel system, (c) the room-module systeme

The frame system

Frame systems are composed of linear building elements such as columns and beams. To create a stable construction which can withstand both vertical and horizontal loads a frame system needs bracing elements such as rigid frame corners, diagonal connections or sheer walls.

One of the main advantages of buildings whose load-bearing system is designed as a frame, is the fact that the building envelope and the internal fit-out are completely independent from the load-bearing structure. This allows a high extent of flexibility in terms of the configuration and adaptation of (living-) units without having to recalculate the engineering. [17]

The frames can be filled out with all kinds of wall panels and floor slabs or even room-modules can be inserted into the framework. Due to their independence of the load-bearing structure, these elements can be exchanged after some time, allowing for a great adaptability.

Panel systems

The biggest difference to frame systems is that panels are self-supporting construction elements. They build the load-bearing structure and enclose space at the same time. That means that load-bearing walls can't be removed or relocated as easily as they can in frame systems. Only by changing the position of internal non-loadbearing walls a (living-) unit can be reconfigured.
Panels can be constructed of steel, timber, concrete or masonry and are prefabricated elements that can be flat packed on a truck to deliver them to the building site. It usually takes less time to assemble them than it takes to set up a framework with its in-fills. The dimensions of the panels are dependent upon material choice, transport conditions and constructional grid dimensions; panel height is equivalent to story height. [18]

Room-module systems

Room-modules are components that are volumetric in shape and form a completed part of a building (or a complete small building itself), and only need to be placed and interconnected on site. According to the constructional concept they can either be loadbearing or non-loadbearing (in combination with a frame). Depending on the intended function, the units can be manufactured with a level of prefabrication of up to 95% with all the necessary services, internal fittings and built-in furniture included. In the 1960s and 1970s many visionary architectural designs were based on the use of room modules. Today, room-module systems are gaining attention again and are predominantly employed for projects which consist of a high number of equally or similarly designed units like student housings, hotels or hospitals. These systems are also advantageous when site assembly needs to be completed as quickly as possible as it is the case in downtown city areas for example. The load-bearing system for room-modules is usually of steel, timber or concrete. Dimensions are determined by the methods of transportation available. When a more flexible layout is desired, room-modules are produced that are closed on two sides only. Common dimensions of modules are approximately 3 m in width and 8 m in length. [19]

Materials in system building

In element-based building systems prefabricated products used for loadbearing constructions are generally of steel, timber or concrete.

Steel

In the beginning of the 19th century steel became available in high quantities and has played a big role in the building industry ever since. Steel has an excellent structural behavior and allows constructions with large spans too be built.Especially in terms of factory production and prefabrication of building elements steel offers many possibilities, which were particularly further developed by the architects of the Modernism.

Due to their dimensional accuracy, steel building elements are very suitable for use in modular building systems. Steel constructions are generally put together by screw connections which allow them to be easily dismantled. This feature guarantees great flexibility and adaptability over the life cycle of a building as requirements and needs of the user change. This reduces the ecological footprint of a building because units can be reconfigured and building elements reused, without having to spend new resources. Structural steel can be worked easily and in a variety of different ways and has great economic and ecological advantages. Although the manufacture of steel requires a great deal of energy, the material can be 100% recycled. [20]

Timber

Building with timber has experienced a revival over the past few years, especially because of the ecological aspects. As people get increasingly aware of our impact on the environment and the upcoming resource shortage, green and sustainable building methods become more and more important. Choosing timber as primary building material contributes actively to climate protection, because it grows naturally using energy from the sun, is renewable, sustainable and recyclable. It is an effective insulator and uses far less energy to produce than concrete or steel. Wood can also mitigate climate change because wood products continue to store carbon absorbed by the tree during its growing cycle.

But not only the sustainable aspect, also the quality, the local and natural availability and the easy methods of processing it led to a boom in the timber industry. Modern timber constructions use the principles of frame systems, panel systems and room-module systems, while the first two principles make up the largest sector on the market. Especially prefabricated solid timber panels such as the Austrian product “KLH-Platten” are getting increasingly popular in the building industry. These elements can be used in a variety of ways in building floor slabs, walls and roofs. They are at a high level of quality, almost on demand and meet all the requirements of building physics. Timer frame systems however, are more flexible due to the independence between loadbearing structure and all other elements and easier to transport and assemble because of their light weight and moderate dimensions. [21]

Concrete

The main advantages of concrete are its great loadbearing capacity and the variety of ways in which it can be formed. Analog to steel and timber all three principles to establish a structural construction can be applied; frame, panel and room module systems made of concrete are possible. Since steel and concrete are widely available, reinforced concrete is a very economical building material that can be produced with simple production techniques. Therefore reinforced concrete is particularly suitable for the serial production of prefabricated elements which are manufactured in production facilities. [22]

Summary

The main potential of industrialized approaches to construct buildings especially in combination with modular systems can be summarized by the following:

- reduced overall construction time,
- greater quality of buildings,
- increased labor productivity,
- better control and more efficient use of resources,
- development of assembly/disassembly techniques,
- greater possibility to reconfigure structures according to new demands,
- greater match between requirements and materialized solutions, and
- greater quality of life because buildings can be matched to individual preferences. [23]

They can only be achieved however, if the use of industrialized production methods is not only based on economic benefits, because that would lead to the same mistakes as in the post-war era. But prefabricated elements have a great potential to contribute to a sustainable building practice if they are incorporated into a modular system, because they enhance its performance in terms of production, assembly, disassembly and adaptability. These aspects correspond to the goal of sustainability, which is to provide structures that consume the minimum amount of material and energy over their life span while answering to the specific need of users. The next two chapters will focus on the positive effects a modular system which is well-performing in terms of design and technological aspects can have on society as well as on environment.

NOTES:

[1] http://re4a.com/the-modern-modular/

[2] cf. ibid

[3] cf. Staib, Gerald/ Dörrhöfer, Andreas/ Rosenthal, Markus: *Components and Systems* - Modular Construction. Munich: Birkäuser Verlag AG 2008 p. 92

[4] Lazor, Charlie: *How to Play Flatpak.* In: Dwell Magazine (April/May 2005) p. 134-143 on p. 141

[5] ibid.

[6] Source: Official website of MVRDV
Link: http://www.mvrdv.nl/projects/415_rodovre_skyvillage/#, 2013-05-18

[7] ibid.

[8] cf. http://en.wikipedia.org/wiki/Standardization

[9] cf. *Components and Systems* pp. 40ff

[10] cf. *Components and Systems* p. 40

[11] ibid.

[12] cf. Schoenborn, Joseph M.: *Case Study Approach to Identifying the Constraints and Barriers to Design Innovation for Modular Construction.* [Thesis, Blacksburg, 2012] Virginia Polytechnic Insitute and State University 2012 p. 4

[13] cf. Austrian *Kraftfahrgesetz* 1967, edition of 2013

[14] cf. *Case Study Approach to Identifying the Constraints and Barriers to Design Innovation for Modular Construction p. 15*

[15] cf. *Components and Systems* p. 47

[16] *Components and Systems* p. 42

[17] cf. *Components and Systems* p. 54

[18] cf. *Components and Systems* p. 110

[19] cf. *Components and Systems* p. 160

[20] *Components and Systems* p. 50

[21] cf. *Components and Systems* p. 51

[22] cf. *Components and Systems* p. 52

[23] cf. Durmisevic, Elma: *Transformable Building Structures*. [Diss. Delft 2006] Delft: Cedris M&CC 2006 p. 135

FLEXIBILITY

“

*We should not try to forecast what will happen,
but try to make provisions for the unforeseen.*

(N. J. Habraken)

”

CHAPTER ■■■■

FLEXIBILITY of MODULAR SYSTEMS

As already mentioned one of the main features of a system based on modularity is its flexibility and adaptability. By exchanging, adding or removing units a modular building system should provide a wide range of possible configurations and the possibility to re-configure the building over its life cycle in order to adapt to unpredictable conditions in future. The customization of living units as well as their adaptability to changed spatial or functional needs improves the living condition of a dweller as well as a building's general social sustainability. Besides the social impacts, flexibility and adaptability also lower the ecological footprint of a building because its life cycle extends and components can be reused. This chapter discusses the necessity of flexible structures considering our ever-changing society and argues that the use of a modular system can increase a building's flexibility significantly. This will be supported by examples of flexible buildings which make use of modular systems at the same time. This chapter will also provide a short overview on the technical requirements a building needs to fulfill in order to realize a flexible and changeable structure.

1. DEFINITIONS

Flexibility in terms of housing

Tatjana Schneider and Jeremy Till define *Flexible Housing* in their equally named book as housing that can adjust to changing needs and patterns, both social and technological.

These changing needs may be:
> personal (say an expanding family),
> practical (i.e. the onset of old age) or
> technological (i.e. the updating of old services)

The reasons requiring these changes might be:
> demographic (for example the rise of single person households)
> economic (i.e. the rise of the rental market) or
> environmental (i.e. the need to update housing to respond to climate change). [1]

This definition is rather broad because it includes the potential to make changes prior to occupation ("customization") as well as the ability to adjust someone's home over time after occupation ("transformation"). Prior to occupation, a flexible approach will allow future users a degree of choice as to their layouts. Post occupation enables people to occupy their homes in a variety of ways and allows them to make adaptions to a later date.

Flexibility and adaptability

Basically, flexible housing can respond to the inconstancy of dwellings – by being adaptable or flexible, or both. These two terms are often used to describe the same thing. Steven Groak differs these expressions by defining adaptability as "capable of different social uses" and flexibility as "capable of different physical arrangements".
Adaptability describes spaces that can be used in a variety of ways, generally without making physical changes. It is achieved by designing rooms or units so that they can be used differently, mainly through the way that rooms are organized, the circulation patterns and the designation of rooms.
Flexibility on the other hand is in Groaks definition achieved by altering the physical fabric of the building: by joining together rooms or units, by extending them, or through sliding or folding walls and furniture. Flexibility applies to both temporary changes (such as a sliding wall) and permanent changes (such as moving a partition wall). [2]

In this thesis the term flexible housing is used to cover both, adaptability and flexibility.

2. IMPORTANCE of FLEXIBILITY

Why to include flexibility and adaptability in housing?

Even though it is basically common knowledge that flexible and adaptable buildings are more sustainable and economical in the long term, most building projects are still characterized by a static and rigid structure. These short-term visions which have been applied for many centuries lead to obsolescence of many buildings because they are not able to keep up with new requirements and needs. Just building additional houses meeting present needs does not solve the problem. The only way to get over this issue is to:

"[...] build buildings that are flexible enough to accommodate new demands on the build environment such as changing demographics, ageing users and changing working patterns. We shall see this has further benefits in terms of life cycle costing, sustainability and the incorporation of new technologies." [3]

Changing External Demographics

One reason why a static housing project will cause problems is the changing demographics of our society.

In the last 20 years there has been an increase of single-family households, a decrease in the number of traditional family units, a higher proportion of older people, an increased demand for shared accommodation, a growing move towards cities and an increase in the number of people working from home. [4]

In Austria the number of single-households rose by 74% from 1985 to in 2012; further rises are predicted. [5] This increase is primarily based on the rise of young urban singles and people over the age of 65 living alone. Another factor which changes our demographic structure constantly, and with it the possible configuration of living units, is immigration. Each migrant group brings with it a certain cultural experience regarding living patterns and spaces and they may find themselves restricted and uncomfortable having to live in standard layouts based on our culture.

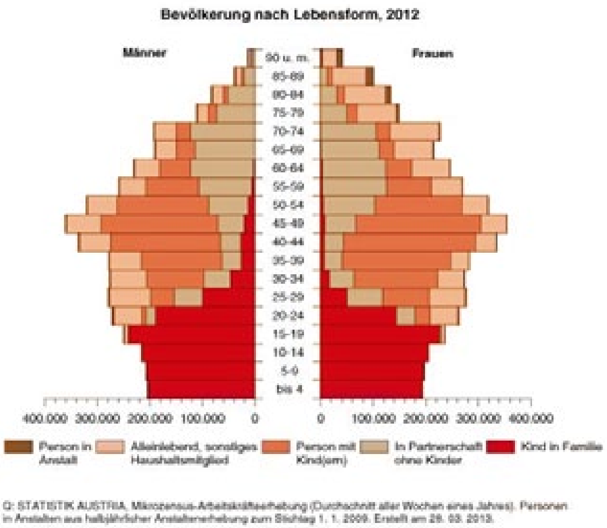


Fig. 45: Demographic structure in terms of family and household constellations in Austria, 2012

Changing Internal Dynamics

But housing should not only be capable of responding to external demographic change but also to internal changes during the lifetime of its occupants. If it cannot adapt, then the users will have to move on, which is both socially and financially disruptive. Housing in this context has to be flexible enough to deal with two conditions:

(1) The first is the need to adapt to the changing needs of the individual as they grow older or less physical able. This becomes remarkably evident when taking a look at the tremendous increase of older people among our society. In order to meet their and our future needs, housing needs to provide features such as level access to front and back doors, wider halls and doors and enough turning space for wheelchairs.

(2) But this does not go far enough yet, there is a second condition housing needs to deal with: The changing constitutions of a family as it grows and then contracts or the change of size/age of individual groups. *"For example, if a house becomes too big and therefore too expensive to run, the designed-in possibility of division and letting out sections would mean that people do not have to move some elsewhere. If someone becomes physically less able through age or illness to navigate their existing dwelling, an adaptable house could provide the continued independence to the dweller. If economic or family circumstances change, an adaptable house should provide the possibility of re-designating existing rooms or use patterns."* [6]

Sociological aspect: A means of self-expression

John Habraken severely criticizes the way large housing projects (he calls them mass-housing) are build. He argues that mass-housing takes away a man's act and presents him with a finished form which he has to adapt to. This lack of self-expression leads to a disturbed relationship between the user and his dwelling because it suppresses the user's ability to claim their housing unit as their own home. *"In short, it all has to do with the need for a per-*

sonal environment where one can do as one likes; indeed it concerns one of the largest urges of mankind: the desire for possession." [7]

Housing projects which involve the user therefore mean an improvement of their living quality due to a higher rate of identification and emotional ownership to their dwelling. As already mentioned this can be achieved by concepts which allow for customization on the one hand and adaptation on the other.

Another positive social aspect of flexible housing is its potential to provide a diversity of dwellers and maintain it over time. This is in contrast to many contemporary housing developments which provide only a single type of unit with the result that certain city districts are covered with one-person apartments or student housing with few public, family or community facilities. But a social mix in terms of income and household diversities is recognized as an important part of a sustainable living environment, because it means vibrant, enduring and mature urban neighborhoods.

Financial arguments

Housing that is capable of coping with these changing needs and structures might take some extra effort to design and probably higher initial costs, but a Canadian study in the Convertible House shows it more likely saves money over the long term either for the individual owners in the private sector or the housing associates in the public sector. [8]

It seems logical that buildings with flexible feature will last longer and will be cheaper in their entire life cycle because they reduce the need and frequency of refurbishment in a large scale. Even though people are getting increasingly aware of the importance of life cycle costs, they are seldom taken fully into consideration and many projects are still calculated on the basis of initial costs.
Overall the financial argument for flexible housing is compelling. In market terms, it leads to higher consumer satisfaction at point of purchase or occupation. In technical terms, flexible housing reduces maintenance costs. In physical terms, potential future obsolescence is reduced significantly, with the ability to adapt and upgrade buildings rather than pulling them down. In social terms, it limits the need of the user to move. [9] Habraken formulates the necessity for flexibility this way: The question is not whether we can afford to do without flexibility, but whether we can afford to do without it. [10]

Ecological sustainability

The most evident positive effect that flexible buildings have on the environment is the reduction of spent energy and resources. The possibility to adapt a building simply extends its life cycle significantly. This delays the necessity of building new houses which implies savings in raw material, energy and waste. It also avoids that buildings are designed which only intend to meet present needs and get obsolescent after a while, i.e they need to be demolished. This short-term vision which is common today causes million tons of waste every year worldwide and means an irresponsible misuse of our resources. In times of proceeding resource-shortage and increasing awareness of environmental issues this waste of energy will soon have to stop and flexible buildings can make a great contribution. The environmentally sustainable aspect of flexible housing will be further discussed in the followin chapter.

3. DESIGN PRINCIPLES for FLEXIBILITY

After having pointed out the importance of flexibility in buildings, I will now focus on the basic principles of designing flexible housing, especially in regard to modular building systems. In order to allow the application of a modular system a building needs to be based on some kind of organizational structure – basically a background frame that enables a variety of forms to evolve within. This frame can be understood in a literal sense as the structural frame, but also metaphorical as a frame for action within.

The rack ("Regal") - principle: Modules are inserted into a framework

One approach is to provide a structural framework and within an empty generic space that can be infilled and adapted over time. This principle is based on the idea of separating a building into a loadbearing structure and non-loadbearing inserts that have the potential for change. The frame is responsible for the physical stability of a building and thus is permanent and unchangeable. Modules, which can be all kinds of non-loadbearing elements, can be inserted into that frame and provide many possibilities for adaption since they are independent from the static system. This provides the possibility to add more modules and to exchange or replace them if they are not needed any more. So not only units within the bulilding can be changed but the building itself provides constant transformation possibilities. [11]

The following examples, the first using panels and the second room-modules as non-loadbearing modules, illustrate this principle.

Wohnregal - Stürzenbecher/Nylund, Berlin 1986

A cheap prefabricated reinforced concrete frame and slab structure builds the static system of this multi-story apartment. It acts as a shelf onto which future residents could build facades, partitions, party walls and intermediate floors using a modular timber building system. The infill grid is based on a 1-meter span, a dimension which is used for doors, windows, openings and corridors. Within that grid and the structure defined by the concrete frame floor, layouts and elevations were individually determined by the users. To help them visualize the plans and specify the exact position of walls, windows and balconies, a 1:20 model was used. The result is a flexible housing scheme which allows for a very high rate of customization, but also provides the possibility of re-arranging single units in future. [12]

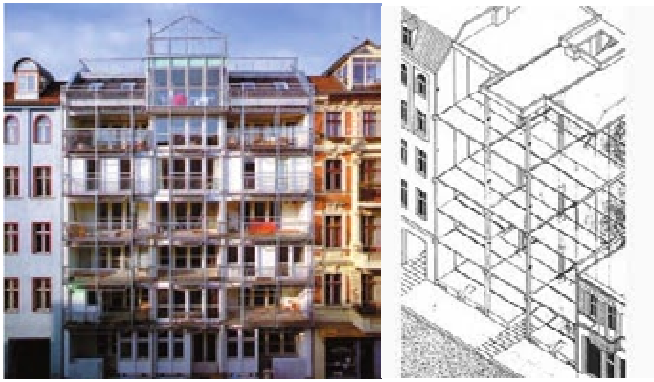


Fig. 46-47: Wohnregal, Stürzenbecher/Nylund. Left: Diversified facade due to user participation, right: supporting-structure based on columns to achieve flexible units

domino.21 - J. M. Reyes, Spain 2004

domino.21 is a modular building system that was developed by students of the Madrid School of Architecture. The framework of this multi-story apartment is constructed of standard available components of steel and timber. The basic unit consists of a core space which can be extended to both sides by the addition of prefabricated modules or "cubes". The resident can choose the number of modules he wants to add, depending on his spatial needs. The modules are already furnished, including bathrooms, kitchens, bedrooms, etc. but they can be relocated in order to make the dwelling adjustable to future requirements. Additional modules can also be added to a later stage. Potential clients are meant to order types and materiality of their modules by catalogue. The assembly of five different apartments took only 15 days and now the building has been totally dismantled. All parts are reused in other buildings or have been recycled. [13]

Fig. 47-48: domino.21. Left: Construction process, right: floor plan

The stack (“Stapel”) - principle: Modules get piled up or horizontally combined

The second approach is very different from the first. Instead of the provision of open space, it starts with a modular and cellular structure. Flexibility over time is provided in two ways. First, the rooms or modules are indeterminate in their function which means that they can be used in a variety of ways. Secondly, the divisions are structured in a way that allows them to be connected together in multiple configurations; often they will incorporate predetermined openings that can be filled or knocked through. In contrast to the “rack-principle” the modules are not independent from the building structure because they are stacked on top or next to each other and create the static system of a building itself. That means that entire units cannot be removed but additions and combinations are easily possible. [14] This principle can be illustrated by the already mentioned modular tower by MVRDV.

Rødovre Skyvillage - MVRDV, Copenhagen 2008 (not realized yet)

A basic module of 7.8 x 7.8 m is repeatedly used to form the structure of this mixed use building. The units, which are stacked next and on top of each other, don’t have a determined function. Due to their reasonable size, they can be used as apartments, offices, shops, etc. Several modules can also be joined together horizontally or vertically to form larger spaces. This flexibility of functions and spatial arrangements is not only provided before the users move in, but can be realized during the building’s entire life cycle.

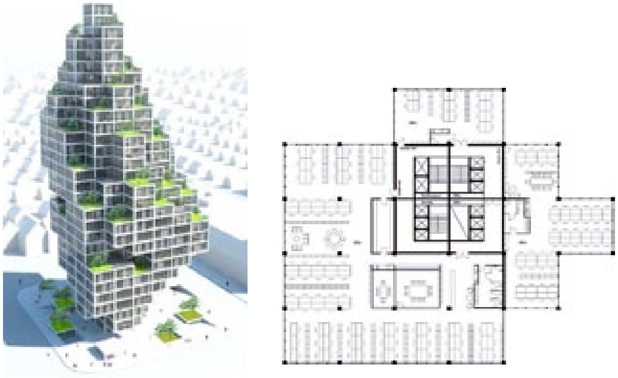


Fig. 49-50: Pixel-Tower. Left: Visualization, right: floor plan based on equally sized living-modules

4. TECHNICAL REQUIREMENTS for FLEXIBILITY

Independence of layers

Even though creating a flexible building system which works in theory can be challenging, the architect must also find technical solutions to make it realizable. To make a building adaptable in terms of elimination, addition and relocation of elements, some technical requirements need to be considered.

According to Elma Durmisevic the key requirements in order to transform an existing building structure are the independence and exchangeability of its parts. The question of how to decompose a building into separate layers in order to achieve flexibility has been addressed in different ways many times in the past. One influential figure in finding a theoretical solution how building parts can obtain independence was the Dutch architect and chairman of SAR (Foundation for Architects Research) N. John Habraken. He made a distinction between support and infill level. He defined the support structure as some kind of constructional framework which is capable of containing individual dwellings (as a bookcase contains books) which can be removed and replaced separately without having impact on the entire building. The support is intended to be a permanent structure and to last for several decades, whereas the in-fills, which are the individual dwellings, can be changed whenever desired. [15]

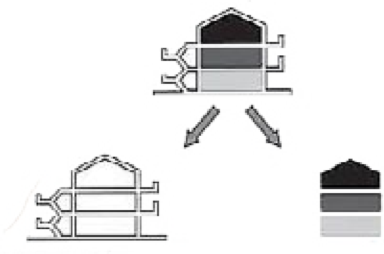


Fig. 51: Illustration to show how a building can be devided into the support and the infill elements

Steward Brand divided a building in even more layers in order to achieve the potential of flexibility throughout the lifespan. He argues that a building should be separated into 6 categories: Site - Structure - Skin - Structure - Space Plan - Stuff. These layers, shown in the diagram, have varied degrees of permanence, with "site" (the thickest line in the diagram) being the most permanent, and "stuff" (thinnest lines), which is furniture and other moveable property, having the least stability. Similarly, the frequency of how often these components change differs. The structure is intended to last for the longest (as illustrated by the arrows) while the stuff can change within days or months.

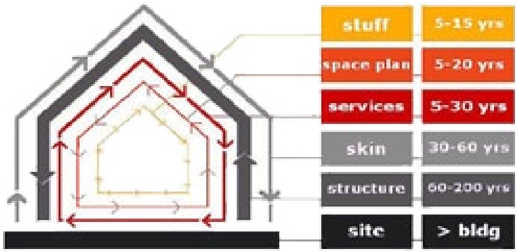


Fig. 52: Stewart Brand devides a building into six layers

Architects have developed even more categorizations of layers and the point is not which of them is "correct" but rather that the principle of layers can lead to flexibility, both during the design process and after occupation. It is not given that layered construction leads to flexibility; the layers have to be separable, and preferably, legible. One needs to be able to take one layer apart without disturbing the others and so this it is best to be able to see the articulation between the various layers. [16]

Spatial vs. technical flexibility

In terms of using modular building systems this means that a building needs to be divided into permanent parts which are intended to last and into adaptable zones which can be transformed by adding, exchanging or eliminating modules. The use of pre-selected and most likely prefabricated modules simplifies this process of transformation enormously. The reconfiguration of an existing building usually includes the removal of some elements to make room for new arrangements. Considering this, one can say that in order to accomplish flexible structure, buildings or at least certain parts should be designed for easy disassembly. If disassembly is possible, modules can be removed without too much effort and new ones can be installed. If this is not considered in the design of a building all good intentions of providing a flexible structure would be for nothing. For example, if the wall modules of the in chapter 3.1.1 mentioned “Wohnregal” were not made of timber but of brick and mortar, nobody would make use of the possibility to change their position because it would simply cost too much effort. Or if all the service pipes are permanently integrated into the walls, they couldn’t be changed either. Therefore, when designing a transformable building, two kinds of flexibility need to be considered:

1. Spatial flexibility: The building needs to be based on an organizational structure which allows for space transformation during the life cycle. This includes extendibility and rearrangement of units, as well as multi-functionality and the mutation from one function to another.

2. Technical flexibility: This term describes the ability of building components and systems to be easily replaced, exchanged, reconfigured, reused and recycled. It is possible when the building is (1) separated into independent layers and (2) when the components belonging to those layers can be at least partly disassembled and exchanged.

What exactly needs to be considered to simplify disassembly is explained in chapter 5. It is also argued that technical flexibility associated with disassembly is one of the key features to a more sustainable construction. This assumption is based on two reasons: (1) The capability of disassembly makes buildings adaptable to trends and changed requirements which extends a buildings overall lifecycle and (2) it increases reuse and recycling of its components possibilities. This is especially true when the design is based on a modular system, because an entire building or parts of it can be disassembled into modules. This means that building parts don’t have to end up as waste on landfills but can actually be reused for constructing a new building - saving energy and material resources. [17]

NOTES:

[1] Schneider, Tatjana/ Till, Jeremy: *Flexible Housing.* Oxford: Elsevier Inc/Ltd. 2007 p. 4
[2] cf. ibid. p. 5
[3] ibid. p. 37
[4] cf. ibid. p. 37
[5] Source: Statistik Austria
[6] *Flexible Housing* p. 41
[7] Habraken, N. John: *Supports* - An Alternative to Mass
[8] Housing. 2nd edition, U.K.: The Urban International Press 1999 p. 15
[9] cf. *Flexible Housing* p. 43
[10] cf. ibid. p. 46
[11] cf. ibid. p. 97
[12] cf. ibid. p. 39 + 168
[13] cf. ibid. p. 99
[14] cf. ibid. p. 126
[15] cf. ibid. p. 40
[16] cf. *Supports* p. 70
[17] cf. *Flexible Housing* p. 171
[18] cf. Durmisevic, Elma: *Transformable Building Structures*. [Diss. Delft 2006] Delft: Cedris M&CC 2006 pp. 69ff

SUSTAINABILITY

“

We have to ethically start taking responsibility for the end of life of what we have made.

(Stephen Kieran)

”

CHAPTER ■■■■■

SUSTAINABILITY of MODULAR SYSTEMS

“The main question of sustainable building is how to find a balance between the increasing dynamics of change (population, migration, life style, life span, etc.), which is related to the increased resource consumption, and the key principle to sustainable engineering.” [1]

As in chapter 4 already stated our society is constantly changing and with it the requirements a building needs to fulfill. Conventional buildings can’t cope with this development because they are designed as fixed and permanent structures with little or no possibility for adaption. As a result that many buildings are not suitable for the market anymore, they are being demolished after a few years, even though they were designed to last probably 50-75 years. The demolition of a building has a high impact on the environment, causing large amounts of solid waste and wasting embodied energy, material and natural resources. For that reason the building industry needs to change towards an alternative way of building which allows for future adaptions in order to extend a building’s life cycle. The more often a building can be modified to different requirements the longer it can last and the more sustainable it is. One can say that the capacity for adapting a building relies on a high disassembly potential. If building components can be disassembled they can also be exchanged, removed or extended.
Another reason why we should design buildings that can be disassembled is the potential of reusing their components for a different building project. This would also lead to a reduction of waste and minimize the amount of energy and resources which are needed for producing new building parts. If reuse is not an option, the parts can at least be proper recycled once they can be dismantled into different materials.

This chapter will focus on the potential of demountable buildings to contribute to an ecological more sustainable building industry and what needs to be considered in order to simplify the disassembly process. It is also argued that the use of modular building systems, whose structure is already separated into modules, make the process of disassembly easier and, accordingly, (1) extend a building’s lifecycle through transformation and (2) increase the possibilities for reuse and recycle of components.

1. TODAY'S BUILDING INDUSTRY

A global perspective

Recent studies have shown that the building industry is the greatest consumer of world's natural resources and energy, as well as the greatest dumper of waste. Accordingly, this makes the building construction sector to one of the largest contributor to greenhouse gas emissions globally. Referring to a study of WBCSD (World Business Council for Sustainable Development), buildings account for 40 percent of the world's energy use with the resulting carbon emissions substantially more than those in the transportation sector [2]. Considering the fact that the world's population will increase rapidly (up to 10 billion people in 2050 estimated by the Population Reference Bureau) and with it our built environment, the need for an alternative way of building seems to be undeniable.

Governments, developers, architects and the building industry need to reconsider current ways of building which have been proven to be unsustainable and inefficient - causing depletion of natural resources, waste of energy and material and with it far too high emissions of carbon dioxide responsible for global warming.

How to build in future

To contribute towards an environmentally responsible architecture, buildings will need to be designed incorporating energy saving processes and the reduction of natural resources and waste production. Many studies have shown that this can be achieved by extending the life cycle of buildings and their materials, because the longer the life cycle is, the less raw materials and energy is needed for new production and accordingly the less waste is produced. [3] The current building market is exposed to a lot of changes which our traditional buildings can't handle very well due to static, inadaptable structures. Today, users - and with them functional and technical requirements of a building - change more frequently, as well as living and working patterns in general. Conventional buildings are not designed to meet these changing requirements of our society, because they are usually seen as fixed and permanent structures. As a result, buildings often have to be demolished or extensively renovated even though their technical life span is by far not reached yet.

But if buildings were designed for transformation their life span could be extended. In order to be adaptable they need to be demountable. This chapter argues that the application of modular building systems which allow for transformation by means of disassembly are the key element for extending the life cycle of a building and accordingly reduce environmental impact (fig. 53).

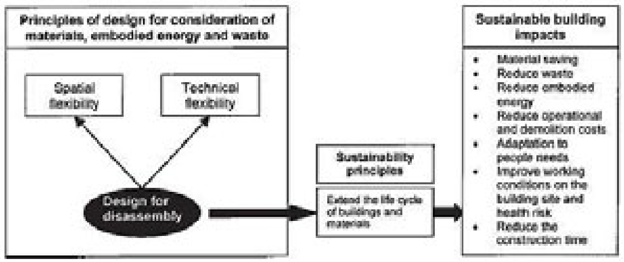


Fig. 53: Relation between disassembly and sustainable building

2. FUNCTIONAL AND TECHNICAL LIFE SPAN

Problematic disproportion

Our society experiences constant change driven by shifts in economics, diversity in working and living patterns, and the varying composition of our demographic structure. Recent trends in housing and office markets show that the rate of change is accelerating and that the general life cycles of buildings are becoming much shorter.

The functional life span, which is related to the building's use, and the technical life span, which is determined by the technical condition of the building and its parts, is not balanced anymore. Very often the functional life span ends earlier because today users usually change after a few years and with them the requirements and spatial needs a building has to fulfill. If the functional life cycle of a building component is shorter as the technical life cycle, then the component will be disposed. Decades ago this was not seen as a problem, since the functional life cycle was more or less equivalent to the technical life cycle. But this has changed, which can for example be observed in the U.S., where the average family moves every 10 years. [4] This means that buildings need to undergo many renovations over their lifetime in order to adjust to their new user. Since renovations can be quite expensive, in some cases buildings, whose technical life span is not reached by far, simply get demolished in order to make room for a new building.

Either way, excessive renovations or demolitions, have a huge impact on our environment:

Waste production

One of the results of the demolition processes is an enormous amount of waste material. The US Geological Survey has estimated that 60% of all material flows (excluding food and fuel) in the US economy is consumed by the construction industry. The US EPA (Environmental Protection Agency) has estimated that 92% of all construction-related waste produced annually in the US is the result of renovations and demolitions, with only 8% produced from new construction. [5] In the U.S. as well as in the EU the construction and demolition waste represents close to a third of all produced waste.

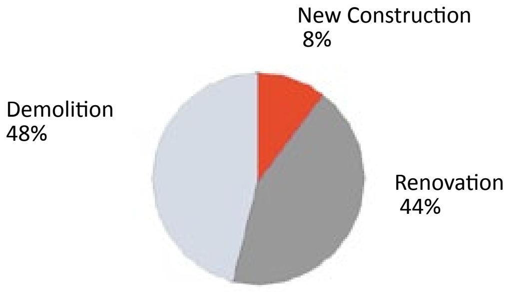


Fig. 54: Factors responsible for causing waste in the building sector in the U.S.

Loss of embodied energy

Besides the big amount of waste originating from demolition of building structures, another reason for reusing components is the embodied energy. Embodied energy is the energy required to produce or manufacture a product and includes:

> direct energy used in the manufacturing process,
> indirect energy required to extract and transport raw materials, and
> energy needed to produce the infrastructure required for these production activities. [6]

The embodied energy in recycled materials is generally less that in newly produced materials. Although manufacturing with recycled materials can involve transporting, cleaning and sorting, this often requires far less energy than manufacturing from a virgin resource. Figure 55 gives an overview of the amount of energy required to produce building materials from raw resources and the percentage of saved energy by using recycled material.

	Energy required to produce from virgin material (million Btu/ton)	Energy saved by using recycled materials (percentage)
Aluminum	250	95
Plastics	98	88
Newsprint	29.8	34
Corrugated Cardboard	26.5	24
Glass	15.6	5

Fig. 55: Potential of saving energy by using recycled materials

3. LIFECYCLE APPOACH

Extension of the life cycle of an entire building

The main reason for the crucial imbalance between functional and technical life span is based on the fact that conventional buildings mainly focuses on providing short-term solutions. Instead of developing new design approaches which have the ability to adapt to constantly changing requirements, buildings are still conceived as fixed and permanent structures with hardly any possibilities to be transformed. These inefficient building processes are the result of traditional building practices that focus on three competitive factors: construction costs, quality and time.

But considering the impacts on our environment that are caused by our traditional building methods, it is time for building designs that deal with resources more responsible and are able to provide long-term solutions. Therefore they need to be adaptable to all kinds of changes in future. The more often a building can be modified to different requirements the longer it can last and the more sustainable it is. The life cycle of a building in context of sustainable design is based in repetitive sequences, illustrated in figure 56. The number of loops that can be made between the design and demolition/final disassembly depends on how transformable, and accordingly how demountable, the building's structure is.

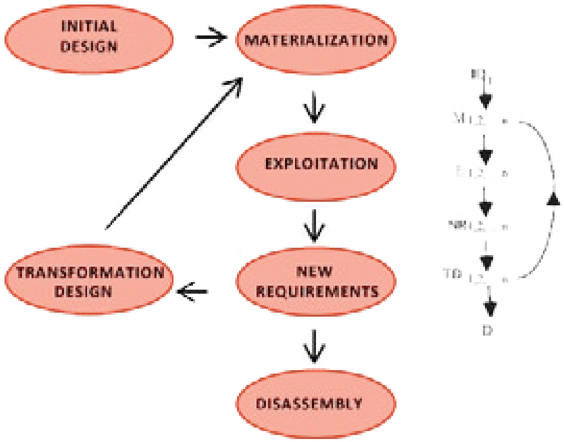


Fig. 56: Number of sequences in building use

Extension of the life cycle of building parts

Besides the extension of a building's overall life cycle by transforming it according to changing requirements, the potential of disassembly has a second positive effect on the environment: building parts and materials can be reused and better recycled. So it is not only important to focus on the phase of use, but also to think about end-of-life scenarios. Stephan Kieran from KieranTimberlake Architects argues that

"[...] we have to ethically start taking responsibility for the end of life of what we have made, not just the origins, the forms that we bring into the world." [7]

That means that in order to achieve a sustainable approach in building and construction, the design focus has to incorporate all stages of a building's lifecycle, including the final stage.

A building's lifecycle includes its energy consumption of all life stages, starting out with the raw material acquisition, followed by the product manufacture and transportation, the construction/assembly phase, the phase of operation and maintenance, renovation (optional) and is ended by the demolition of the building. Demolition in general can be defined as the process whereby the building is broken down, with little or no attempt to recover any of the building parts for reuse. Most buildings are designed for such an end-of-life scenario, because their building system does not allow alterations or disassembly. [8]

From a linear to a closed lifecycle

This means that their life cycle is linear and has bad impacts on the environment. A closed life cycle in the building industry focuses - in contrast to the linear model of extraction, use and landfilling - on reuse, reconfiguration and recycling of components and materials. On the left side of figure 57 we see the conventional building method ending with demolition, and on the right a cyclic material flow approach which allows for an environmentally responsible use of building components and materials (reuse, reconfiguration, recycling). This can be achieved if a building's structure is designed for disassmbly.

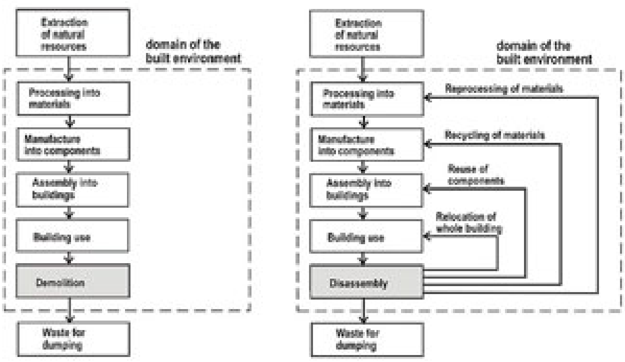


Fig. 57: Linear vs. closed lifecycle

Design for Disassembly

These different end-of-life scenarios are also an important part of the concept of Design for Disassembly (DfD). This new design principle is a growing topic within all kinds of manufacturing industries. As the environmental awareness increases, DfD aims to responsibly manage end-of-life building materials to minimize consumption of raw materials and the amount of waste that pollutes our environment. By capturing materials removed during building renovation or demolition and finding ways to reuse them in another construction project or recycle them into a new product, the overall environmental impact of end-of-life building materials can be reduced.

The way in which building parts are put together has a great influence on whether or not elements of a building or the whole building itself can be recycled. In other words, the building process is responsible for the extension of the life cycle of the building and its components, and ultimately for the reduction of waste and use of raw materials. [9]

"This means that we must consider how we can access and replace parts of existing building systems and components, and accordingly, how we can design and integrate such open building systems and components in order to be able to reconfigure or to replace them later on. " [10]

Recycling vs. reuse

As an end-of-life scenario reuse is generally preferable, therefore te goals of design for reuse and design for recycling are not interchangeable.
The recycling process is perfectly suitable for some materials, for example for steel. Steel has a huge amount of embodied energy and thanks to its recycling qualities it can regain the original quality of material and some of its embodied energy. However, the environmental benefits of recycling don't always apply; for example, concrete can be recycled but only as a low value aggregate; wood can

be ground up for wood fiber or mulch, but thereby loses its most valuable properties. This process is called “down-cycling”. [11]

This is why the most ecologic end-of-life option is reuse. Reuse means that components and materials can be removed while maintain service and aesthetic qualities and used in a different project. It is more advantageous from an energy and resource point of view, because reusing materials closes the loop of resource use. In this case, a building component (or entire structure) is simply moved from one location to another. This avoids logging and mining new virgin resources from our ecosystem and accordingly, reduces the environmental impact, especially greenhouse gas production.

When it comes to reuse and recycling of components, it is not only important that the building’s structure is demountable; also the materials have to be suitable for doing so:

Materials

In terms of material following principles apply: *“In the end, the ideal material is one that can be used multiple times, maintain acceptable quality and can be recycled (cradle-to-cradle), burned (instituted energy recovery) or decomposed (a natural recovery process) with little to no harming off-gassing.”* [12]

Generally speaking there are two key principles which can be applied in terms of material choice in order to ease the process of disassembly:

(1) choose materials that have high quality and will retain value for reuse or recycle, and

(2) minimize the different types and the amount of materials.

> Concrete:

Prefabricated concrete columns, beams, and slabs have the potential for reuse if the connection between the elements is made of stainless steel and removable fasteners. Concrete is highly durable and can be formed in modular units for flexibility. Concrete can be recycled, however, by doing so the result is a low value aggregate which is mainly used as sub-layer for roads and pavements. It is generally accepted that about 20% of the amount used for structural applications can be replaced by recycled concrete. The main components of concrete (sand, rock, water) are from non-toxic and readily available materials, although the production of cement is very energy-intensive and causes a high a rate of greenhouse gas emission. Even though the recycling of concrete minimizes (1) the need for virgin resources and (2) the amounts of solid waste, it has no appreciable impact in reducing greenhouse gas emissions. Because in the product life cycle of concrete, the main source of carbon emissions is the cement production process and cement can’t be effectively separated and reused or recycled into new cement. [13]

> Timber:

Wood can be reused, recycled, bio-degraded or burned (for utilizing its energy content), as long as it is not contaminated with toxic preservatives or paint. Solid lumber of sufficient dimension is a highly flexible material for reuse and remanufacturing because it can be cut and worked to different sizes and shapes without losing its material characteristics. Light wood-framing is not as suitable for disassembly due to the large amount of nails and many small amounts of materials of relatively small dimensions. However, entire light frame wall panels provide the potential for recovery because they can be reused in their entirety, maintaining higher value.

Engineered timber (plywood, OSB, cross-laminated timber, etc.) has the advantage that only a minimum of material is needed while maintaining a high degree of quality and strength characteristics. These characteristics are beneficial for reuse as structural material. Recycling of engineered timber however, is problematic because of the use of adhesives (glue) and binders, which cause environmental impacts. [14]

> Steel:
Although the manufacture of steel requires a great deal of energy this material has a very high potential of reuse and recycling. Steel buildings are environmentally friendly as they can be taken down almost entirely if their connections are demountable, i.e. bolts. Due to its high load-bearing capacity, long durability and adaptability whole buildings can be disassembled and rebuilt elsewhere or individual elements can be reused. Any steel which is not reused is captured and recycled for further use in construction or in any other field. It is one of the world's most recycled products. Steel is theoretically 100% recyclable: if recovered at the end of each use phase, the life cycle is potentially endless. [15]

4. TECHNICAL REQUIREMENTS for DISASSEMBLY

The need for separation

Independence and exchangeability

Since the topic of disassembly is strongly related to flexibility, some aspects that need to be considered for a demountable building have already been described in chapter 4. The most important requirements are that a building needs to be (1) separated into independent parts or "layers" and (2) that the components belonging to those layers are exchangeable.

(1) Independence of parts is primarily determined by how the overall building structure is defined, i.e. the relationship between materials, elements, and components. Independence is achieved if certain building parts can function individually and are functionally not depending on each other. This means that a building is functional decomposable.

(2) Exchangeability of parts is predominately defined by technical and physical design domains which deal with the accessibility of components and if they can technically and physically be removed of the building's structure. This depends on the hierarchical order of elements within structures, and on the chosen connections between elements. In order to achieve that exchangeability a building needs to be technical and physical decomposable.

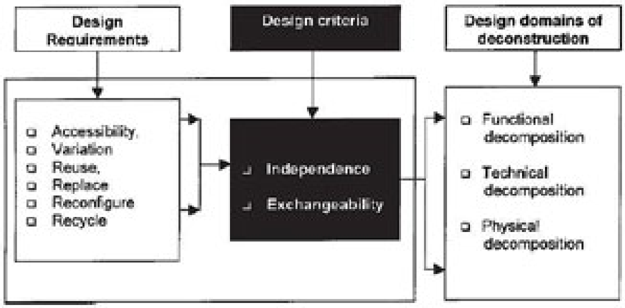


Fig. 58: Relevant requirements to disassemble a building

Different kinds of decomposition

1. Functional decomposition | Independence

The problem of conventional buildings is that they are often developed in the form of closed (static) systems whose materials, elements, components rely on each other in order to provide the desired functionality of the system. [16] But a building component can only be taken from a building, if it is an independent part of the building's structure. Most buildings are characterized by a fixed integration of different functions into one component instead of achieving separation between functions and components (Fig. 59). This has negative effects on the capacity of making changes within a building. For example, one considers the relationship between structure and services. If a structural element is part of a building's service system, i.e. a massive concrete wall is used to store heat, it can't simply be removed or relocated because this would affect the energy performance of the entire building.

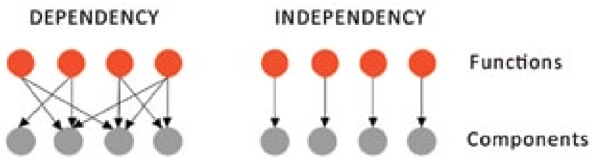


Fig 59: Separation between functions and components

2. Technical decomposition | Systematization

This required independency of components and functions doesn’t mean that a building should consist of only single parts, because that would make assembly as well as disassembly much more complicated. The clue is to systemize the building in sub-assemblies according to their life cycle performance, in terms of functional as well as technical life span. This also minimizes the number of relations between elements within the structure.


Fig. 60: Systematization of building components into sub-assemblies

Buildings with static assemblies can hardly be disassembled and therefore reconfigured, because the removal of one element could have considerable consequences on related parts. This is especially true if buildings are entirely erected on site and don’t make use of prefabricated construction elements.

Figure 61 shows two examples how a wall element could be structured. Principle 1 is based on the assumption that building parts are assembled on site with the result that parts of the façade cannot simply be removed or exchanged. They are stuck together and a single change would have consequences for stability of the total structure. In Principle 2 the loadbearing function (a) is taken out and defined as independent assembly. In this case, the loadbearing elements act as frame for the entire building and façade elements can be removed if needed. [17]

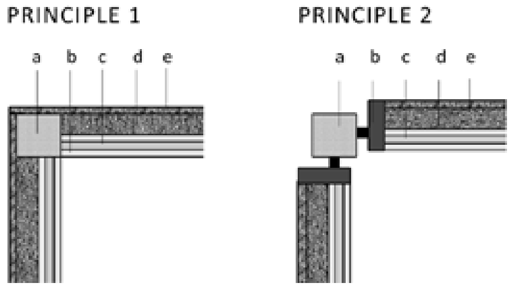


Fig. 61: Difference between traditional building methods and modular construction in terms of independency of elements

3. Physical decomposition | Connections

Besides the capacity for functional and technical decomposition, a building structure also needs to be physically decomposable. This aspect is mainly related to the type of connection and the design of interfaces.

To disassemble a building it is necessary to use connections that are demountable, i.e. bolts, screws or nails. The use of chemical connections should be avoided and replaced by dry-jointing techniques as far as possible. Further key principles regarding connections are accessibility, readability and simplicity in terms of tools and actions that are required to work on them. Connections will be a large factor of on-site disassembly processes and if they are inaccessible or difficult to understand, the disconnection process is inefficient or might not even be possible. [18]

5. DISASSEMBLY and MODULAR SYSTEMS

Design Strategies for DfD

Many of the requirements which have to be considered in order to make a building disassemble-able match with the characteristics of modular systems.

By creating a building of certain predetermined modules, not only the efficiency of assembly but also the capability of disassembly and transformation increases.

Traditional buildings are constructed on site to the largest extent and consist of a countless number of single building elements which make deconstruction far too complicated. Furthermore, building components are usually incorporated into a rigid structure and can’t simply be removed without affecting the entire building or at least parts of it. But with the application of a building system which exhibits principles of modularity, independence and standardization, disassembly and accordingly the interchangeability and the reuse of elements becomes possible. In order to simplify disassembly, a modular building system needs to be based on the following principles in terms of structural composition:

1. Limitation of elements. Using as few components and component types as possible - which is one of the main features of a modular system - doesn’t only make the process of planning and assembly easier but is also highly beneficial when it comes to disassembly. It makes the building structure easier to understand, to deconstruct and to relocate.

2. Dimensional standardization. The use of a standard dimensional grid allows for standard sizes of components. Specific limited sized of elements, beams, trusses, walls, etc. are an important requirement to guarantee the reuse and the exchangeability of components.

3. Independency of layers. The subdivision of a building into different layers creates a flexible and changeable structure. For example, separating the loadbearing structure from the cladding allows for increased adaptability and separation of non-structural deconstruction from structural deconstruction.

4. Exchangeability.

- Sub-assemblies: The separation and decoupling into modular sub-assemblies which have different functional and life cycle expectations makes it possible to replace or remove only parts of a building. Modularity allows for independent components that can be modified without affecting other parts.
- No permanent connections: Connections need to be demountable
- Accessibility: To replace parts of an existing building system it is important to think of a structure that enables the accessibility of components or modules and connections.

Modular buildings designed for disassembly

The following two examples of modular buildings have been especially designed with the potential of disassembly in mind. They also represent the most commonly used structures for disassembly:

(1) Frame and panels: The first example makes use of prefabricated frame and panel modules which can be easily dismantled and used for something else after the building isn’t needed anymore. The structural system of most buildings which are designed for adaption and disassembly is based on a framework. This construction principle offers the most possibilities in terms of flexibility and is highly adaptive. It is usually combined with all kinds of different panels for the building envelope. Instead of panels a frame could be also combined with 3-dimensional cubes.

(2) Room-modules: The second example is based on prefabricated room-modules. They are not intended to be disassembled itself, but the building can easily be split up into those modules, which can then be relocated and reused as entire unit somewhere else.

Werner Sobek - R 128, Stuttgart 2001

The structural system of most buildings which are designed for adaption and disassembly is based on a framework. This construction principle offers the most possibilities in terms of flexibility and is highly adaptive. It is usually combined with panels. The *R 128* house by German architect Werner Sobek is a good example to illustrate this construction principle. This residential building has an explicit mission to be dismantle-able and to allow for all its materials to be either reused or recycled. It is also unique for its use of prefabrication and highly modular system. Sobek designed the *R 128* house focusing on the application of prefabrication to increase efficiency, eliminating permanent joining methods which are difficult to recycle and the avoidance of mechanical and plumbing systems that are covered by plaster or burried in concrete.

Fig 62-63: House R 128, Werner Sobek, 2001

Structure. The structure is made of an exposed steel frame to minimize mass and maximize efficiency of construction and connections. The frame elements are connected with bolts and can be un-bolted for disassembly. The floors are a series of panels that are inserted into channels between floor structural beams without the use of nails or screws. The ceilings are metal panels which are clipped into place.

Skin. The envelope consists of triple-glass insulated glass panels and operable windows, providing the possibility to replace them if needed.

Service. There are no cables or pipes embedded in the walls, instead they are hidden within the structures of the floor and ceiling.The bathrooms are made of prefabricated modules inserted into the building, meaning that they are independent components. [19]

Concrete Architectural Associates - CitizenM Hotel, Amsterdam 2009

The Dutch architectural firm Concrete Architectural Associates chose a different constructional approach in order to achieve a demountable building system. They design hotels for a new hotel chain called CitizenM all over Europe, using room modules as building blocks. Their construction is based on an *Industrial, Flexible and Demountable* way of building, called *IFD* and firstly introduced in the Netherlands. The hotel consists of 215 rooms of 14 m² each and since they are all prefabricated, including the façade, they can easily be disconnected and moved somewhere else. Moreover, adding a complete extra floor, or additional rooms in line with the existing hotel is more time efficient than ever. This means a prolonged extension in the endurance of the CitizenM hotels. CitizenM wants to expand the concept by building over 20 hotels the coming years, all with the concept of room-modules as building block. [20]

Structure. All rooms are completely prefabricated as modular units constructed of aluminum frames. They arrive nearly finished on site and only get stacked on top of each other; no structural framework is needed. Only the ground floor is built in the traditional way.

Skin. The façade system consists of prefabricated aluminum window frames and glazing. Its elements are integrated in the factory, as well as bathrooms and service facilities.

Fig. 64-65: CitizenM Hotel, Amsterdam, designed for disassembly

Conclusion

To sum it all up it would be very beneficial for the environment if we started to design houses which have the potential to get disassembled. One the one hand this would lead to transformability and thereby to an extended life cycle of the building itself. On the other hand it would result in the lifecycle extension of single building components and materials because elements can be reused for other projects. Both consequences minimize the need of new resources and energy and reduce the waste produced through demolition processes. The use of modular building systems is insofar advantageous in this respective as building structures based on a limited number of modules can simplify the disassembly process and increase their potential of being reused. Furthermore buildings based on a modular system are already devided into multiple layers and subassemblies when they arrive on site and are not constructed of an endless number of single parts as it is the case withtreditional site built elements. This fact also makes dissasembly easier. [21]

NOTES:

[1] Durmisevic, Elma: *Transformable Building Structures*. [Diss. Delft 2006] Delft: Cedris M&CC 2006 p.8

[2] Schneider, Tatjana/ Till, Jeremy: *Flexible Housing.* Oxford: Elsevier Inc/Ltd. 2007 p. 4

[3] cf. *Transformable Building Structures*. p.9

[4] Source: US EPA study: *Buildings and their Impact on the Environment - A Statistical Summary,* 2009. Link: http://www.epa.gov/greenbuilding/pubs/gb-stats 10.06.2013 10:23

[5] ibid.

[6] cf. *Transformable Building Structures*. p. 28

[7] Clouston, Peggi: *Without a Hitch* - New Directions in Prefabricated Architecture. Amherst: University of Massachusetts 2009 p. 13

[8] *Transformable Building Structures*. p. 43

[9] cf. ibid.

[10] cf. ibid. p. 45

[11] cf. Guy, Brad/ Ciarimboli, Nicholas: *Design for Disassembly in the build environment.* Seattle 2010. p. 9 [Link: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Design_for_Disassembly-guide.pdf] 30.06.2013 15:20

[12] *Design for Disassembly in the build environment.* p. 38

[13] cf. *Design for Disassembly in the build environment.* pp. 40f

[14] cf. ibid. p. 42

[15] cf. http://www.steelscape.com/Files/sustainability/sustainability_technical_bulletins/Steelscape_Sustainability_Technical_Bulletin_4_-_Recycling.pdf 12.06.2013 12:27

[16] *Transformable Building Structures*. p. 16

[17] cf. *Transformable Building Structures*. pp. 171ff

[18] cf. *Design for Disassembly in the build environment.* p. 21

[19] cf. ibid. p. 31

[20] cf. http://www.aluminium-award.eu/2008/entries/industrial/en-citizen-m-amsterdam-schiphol 12.06.2013 17:17

[21] cf. *Design for Disassembly in the build environment.*

TRENDS

“Architects must consider whether to think of buildings as complete artifacts or perpetual works-in-progress.”

(Jonathan Hughes)

CHAPTER ■■■■■■

LATEST TRENDS and FUTURE VISIONS

Since the term “module” can be interpreted in many different ways, the topic of modular building systems in a broader sense is almost never-ending. There are a lot of other interesting architectural examples which make use of modules in addition to the ones that have been mentioned so far. This chapter will point out what else can be considered as a modular building, with the focus on latest trends and future visions. Even though their approaches are different, they all intend to provide solutions for a new way of living and a new way of building our houses, considering our constantly changing society and the increasingly importance of environmentally-friendly building methods. Some keywords are: minimal building sizes, houses “to-go”, reuse of materials, container architecture, factory-production, green features, flexibility, affordable housing, emergency housing, etc. The following examples give an overview on some innovative modular systems aiming to improve the quality of our life and of our environment.

1. MINIMAL + MOBILE HOMES

Generally speaking the average floor space of homes has enormously increased over the last decades. The average new built single-family house in the U.S. has a size of more than 200 m^2. However, especially after the house crises in 2007, the market for small or minimal houses increased in the US. This tendency is known as the "*Small House Movement"* which is joined by more and more people each year who believe that American houses in general are too large, wasteful and energy-inefficient. The tendency of increasing living space can also be seen in Europe, even though averages sizes are still significantly smaller).

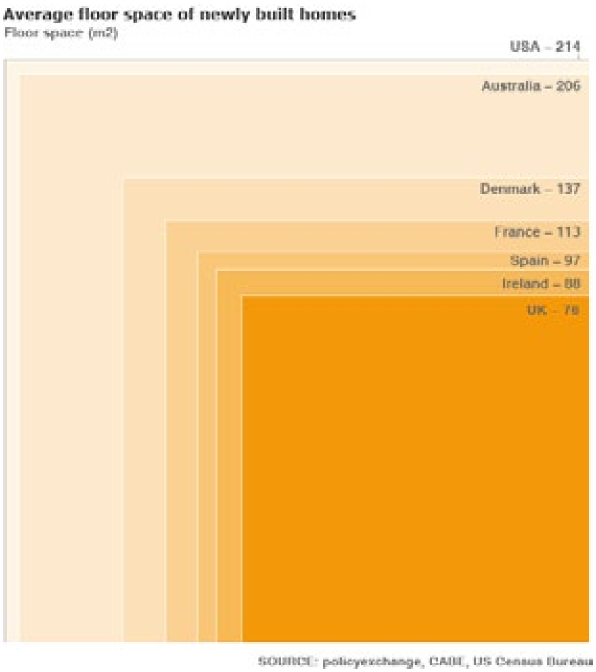


Fig. 66: Average floor space in different countries. The Cabe survey questioned residents of newly built homes built between 2003 and 2006

Since customers show significant interest in smaller houses in order to minimize their ecological footprint, architects react to that need by designing small modular houses. They either consist of only one module which arrives entirely finished on site, or they are constructed of a small number of construction modules which can quickly be assembled. Many of these examples try to integrate the mobility of living units into their design as well. Reason for that trend towards minimal houses "to-go" is the growth of single-households, the increased need of mobility and flexibility in our society, the lower initial and running costs, and the growing awareness of environmental issues. More and more architects, existing firms as well as new ones, are coming to the market with ideas and modular concepts focusing on smaller, simpler and more sustainable ways of living. Even though they might not be a solution for everybody, they can surely provide perfect accommodation for short-term stays or add easily additional space to an already existing building.

Micro Compact Home

One of the first European examples was the *Micro Compact Home*, which was designed by British architect Richard Horden as part of his design studio at the Technical University in Munich in 2005. *"The micro compact home is a high quality compact dwelling for one or two people. Its neat dimensions of a 2.66m cube can adapt to a variety of sites and circumstances, and its functioning spaces of sleeping, working/dining, cooking and hygiene make it suitable for everyday use."* [1] Due to its compact dimensions (2.66 x 2.66 x 2.66 m) and its light weight (approximately 2.0 tons) it can easily be delivered, relocated and integrated into any landscape. It is completely finished once it arrives on site and can be easily delivered by truck. Potential uses are social or student accommodation, short stay business or weekend/holiday accommodation. It may be arranged as single unit or the modules can also be grouped in horizontal or vertical arrangements. Its construction is based

Fig. 67-70: Micro Compact Home, Richard Horden, 2005

Fig. 71: LoftCube, Werner Aisslinger, 2004

on a timber frame structure, isolated with polyurethane horizontal or vertical arrangements. It is produced in Austria and can be delivered within 8-10 weeks all over Europe at a guide price of EUR 38,000. That includes all interior fitting but not the delivery or installation. [2]

LoftCube

German architect, Werner Aisslinger, designed with his *LoftCube* an attractive temporary or everyday living unit for people interested in the nomadic lifestyle. The cube can be placed anywhere but is especially intended as modular living unit which can be placed on flat roofs of high-rise buildings in big cities for the modern “city nomad” - businessmen and women who often have to change their location due to their job and want to stay in a modern and urban surrounding. In order to make the *LoftCube* mobile, an important part of Aisslinger’s design was to create a structure that could easily be assembled and disassembled. It is constructed of a 7.25 x 7.25 m steel extrusion frame which is cladded by glass panels and windows to guarantee light and a stunning 360° view. The *LoftCube* can be set up in only a few days; disassembly takes around 2 days. The frame is made of aluminum to minimize weight so that the living unit can be also relocated by helicopter once it is assembled. All elements are restricted in size to allow them to be shipped in standard containers. The interior provides around 40 m² of living area, divided into a kitchen, a bathroom, a living room and a bedroom but can be rearranged if desired. The client is given a variety of options for interior finishes to allow him to create his own personal space. It is also possible to connect several cube modules horizontally to create a larger living or working area. In order to provide running water, the dwelling has to be connected to utility lines through the roof to the building below. Since the inception of the *LoftCube* in 2004, they’ve popped up in gardens and on rooftops all over the world: in Spain, Belgium, Canada, etc. Costs range between EUR 65,000 and 75,000. [3]

Fig. 72: The *LoftCube* module can be combined to form larger (living-) units

2. MASS-CUSTOMIZATION with ROOM-SIZED MODULES

Especially in the U.S. there is a big revival of prefabricated modular housing going on; it is one of the fastest growing sectors of the construction industry. Modular housing in this respect means that entire room-modules are built in factory almost to completion (up to 95%), transported to the site and installed. The factory-production of entire houses has a long history in the U.S., but in contrast to the rather cheap and low quality “mobile” or “manufactured” homes, which usually end up in trailer parks, the new generation of prefabricated houses aims not only for affordability but also for high quality, modern design, and sustainability. Another new feature is the remarkably high grade of customization which is offered to the client. Due to new digital programs and production methods prefabrication is not bound to uniformity anymore. Homebuyers can either choose between certain pre-designed house modules that they can combine to their taste or completely customize their own ones which will then be manufactured in a factory. The time has come where the kind of mass customization Walter Gropius was dreaming of has finally become possible. As the stigma of low budget and low quality associated with prefab is fading away, people realize the advantages prefab can offer in terms of reducing time, costs and environmental impact and an array of options is hitting the market.

Fig. 73:Delivery of almost entirely completed volumetric modules

One of these prefab companies is Seattle based *Method Homes*. They offer their own modular system: units of a house (a kitchen, a bathroom, a bedroom, etc.) are made as modules in the company's own factory and then trucked on site 80 to 95% complete. Clients can either choose between a number of pre-designed modules or work with an architect and bring their own modular design for *Method Homes* to manufacture. The only limitation is that it needs to fit on a truck. The reason why they founded a high-end custom prefab company in 2007 is according to one of the cofounders: *"We saw an opportunity to be more innovative in the way homes are built. With prefab, you get fixed costs and predictable timeline, which puts you far ahead of the game going up against site-built projects."* [4] Method Homes can build a custom home 60 % faster than the traditional site-built construction cycle. Their homes are all designed to LEED Gold certification and feature environmentally-friendly materials and energy efficient appliances. Costs per square foot range between $ 125-200 and only include the finished room modules (foundations, transportation, and installation come extra). The timeline for construction is only set to 2-4 months. [5]

Similar to this example of *Method Homes*, there are a lot of other architects and house companies in the U.S. which make use of the same concept. These kinds of high quality prefab houses don't come cheap but their costs tend to be still significantly lower than a traditional customized, site-built project. And they have lots to offer too, such as:

> fixed costs,
> a predictable and remarkably short construction schedule,
> high quality in terms of design, construction and material,
> lots of options for customization,
> green features,
> and no stress associated with the building process for the client.

Fig. 74: Project carried out by Method Homes, showing that prefabrication and modern design are not a contradiction.

Fig. 75: Container City London, Nicholas Lacey, 2001. Residential

Fig. 76: Puma City, LOT-EK, 2008. Commercial

Fig. 77: CONTAIN ME! Graz, Maresch and Brencic, 2013. Residential

Fig. 78: Freitag Flagship Store Zürich, Spillmann Echsle Architekten, 2006. Commercial

Fig. 79:Cité a Docks, Cattani Architects. Student housing

3. CONTAINER ARCHITECTURE

Another kind of modules that can be integrated into a building structure, are shipping containers. They also provide great design possibilities but are mostly used as environmentally-friendly and resource-conserving alternative to traditional building materials. There are countless numbers of empty, unused shipping containers around the world just sitting on shipping docks taking up space. The reason for this is that it's too expensive for a country to ship empty containers back to their origin and in most cases it is cheaper to buy new containers. The result is an extremely high surplus of empty containers which are just waiting to become modular units for homes, offices, apartments, schools, dormitories, studios, emergency shelters and everything else. In short the container is an idea with a promising future. Standardized, robust, stackable, and available all over the world, inexpensive, easy to erect and dismantle, cheap and sustainable - containers offer lots of advantages. It is no wonder, therefore, that architects, designers, and artists all over the world integrate them into their projects.

Due to their standardized dimensions they are very beneficial for buildings which require a high amount of similar units like student dormitories or apartments. In this case the "1 container = 1 unit approach" can be applied which makes the construction very efficient. But they are also used differently; the modules can be stack together in all kinds of ways and create livable, adaptable spaces (as it can be seen in the Container City in London). Or, they can also be perfectly used for providing an extra room or home office to an existing building. But despite all these innovative and creative designs, there are some negative aspects of using container which should at least be mentioned. For instance, the coatings that are used to make the containers durable for ocean transport can contain harmful pesticides, or the types of goods that have been transported may have left toxic traces. That means that it takes quite an amount of work and energy until containers are actually habitable. But after cleaning and the appliance of insulation and ecological materials on the inside they can be used without any health concerns. [6]

4. EVER-CHANGING STRUCTURES

Besides all these realized projects there are quite a number of utopian visions how modular buildings, or buildings in general, could look like in future. Their designers primarily want to provide innovative living solutions that are capable of dealing with our constantly changing society and the increasing importance of flexibility. Based on predictions that our cities will further grow and space will get rare, they also try to give answers in terms of the issue of living in dense urban areas while achieving a high quality of living.

Fig.80: "houses on the shelf", h3ar

Fig. 81: Corb v2.0, Andrew Maynard Architects

Concepts of example by h3ar or Andrew Maynard Architects pick up again the utopian ideas of plug-in cities which were developed in the 1970s and translate them to present. They envision a modular housing system designed to accommodate homes that are plugged into a grid, occupied for a period of time and then removed by a crane. If the user moves he can bring his living-module with him to another city where he can plug it into a framework again and feel home right away. This indeed is a futuristic idea, but considering the ever-changing world we live in, it might not be as utopian as it was in the 1970s anymore.

5. OPEN SOURCE ARCHITECTURE

I would like to end this chapter with a socially motivated building system that could mean a great improvement of living quality especially for poor people all over the world.

Fig. 82: Download houses which are created and shared in an open library by a community of designers and makers from around the world

Considering the fact that the fastest growth of population won't happen in skyscraper cities but rather in form of self-made shelters and favellas, we should try to improve the way how socially deprived people build their homes. If we really want to make a difference in terms of climate change, urbanization and health issues it won't be enough for architects to focus only on exclusive architectural projects for the richest 1% of people in the word. The challenge the next generation of architects has to face is "*how are we going to turn our client from the 1% to the 100% of the world's population?",* thinks Alastair Parvin, co-founder of an open-source construction system called WikiHouse. [7] The idea behind this system is to generate architecture for the people by the people. In times of 3D plotters *"factory is everywhere and the designteam is everyone"* which could lead to a major change in how we build houses. WikiHouse's aim is to create a freely shared open-source library of houses which everyone can download online and adapt it in Google SketchUp to his or her needs. Lengths and widths of the house are customizable, the only guideline is that the width needs to follow a modular grid of 1.2 m.

There are 3 differently wide modules, the A (1.2 m), the B (2.4 m), and the C-series (3.6 m) which can be combined in any sequence and result in different widths of the house, depending on the user's spatial needs.

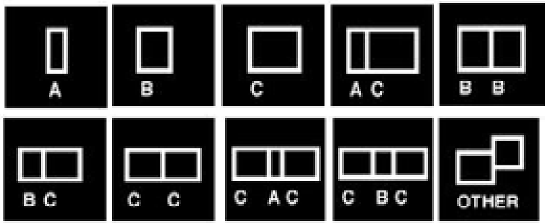


Fig 83: Different combinations of the 3 modules equal a variety of widths

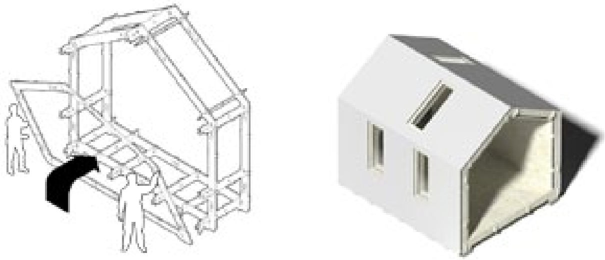


Fig. 84: The lightweight frames can be raised by hand and connected into a finished house structure

Then, with almost only a mouse click a set of cutting files is created and all you need to generate building materials out of those files are a CNC-machine and 18 mm plywood sheets. The parts which are cut out by the machine are numbered and can be set up by a team of 2-3 people within a day, with no need for specific skills or tools. The result is a basic shell of a house which can be equipped with further elements like windows and a electrical system, based on what is cheap and available in the particular country and location. Thereby a kind of architecture and proper, low-carbon housing is offered to everyone - no matter what social class they belong to. And anyone can contribute to this project, in form of financial funds or design ideas. [8]

NOTES:

[1] Source: Official website *Micro Compact Home*
Link: http://www.microcompacthome.com/
26.06.2013 16:32

[2] cf. ibid.

[3] Source: Official website *LoftCube*
Link: http://www. loftcube.net/ 26.06.2013 09:10

[4] American Prefab: A Shopping Guide. In: Dwell Magazine Dec/Jan 2012. p. 83-81

[5] *Method Homes* cofounder Mark Rylant. ibid. p. 80

[6] cf. Pagnotta, Brian. “The Pros and Cons of Cargo Container Architecture” 29 Aug 2011.
Link: http://www.archdaily.com/160892 14.06.2013 12:01

[7] Alastair Parvin, co-founder of WikiHouse on in his talk at TED 2013
Link: http://www.ted.com/talks/alastair_parvin_architecture_for_the_people_by_the_people.html
18.07.2013 20:35

[8] cf. ibid.

CONCLUSION

CONCLUSION

Without any doubt, it can be said that “modularity” in terms of buildings is a very broad tropic, because the term itself leaves room for many different interpretations. Basically any building that consists of a limited set of repeatedly used components can be called modular. This variety of possible modular buildings is best expressed in the previous chapter which intends to show a broad range of how modularity is applied by different architects. But the focus of this thesis is on the following two main approaches of incorporating modularity into a building:

(1) For one thing, a buildings’s layout can be based on varying planning modules, such as different rooms or entire units, which can be combined with each other to generate diverse floor plans and unit sizes. (2) The second possibility is that the building is erected of a certain set of construction modules, meaning that in order to actually build it, standardized and prefabricated wall-, floor- and other necessary modules are used which only need to be assembled on site with the minimum on effort.

While option 1 focuses primarily on customization possibilities and user’s involvement, the main aim behind option 2 is to increase speed and quality of the construction process itself. It can be understood as an attempt to improve the traditional way of building which is very often characterized by time delays, budget overruns and inefficient workflows on site. With the application of prefabricated elements these kinds of issues could be minimized tremendously because a lot more effort is devoted to the planning stage of a project. In order to manufacture exactly fitting elements it is essential to design the individual building parts and construction details precisely beforehand - with the result that during construction not many mistakes can occur. Further reasons which boost the reliability of prefabrication are the weather-independent production environment and the fast and efficient assembly on site.

Even though most projects are still designed to be carried out with traditional building methods, a slight trend towards the use of industrialized building elements can be noticed. However, this application of prefabrication is primarily limited to the construction of single projects for which they are individually developed and produced. There are very few examples of concepts that are not based on designing a one-off building but try to establish a system which makes use of prefabricated elements and can be applied for the design of different buildings; some concepts are offered by single-family-house companies, however, they are only limited to this kind of building and cannot be transferred to accommodate multiple units.

One of the reasons therefore is that the establishment of such a multi-functional system is very complex because it needs to integrate a high extent of flexibility in order to adapt to different sites and different users. In this regard the - as option 1 described - modularity of layouts and floor planes becomes important and has to be integrated into the system because this feature allows for a wide range of possibilities as every user is individual and has different wishes in terms of the design of his living space. This means that a building system designed for a multi-unit and multi-story apartment should consider modularity in terms of the technical and constructional aspect, i.e. consist of a kit of elements, and needs to provide the possibility of modular floor plan arrangements.

The reason why such a modular building system would be desirable and sustainable in many ways is not only based on an increased efficiency of the construction process but also on its social aspects. Especially people, who cannot afford to pay an architect to design their living space could benefit of such a concept. Even though the options are not endless they could still customize their units within the generated framework determined by the architect who established the system. Due to standardized and mass-produced elements, costs could be kept low. Furthermore such kinds of customizable modular systems could mean an attractive alternative to one-single-family houses which are often seen as only possibility to realize someone's individual living ideas.

In terms of ecological sustainability it would be beneficial as well because prefabrication makes the production of the individual building elements more efficient - thereby consuming less material and energy - and the fast and easy assembly lowers the emissions on the environment. Furthermore it could be interpreted as ecological sustainable because a building's life span can be extended as it increases the possibility for disassembly. Modular constructed buildings are already separated into different layers in order to transport them from the manufactory to the building site which makes it easier to exchange or replace individual parts to a later date. This need for adaptability can be required due to technical improvements or occupant's wishes.

Considering these aspects the question whether the integration of modularity in general and of modular building systems in particular would lead to a more sustainable building practice could be answered with a "yes" - as long as technological efficiency and human needs are both considerd.

This gained knowledge built the foundation of my own designed modular system, which will be explained in the second part of this thesis. The ultimate goal was not to establish a system which only focuses on the most efficient application of construction modules but also provides a high level of user choices - thereby maximizing the technological and social potential of modularity in architecture.

DESIGN

DESIGN PARAMETERS

The general design goal was to establish a building system (for residential buildings) that consists of a kit of pre-determined modules, which offer - depending on how they are combined with each other - a great variety of possibilities. This kit of parts contains planning as well as construction modules. While the planning modules guarantee modularity in a conceptional sense, meaning that their combination leads to a great variety of living units in terms of type, size and number, the standardized and industrially manufacturable construction modules allow for an easy and efficient production and assembly.

It can be seen as an attempt to maximize the benefits of modularity through its application during the design as well as the construction stage. It is argued that thus approach leads to a socially and ecologically sustainable way of building.

Besides this main goal,following aspects were considered in the design process:

Multi-Story housing. Even though the idea of this thesis is based on developments in the sector of one-family-houses, this system should be applicable for residential building which can accommodate more than one family. The reason therefore is twofold: (1) On the one hand single-family houses do not match with resource-conserving and sustainable architectural values. (2) On the other hand there is simply a lack of systems that can be applied in a larger context. The Austrian architect Hermann Kaufmann argues in the specialist journal “Zuschnitt” that almost all modular building systems that are available in Europe aren’t sophisticated enough and focus only on the design of customizable single-family houses. Besides the developments in this field, there is no worth mentioning industrial prefabrication system. There are only some specific systems which offer prefabricated wall, floor or roof elements which are ordered and delivered as single-components on site. However, an all-embracing modular system based on prefabricated elements for multi-story apartment buildings is missing. [1]

Site responsiveness. The building system should not be designed for a specific type of site but should be adaptable to all kinds of conditions, meaning that it is applicable on differently sized, located (rural/urban surrounding) and orientated sites. Furthermore it should allow for a vertical and horizontal connection to achieve a different number of units and building density requirements.

Flexibility. It should guarantee a flexible building structure with the possibility to create differently sized buildings and a great variety of living units.

Simplicity. The system should not consist of complex construction modules that are difficult and expensive to produce. My goal was to generate a building system which allows the application of simple modules which can be built of off-the-shelf materials by various manufacturers to make the system broadly available and applicable.

Off-site production and prefabrication. The application of standardized and repeatedly used construction modules offers a great chance to make use of off-site production methods. Prefabrication brings many advantages with it, first of all it shortens a project's time schedule, enhances its quality and predictability, and lowers the waste of energy and material.

Resource-conserving: The construction modules should be built with an environmentally friendly material to achieve a good life-cycle-assessment of the overall building. Another important aspect is to achieve energy efficiency by meeting low-energy house standards.

Longevity: The system should, once the building is built, allow for future change, so that it does not become obsolete after a short amount of time. Requirements for change can either be the result of necessary technical adaptions or be based on changed user wishes. Therefore building parts should be exchangeable without too much effort and the size, type and number of units should be adaptable post-occupational.

Multifunctionality: The system may give the opportunity to use parts of the building not only residential but also allow some offices or at least home-offices.

User resposiveness: Various living patterns should be possible to accommodate in order to guarantee and maintain a social diversity within the dwellers structure. By making the building adjustable to a later date, dwellers don't have to move out if their spatial needs have changed and they need more living space.

Participation: Users should have some say when it comes to the design of their future living unit. The system should be simplified to such an extent that it can also be understood and applied by a layman. Customization possibilities shall be provided at various scales. Depending on who is in charge of the planning and building process, there could be a different extent of user involvement, varying between the possibility to determine the number and layouts of rooms in general, the design of the windows or the option to personalize their unit with additional elements, etc. Units should also be designed in a way that enables the user to choose the function of a room individually.

HOW TO ESTABLISH A MODULAR SYSTEM?!

CHALLENGE 1: CHOOSING MODULES

I would like to start this paragraph with a short repetition of the most important aspects of modularity: The main characteristic of modularity is the division of a whole into a number of components which are called “modules”. These components or modules may be mixed and matched in many different ways which leads to a variety of possible configurations. To establish an efficient modular system it is important to limit the number of modules to a small amount and use them repeatedly - variation is achieved through combining them differently. To make a wide range of combinations possible, modules have to be standardized and have matching interfaces. Standardisation and matching interfaces are also essential features when modules need to be exchanged, added or removed.

Before starting the design process, this rather abstract definition has to be transferred into the field of achritecture and the designer needs to determine the main objective he wants to pursue in terms of modularity. Since the term “modular building” can be interpreted in many ways, each approach can be different. When it comes to designing and constructing a building, there is not one specific way how a modular system can be applied but multiple, depending on what kind of modules are used. That a modular building system can be applied in a conceptional or a constructional manner has already been described in chapter 2 and 3 and therefore only the most important aspects will be repeated:

One possible application is to organize the floor plan modular, which means that either the entire building or only particular living units are the result of repeatedly used planning modules. This can make the planning process as well as the overall building structure clearer and guarantee a great variety of possible unit sizes and unit types.

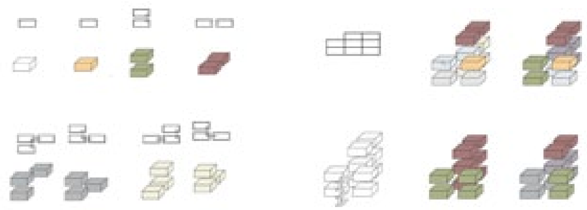


Fig. 85: Examples for planning modules used for the „Smart Price House Case Study #1“, Hamburg, 2012

Another possible interpretation of a modular building system is that the building is entirely constructed and built of standardized and prefabricated elements. These construction modules can be simple components like floor-slabs or columns, wall panels that are highly prefabricated and already include windows and cladding or three-dimensional room-units that arrive on site almost entirely completed (up to 95%). No matter what kind of module is applied, they are usually prefabricated and only need to be lifted in place once they arrive on the building site. Depending on the extent of prefabrication the necessary construction time on site shortens accordingly and makes the building process more efficient, more sustainable and more predictable.

Fig. 86: Examples for construction modules; two- and three-dimensional elements

Some buildings only make use of either the conceptional or the constructional principle. However, in best case those two approaches are combined within one project to maximize the potential and benefits of modular building systems. This means that the dimensions of the modules used in the design stage should be harmonized with construction components and vice versa. They don't necessarily have to have the exact same dimensions, but they should both follow the same grid.

To establish a system which allows for modularity in terms of designing a building's floor plans and can be constructed and build with modular elements is not an easy task. The challenge is to find a dimensional grid which results in a reasonable size for a planning module as well as for a construction module. In terms of determining a planning module it is important that living units or rooms have appropriate lengths and widths while the size of construction modules is primarily influenced by transportation and assembly issues.

CHALLENGE 2: DEFINITION of RULES

Besides this challenge to determine an appropriate dimensional grid, another difficulty is to establish a system which should consist of a minimum of standardized elements and provide a maximum of different layouts, sizes, unit-types, etc. To overcome this dilemma it is helpful to define rules within the system, meaning to accept that not everything is possible and that there have to be some restrictions.

Examples for such restrictions are:

> a limitation of length, width or height of the building

> a fixed position of some elements (usually access and public circulation area, service cores, bathrooms, kitchens, etc.).

It is very important to set some of these rules because that helps to clarify a system. If it leaves open too many possibilities, the system becomes vague and hard to understand for anyone who wants to make use of it.

The trick is to conceive a system which is rigid enough to regulate, but flexible enough to allow for diversity.

Permanent and variable elemens

When designing a system it is advisable to determine rules and permanencies at the beginning to establish a general frame within which change can take place. This frame should provide many possibilities to combine modules differently and thereby ensuring a variety of unit layouts and sizes. In this regard the units and rooms can be seen as the variable and flexible parts of a modular system and should therefore be determined as a final step in the planning process; at first the more permanent elements - the structure, the skin, the access and the services - should be positioned. Because, if one starts with the specifics of the plan layout and from there determine access, service and structure, it is highly likely that the building will be inflexible and won't allow interchangeable units and rooms.

For many designers this will mean reversing the normal sequence of approaching housing, paying less attention to the foreground and more to the background.

Especially the position of services and entrances is very crucial if someone wants to provide a wide possible range of potential layouts and therefore needs to be considered carefully.

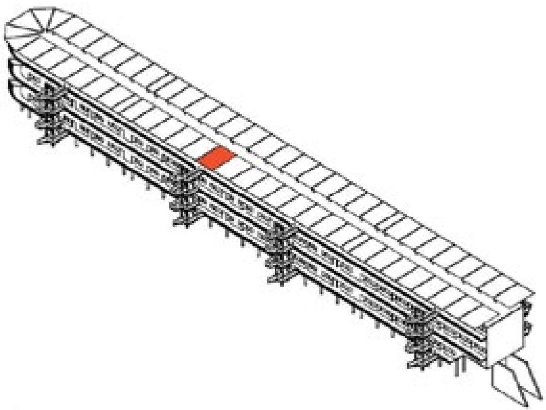


Abb. 87-88: Nemausus, Jean Nouvel, 1987: Only the public circulation and access areas, as well as the service core within each unit was given; unit sizes, types and layouts could be chosen individually

Zoning

Another helpful strategy to structure a system could be to establish permanent and variable zones within the system. The permanent zones build the necessary framework for the system whereas the variable zones guarantee a certain extent of modularity and flexibility. This approach can be illustrated by the multi-story apartment block "Überbauung Hellmutstraße". Permanent are the access and public circulation area and the so-called "wet-zone" where all service cores, bathrooms and kitchens are located. The zone which only contains rooms could be interpreted as variable, because the rooms neither have specific sizes nor are they assigned to a specific unit, meaning that they could be used in various ways and by various units.

Fig. 89: Überbauung Hellmutstrasse, ADP Architektur und Planung, 1991

CHALLENGE 3: ACHIEVING FLEXIBILITY

One of the most important features of a modular building system is the variety of possibilities that can be realized through combining the modules in various ways. In other words the system needs to be flexible, otherwise it could not allow all kinds of different arrangements. But how to make a building system flexible? Before offering some strategies and tactics I want to define the most important requirements in terms of flexibility.

At first it can be said that flexibility is essential in many perspectives and on multiple levels. Generally, flexibility in housing can work either prior to occupation, or post-occupation, or both. In the former, flexible housing design allows future residents to have some say over the layout and/or the look of their home. Post-occupation flexibility refers to the way that the design of a building allows residents and housing managers to make adaptions over time. Generally a technique to achieve pre-occupation flexibility will also enable post-occupation flexibility, and vice versa. [2]

The question of flexibility can be asked first at the building as a whole, then at the level of the housing unit and finally at the level of the individual room. Furthermore the flexibility of different construction methods will be illustrated.

1. Building Level

> *Can you add the building horizontally and vertically?*
> *Can the building system be adapted to different sites?*

A building system which is not only designed for one specific project but should be generally applicable has to be adjustable to all kinds of different conditions. The first question that needs to be solved is how to make it adaptable to different building sites. Because almost every site is unique - varying in size, orientation, location (urban/ rural), and topography - this is not an easy task. To fill a specifically shaped site the system needs to be expandable which can be achieved by stretching it or by multiplying the building and connecting it horizontally and vertically.

Another important aspect in terms of site conditions is the orientation of the building site. The designer has to determine whether he wants the system to be applicable only for specifically oriented sites (i.e. east-west or north-south) or whether it should work for all kinds of orientations. Of course, the latter option is favorable but not easy to realize. The designer has to pay attention that every unit is provided with an appropriate amount of natural lightning. This is especially essential when the building is north-south-oriented. A strategy to avoid living units that are exclusively oriented towards north is to split it up vertically on more than one level.

> *Can the system contain a different number of units in general?*

The size of the building as a whole does not only need to be variable because of the site but also to achieve different building densities which are either determined by law or the builder/developer of the housing project. Each project requires a different number of units and therefore the building needs to be adjustable in length and height.

> *Can the system contain a different number of units per floor?*

A system gets even more flexible and beneficial if a varying number of units can be situated within one floor. This means that even though the size of each level in a multi-story apartment block is the same, the number and size of units may differ. For example, while the ground floor could contain two larger units, the first floor is divided into three smaller units. To make that possible, partition walls need to be relocatable (i.e. non-loadbearing) and the position of the service cores has to allow a flexible number of apartments.

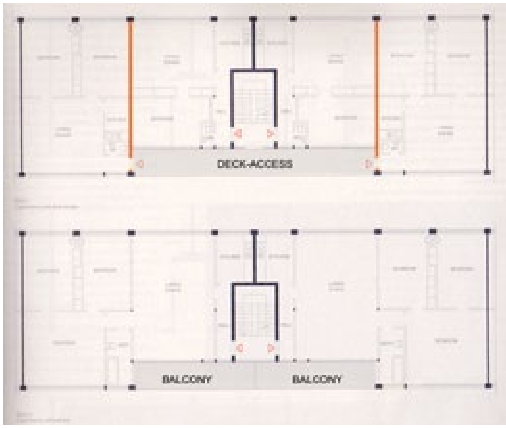


Fig. 90: Verwandelbare Wohnung, Karl Schneider, 1927. One of the first attempts to integrate flexibility into housing - four apartments can easily be combined into two units

2. Unit level

> *Are different unit sizes and unit types possible?*

Depending on how many modules are chosen and combined with each other, differently sized units should be possible. It is advisable that they are aligned with commonly-used unit sizes, i.e. ca. 45-50m² for a two-room apartment, ca. 75m² for a three-room apartment and ca. 90m² for a four-room apartment. These unit sizes are most popular but the system should also provide the possibility to generate some special forms, for example studio apartments, apartments that are additionally equipped with a home-office to combine living and working, etc. Besides different sizes, the variety of units can be further extended by offering maisonette-units as well.

> *Can the units be joined together or divided up?*

Joining. In most housing projects each unit is generally designed and considered in isolation from the next. This prevents or at least complicates the combination of units at a later date. When designing a modular building system the opposite should be the case. The possibility of joining units either horizontally or vertically is an important characteristic of a modular featured building. This allows, for instance, two one-bed apartments to be joined together to form a three-bedroom apartment, allowing a family to stay in place as it grows. There are no hard and fast rules as to how the potential to join units may be achieved, but the following points should be considered:

1. If joining together horizontally, any future openings should be planned and prepared carefully to ease the adaption in the future; this could be achieved through sections in the dividing walls that can be easily knocked through at a later date.

2. When joining together horizontally, the key design issue is that of access. The provision of a more generous shared access space generally facilitates later joining and subdivision.

3. When combining units, one has to deal with the potential duplication of bathroom and kitchen. Once again, the position of the service core is decisive whether it can supply a second unit or not. [3]

Division. The opposite of joining up units is the design of single large units that can be divided up at a later date. This feature can be useful when the children move out and the apartment becomes too large for the parents. If technically and structurally possible, the area which is not needed any more can then be transformed into an independent living unit, room for rent, a home-office, etc.

Shared room. Besides the possibility to join or divide entire units there is another strategy to extend or minimize the size of a living unit. The idea of the "shared room" can be applied. This is a non-specific room that lies between units and can be allocated to either one or the other. It gives the possibility for one of the apartments to gain an extra bed or work room, and then give it to the other when it is no longer needed.
A more sophisticated version of this type of room incorporates a bathroom and services to plug in a kitchen. This room can then be used as small but independent apartment/small office or can be rented by one of the bordering units if additional space is required. [4]

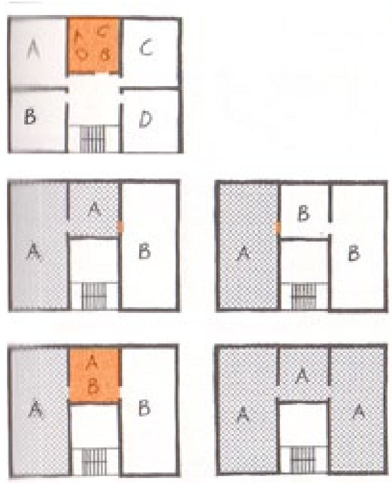


Fig. 91: "shared room" principle

> *Does the location of the services allow for different plan forms?*

The position of the service core is critical in terms of flexibility since it often defines the most permanent elements in a plan, the kitchen and the bathroom. Because kitchens and bathrooms are the least likely rooms to be moved over the lifetime of the housing, it is best to consider them first in the design process and to draw the unit plan based on the position of the service core. One can then see how the space around it can be divided up and whether there are different ways of achieving this division.

Fig. 92:“Smart Price House Case Study #1” consists of equally shaped modules whose only permanent element is the service core; this fact allows many floor plan options

One modular housing system which is based on the position of the service core is he project “Smart Price House Case Study #1” in Hamburg. The architects wanted to transfer the concept of the prefabricated single-family house into an urban context and created a building system which is based on a quadratic living module with a size of 45m². This module consists of industrially prefabricated wall and floor-slab elements and is only structured by the position of the service core. The core is the only permanent element and even though it is located on the same spot in each module its well-thought-out position allows lots of different layouts.

> *Can the unit accommodate a variety of living patterns?*

This feature is not necessarily essential for a modular building system, but is definitely very beneficial in terms of providing a socially sustainable system. Our demographic structure has changed enormously over the last 20 years; the number of traditional family households has decreased whereas an increase can be observed in the number of single-person households, shared accommodations and concepts that include home-working. One can say that our life-styles have become more and more diverse and it is therefore reasonable to design housing projects and unit layouts that are not only appropriate for a typical family with one or two kids.

Fig. 93: Grieshofgasse, Helmut Wimmer, 1996. A brilliant plan that allows rooms with no specific function to be combined in a number of different ways.

A strategy to approach that issue is to provide a number of equally sized rooms off a central hall or circulation spine. The kitchen may be included in one of these rooms, or defined as a separate smaller space. A unit that consists of a number of rooms of equal size invites different social interpretations that are open to diverse cultural scenarios and user groups. A unit could, for example, be used as two bed-rooms and a living room for a small family or else just easily as a shared apartment for three adults. [5]

> *Can the unit be designed by its users?*

This question also rather concerns social than constructional aspects and is strongly related to the previous one. But whereas the provision of equal rooms is a strategy applied by the architect to attract different user groups, this paragraph focuses on participation and user involvement to achieve various layouts for various people. The idea of empowering the user through their active involvement in the planning has been developed in the 1960s and has been thematized by various architects ever since. This approach is based on the belief that every occupant should have the right of choice in terms of location and orientation, as well as a choice of personalization with regard to the layout of a dwelling unit. [6]

Fig. 94: The German architect Matthias Schrimpf focuses in his concept **fertighauscity5+** on user involvement to satisfy different needs for different occupants.

But as a matter of fact, the user's possibility to personalize his unit is mainly limited to the field of single-family houses which are individually designed according to the user's needs and requirements. Multi-story housing projects, especially in the social sector, don't involve future occupants sufficiently. In most cases they move in a unit which has entirely been designed by the architect. Of course, it could be argued that planning would become too complex and time consuming if everyone asked for a special layout. But there are possibilities to involve the occupant at least to some extent and let them make little decisions which don't interfere with the overall planning concept. A building which is based on a modular system makes it easier to involve the user because the planning process is systematized and simplified and parts of it could also be carried out by a layman. So the architect could generate the general frame (dimensional grid, modules sizes, access area, circulation area, etc.) and users could create their own layouts by combining pre-determined modules according to their own desire. There are multiple ways of involving the user: he could choose between different wall-modules to personalize the position of windows and doors, room-modules to determine the number or size of rooms or add-on elements such as additional balconies, loggias or additional living space.

> *Can the unit be used for anything other than purely residential?*

Multifunctionality is also not essential but is often inherent in modular systems. Since they are based on the idea of providing a maximum of different layouts and combinations and aim at being applicable under various conditions, it is not unusual that they can generate offices or multifunctional buildings as well. Exchangeability of functions is a very positive feature because it helps to avoid one of the most common problems in building: obsolescence. Buildings that are constructed and designed in a way that allow functional change can respond to specific social and economic demands and thus potentially extend their useful life span.

3. Room level

> *Can the room be used for more than one function? Can the room be furnished in a variety of ways?*

Flexibility regarding the room level should insofar be considered as it makes a unit be usable not only in one specific way. As already mentioned this is important because it makes it possible to accommodating different life patterns and to personalize the living unit according to the user's needs.

4. Construction level

If one way flexibility can be achieved is through the design of the building, unit or room in plan, the other way is through the methods by which the housing system is constructed. To achieve real flexibility both - plan and construction - have to be considered together. Whereas the previous subchapters investigated particular ways that a system may be physically planned in order to promote flexibility, this section will focus on how a building might be structured, constructed and serviced to enable future change.

> *The overall question is: Does the construction enable change?*

Subsequent questions could be:

> *Does the structure and construction allow different floor plans?*

> *Can the elements of construction be separated?*

> *Are the constructional and structural systems legible and accessible?*

> *Can the structure accept addition?*

When considering the construction of flexible housing at the building level, the following principles are useful: The frame, Layers and Simplicity and Legibility.

The frame

When designing a flexible system, one has to consider that the particular design solution could be modified at any time in the future due to changed requirements. Therefore it is important not to start with the specific layout of the building and units but with providing a background frame that enabled a variety of plan forms to evolve within. This frame can be seen both literal - the structural frame - but also metaphorical - the frame for action within.

Constructionally and conceptionally, the frame should be separate from the infill (partitions, services, maybe even external walls) to achieve a separation between a load bearing structure and non-load bearing inserts. While the infill elements have different and shorter life spans and can be adapted over time, the frame is conceived as permanent skeleton. Probably the most obvious way - which also allows the most flexibility - is to build this frame as a basic post and beam construction in steel, concrete or timber.

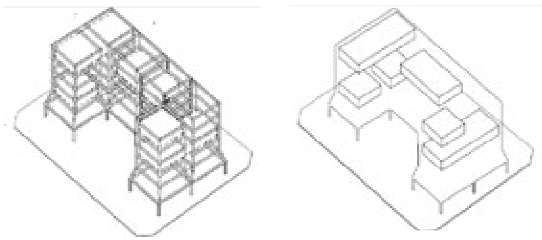


Fig. 95: NEXT 21, Osaka Gas, 1993: The structural frame is entirely separated from the living units. They can be individually sized and inserted into the concrete frame.

But this structural frame could also be achieved through a wall-based construction system, as long as one keeps a separation between the permanent structural elements and the flexible infill elements, and allows a generous free span between the walls. An example of this is the “tunnel” construction where the enclosure of the individual dwelling unit is a permanent load-bearing structure, but there is a clear span across the width of the unit without any permanent partition. This means that while joining units horizontally or vertically is rather restricted, there is a great flexibility in the layout of internal partitions. A popular building which made use of this tunnel” principle is Nemausus by Jean Nouvel. This social housing project is divided into concrete shelled modules of 5 x 12 x 2.5 m which can be connected horizontally or vertically if desired. The living units are only structured by their enclosure and a service core and the user can determine partitions and layouts individually.

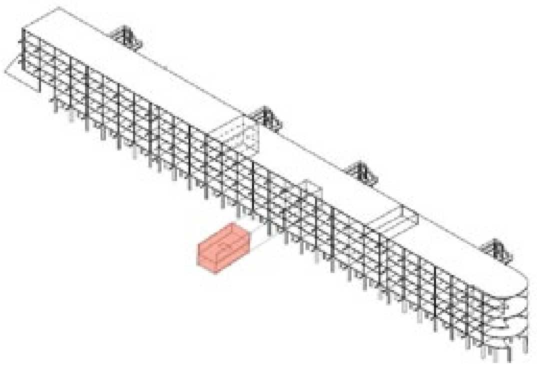


Fig. 96: Nemausus, Jean Nouvel, 1987

The layers

Another strategy when designing a flexible system is to work in layers. Different building elements have different life spans, either because of their construction or use. The structural frame will have a long life span, while kitchen units will typically have a relatively short one and will most likely change in future. Similarly, living units might also be modified in future and should therefore be separable from the load-bearing structure. Normal construction tends to bind all the levels together, so that changing one layer of the system means dealing with all other layers which makes adaptions complicated.

A number of different layering approaches have been identified in the past, but they all follow roughly the same idea of dividing a building into distinct and separable layers according to the different life spans of a building’s elements. [7]

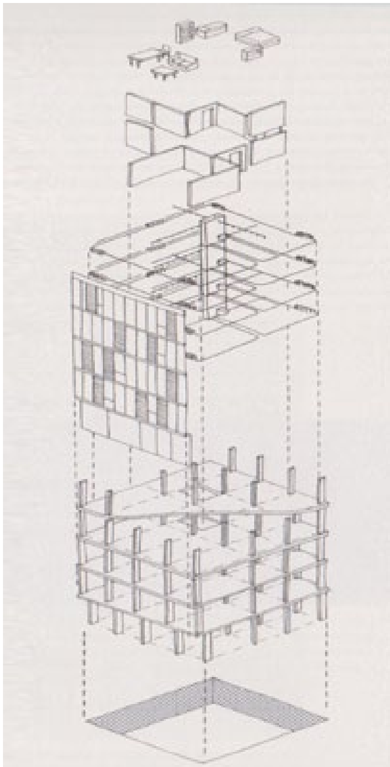


Fig. 97: The six layer system developed by Stuart Brand

One popular approach is Stuart Brand's six layer concept:
1. The first layer is the site, which is always there.

2. The second layer, the structure, is the most durable part of the building and will be there for an average of more than 100 years. It contains the structure (columns, beams, loadbearing walls, trusses and structural floors) as well as the long-term provision for services (risers, cut-outs)

3.The third layer is the skin, which is less permanent and will have to change over time, for example if a new isolation or new windows are necessary. If the external wall is designed to be adaptable, an old part can be taken out and be replaced by a new one. This is especially possible if a building's structure is based on a framework instead of on load bearing external walls.

4. The fourth layer, the services is about wiring and pipes. It will be necessary to maintain and renew them over the years.

5. The fifth layer, the layout-plan, is about the internal partitions which need to be rearranged on a 5-30 year cycle.

6. The sixth layer, which is Brand calls stuff, is about the interior fit-out and the finishes, which are the least permanent elements.

Further principles that should be considered are:

Simplicity and legibility. In order to make future changes without forensic examination and specialist input, it is important that it is clear, which parts are load-bearing and which ones can be removed.

Disassembly and Exchangeability: Design for disassembly works with the principle of layers allowing each layer of a building to be cleanly separated when replacement and changes are needed. This is not only a sustainable approach (because components and materials can be separated, reused or recycled) but also a flexible one (because changes can be easily made at a later time). In this regard the designer has to pay a lot of attention on using demountable connections.
Related to the idea of design for disassembly is that of exchangeability. A building should be designed in a way that allows the exchange of parts without disturbing other parts.

Partitions: One of the most important principles of flexible housing is that, with the exception with the service core one should start the design with the assumption that partitions should be reconfigurable at a future date, meaning that they should not be part of the load bearing structure.

Modularity: The use of modular elements may contribute to the flexibility by providing a kit of parts (doors, walls, framed openings) that can be flexible deployed.

"Prefabricated panel systems contribute to flexibility because they are inherently separated from the structure and thus form part of a layered approach. Throughout the twentieth century, architects have experimented with such systems to varying degrees of success. The more successful projects employ only a small number of elements and the dimensions of the building are coordinated throughout." [8]

CHALLENGE 4: DETERMINATION OF CONSTRUCTION MODULES

This demand for modular and prefabricated construction elements leads over to the next challenge when designing a sophisticated modular system. While the system should be modular in a conceptional aspect (i.e. enable a great variety of different unit configurations through combining and exchanging modules) it should also allow for an efficient application of prefabricated construction modules and an easy assembly. This means that a kit of pre-designed elements (wall elements, floor-slabs, stairs, doors, windows, etc.) has to be defined whose parts can be flexible combined with each other, according to the particular building task. There are many possibilities how a kit of parts could be composed of depending on what type of modules have been chosen. When determining the construction modules many decisions have to be made and it could be helpful to pay attention to following considerations:

> SIMPLICITY
> TYPE
> DIMENSION
> DEGREE OF PREFABRICATION
> MATERIAL

1. Simplicity

As previous chapters have shown, architects have approached this issue in many different ways and with different extents of success. Especially from the 1930s and 1940s on - fueled by the development of new technologies and production methods - a great number of industrially prefabricated and systematized buildings have been designed, ranging from Le Corbusier's System *Dom-ino* to Gropius and Wachsman's *General Panel System* to the *Case Study House Program* in California, to name only a few of them.
The reason why most of them were of limited success and could never establish themselves in the longer-term is traced back by Mark and Peter Anderson from Anderson Architects to the fact that most of them were dependent on one manufacturer or company and therefore not accessible enough for a broad public:

"One of the lessons that can be learned from the many previous attempts at prefabricated housing production is that uniquely proprietary systems of single-source components are too costly to develop and have almost always ended in economic failure, even when excellent in design, detailing, and production concept". [9]

Meanwhile other architects share this opinion and focus on designing systems which can be constructed with off-the shelf and easily available materials, inspired by architectural icons like the Eames House which made use of this principle for the first time. To avoid dependencies on manufacturers, make it available for a broader spectrum of users and lower costs the aim should be not to develop a factory to produce a building system but to base it on a sophisticated shopping list.

2. General type

The most crucial decision that has to be made is which general classification of modules to choose: linear, planar, volumetric or a combination of several of them.

OPTION 1: combination between linear modules, i.e. columns and trusses, which form the load bearing structure and planar modules, i.e. wall elements, which generate the building skin

OPTION 2: combination between linear modules, i.e. columns and trusses, which form the load bearing structure and volumetric modules, i.e. room-units, which are inserted into the skeleton structure

OPTION 3: planar modules in the form of load bearing wall elements

OPTION 4: volumetric modules which are stacked on top of each other and are load bearing as well as space-enclosing.

While the degree of prefabrication increases from 1 to 4 the design freedom declines and therefore this decision has to be made according to the individual requirements of the project.

For example, the application of three-dimensional box modules is generally more cost-intensive but can be highly beneficial for projects that consist of a great amount of equal rooms, such as hotels or senior- and student housing. This method also shortens the necessary construction time on the building site tremendously, which can especially be advantageous in an urban surrounding.

When it comes to choosing an appropriate module type for a flexible housing project, a skeleton structure combined with prefabricated wall-elements could be the right choice. Even though the construction time on site increases, flexibility also does, which might be a more important aspect in a housing project. As we can see, there is no golden rule as to what is the ideal module; this decision is always depending on several aspects, like the type of building, the calculated construction time, the budget, etc.

3. Dimensions

Another decision which has to be made is the exact dimension of the modules. Usually a modular building system is based on a dimensional grid which determines at least the basic lengths of the elements. When it comes to the height of wall- or column-elements, there is the possibility to design them ceiling- or building high. Normally, the larger the element is, the more economical it is because of the reduction of connection elements and joints. However, in this regards the issue of transportation must be considered.

4. Degree of prefabrication

Once the general type and dimension of the modules has been determined, the extent to which the elements will be prefabricated has to be further clarified. This is especially important when using wall-elements. There are several possible degrees of prefabrication, ranging from very basic (only the load-bearing structure without any further layers or windows) to completely finished (including façade, windows, doors). Generally a higher degree of completeness is preferable because prefabrication brings many advantages with it (controlled production environment, increased quality, shorter project schedule, less waste, etc.) and makes the assembly process on site faster, easier and even less expensive since no scaffolds are needed.

Fig. 98: Different degrees of prefabrication in terms of timber wall-elements

5. Material

As already explained in chapter 3 construction modules used in building systems could be of steel, timber or concrete. The application of any of those materials brings advantages as well as disadvantages with it. However, many experts see in timber the most ideal material for producing prefabricated modules, especially for housing projects because of several reasons:

Advantages of timber constructions

> In terms of sustainability it is clearly superior in comparison to concrete and steel, because of its carbon-neutrality. In times of climate change and global warming a characteristic that can't be rated high enough. Another ecological advantage is that it is a renewable material.

> In terms of industrial prefabrication it impresses with easy workability and comparatively with a particular low weight. This feature is extremely beneficial when it comes to the transportation of elements because not only length, width and height are limited but also the weight of a module. While this weight-limitation is often a critical issue for concrete elements, wood constructions are usually not affected by this regulation. Another positive aspect which comes along with the lightness of construction is an easement when it comes to assemble the elements on-site. It also offers a great variety of different prefabrication methods, ranging from producing linear to planar and volumetric modules.

> Further advantages that come along with the application of timber are a comfortable indoor-climate, a high potential to insulate heat and an easy availability of the raw material. [10]

These arguments were crucial to me to focus on timber as construction material and choose accodingly timber modules for the proposed building system which will be further described in the next chapter.

Disadvantages of timber constructions

However, even though wood constructions offer many advantages for the environment as well as for the occupants, their application brings along all kinds of restrictions which have to be considered.

> The most restrictive measure concerns the building height: While recently in Great Britain a nine-story building - entirely constructed from timber - was realized Austrian laws are much less liberal. According to the *"OIB RICHTLINIE 2"* the maximal height for a timber-structured building is limited to four stories above ground level.

> Besides the general height limitation, fire resistance standards have to be considered as well. They are determined for individual building parts, i.e. structural system, substructure, façade, etc. While a building with up to three stories is not so much affected by these rules, a four-story timber building has to fulfill more requirements; for example, in order to avoid that fire can spread from one floor to the other, timber curtain facades have to be provided with horizontal partitions of a width a of at least 20 cm.

Fig. 99: Horizontal fire protection for a timber curtain facade by Hermann Kaufmann, Mühlweg (A) 2006

> Another aspect in terms of timber constructions which must not be neglected - especially in residential buildings - is the acoustic insulation. Particularly when using timber frame elements noise pollution could present an issue, because these kind of constructions lack of solidness and mass which are generally necessary for providing sound insulation. While for single-family houses this is not so much of a problem,special attention needs to be paid to this aspect when building multi-family homes and solutions need to be found to compensate the absence of mass, of example with double-shelled partition walls.

When choosing a solid timber construction the acievement of the minimal requirements for sound insulation becomes much easier.

NOTES:

[1] cf. Kaufmann, Hermann - Der andere Bauprozess. In: “Zuschnitt - Zeitschrift über Holz als Werkstoff und Werke in Holz” (June 2013), p. 4-5

[2] cf. Schneider, Tatjana/ Till, Jeremy: *Flexible Housing.* Oxford: Elsevier Inc/Ltd. 2007 p. 181

[3] cf. ibid. p. 187

[4] cf. ibid. p. 189

[5] cf. ibid. p. 186

[6] cf. ibid. p. 28

[7] cf. ibid. p. 193

[8] cf. ibid. p. 196

[9] *Mark and Peter Anderson* in Smith, Ryan E.: Prefab Architecture - A Guide to Modular Design and Construction. New Jersey: John & Sons, Inc. 2010 p. 40

[10] cf. Kaufmann, Hermann p. 4-5

DESIGN PROCESS

Very soon I decided that I want to base my design on room-sized modules which can be combined to form different layouts depending on what needs the developer or the user has. The next step was to determine the dimsions for these planning modules.

To make the rooms usable for many different functions I chose a dimensional size of 3.60 x 3.60 m since that size can be used as living space, kitchen, bedroom, home-office, etc. If this size is too big for specific functions as it is the case with bathrooms or staircases, I combined it with a second function, for example the entrance area. To be not completely restricted to the use of only one equally sized module when designing floor plans, I extended the repertoire with a half module of 3.60 x 1.80 m, which can also be used for functions which require less space.

DRAFT ONE

The first idea was based on a rather experimental approach to that topic and proposed a modular building system which is physically changeable and adapable to the user's spatial needs at any time. It consisted of a permanent service-zone which included access, bathroom and kitchen areas and a framework to each side in which individual cubes with specific functions could be inserted. Every time the user's needs would change he could exchange a individual room-module for a different one or hand it off to one of his neighbours.

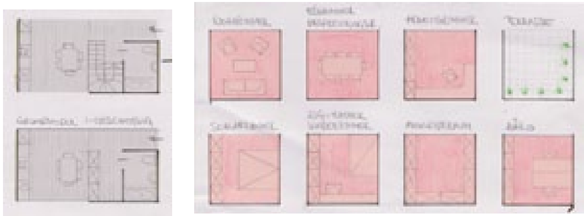


Fig. 100: Permanent service module (grey) that can be extended with a various number of different room modules (orange)

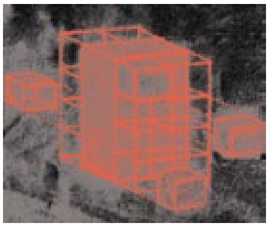


Fig. 101: Modules can be inserted into the framework or removed if not needed any more

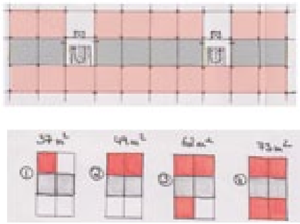


Abb. 102: Depending on the chosen number of room-modules a great variety of unit sizes can be created

DRAFT TWO

Even though I liked the idea of a buidling which is continiously changeable to different conditions and very user-responsive, I realized soon that this concept would be too extraordinary to be generally applicable for housing projects. Therefore the next step was to transfer this idea of a flexible building based on room-modules into a more reasonable context.

The grid of 3.60 x 3.60 m remained the same, but I grouped the living units around a central circulation core. Sizes could be individually chosen before occupation, depending on how many full and half modules were used. Even though this system offered many flexible features, like a different amount of units per floor, different sizes, different types (also maisonettes) and could be combined perfectly in the vertical, the problem was that the building could only stand solitarily and could not be connected horizontally to a second of the same or another building.

However, this adaptability to a building site should be one of the main goals of a generally applicable building system in order to use it under different circumstance. Therefore I paid paricular attention to the aspect of horizontal expandability and addition in my final design which will be explained in the next part of this thesis.

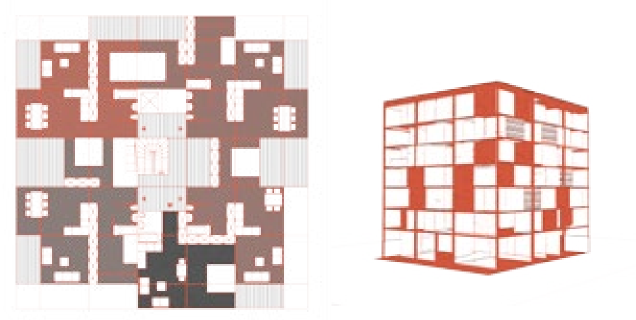


Fig. 103: The room-modules are organized around a central core, providing units that are oriented in every direction with the result that building itself could neither expand nor be horizontally connected.

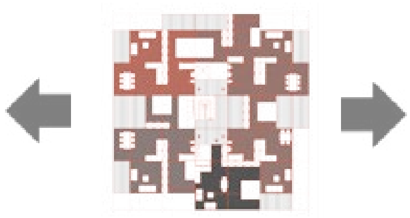


Fig. 104: Next objective was to solve the problem of horizontal adapability

FINAL DESIGN

STEP 1. CHOOSING MODULES and a DIMENSIONAL GRID

Since I continued the idea of basing the building system on the combination of different room-modules, the main conceptional aspects remained the same as in my preliminary drafts.

The overall structure of the system is defined by a dimensional grid of 3.60 x 3.60 m. It was mainly chosen accordingly to the room-sized planning modules which I determined previously. But before I definitely decided on this dimensional grid, I made sure that it also allows reasonable construction elements in order to create a fully co-ordinated system which considers both, planning as well as construction modules.

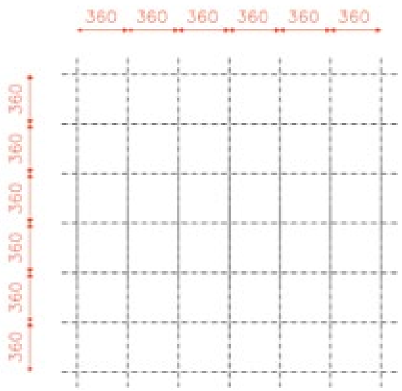


Fig.105: Dimensional grid

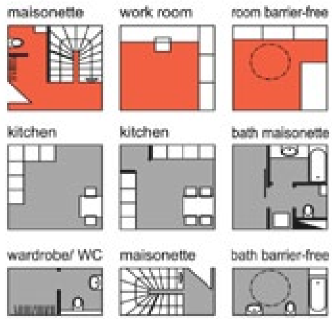


Fig. 106: Examples of planning-modules which can be indvidually chosen to configure each living unit. They are coordinated to the general dimensional grid and therefore measure 3.60 x 3.60 m and the smaller ones 3.60 x 1.80 m.

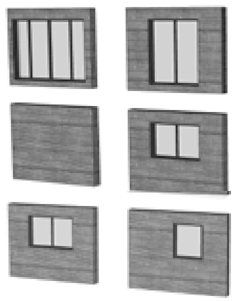


Fig. 107: The main construction modules of the system are prefabricated wall elements which can have different designs but the same dimensions

One of the most important aspects when defining the type and size of the modules that will be used for construction is to make sure that they can easily be transported to the building site. After I had decided on preferring two-dimensional construction elements over volumetric boxes (further explained in “step 4”) I found a general modular length of 3.60 m very convenient because on the one hand it is large enough to be efficient, on the other hand small enough to be transportable without any special permission. This was particularly important for the main construction modules - the wall elements. Their final dimensions were determined with a length of 3.60 m x storyheight - thereby ensuring that they do not exceed the maximal transportation height which is limited to 4 m (the truck included) in Austria.

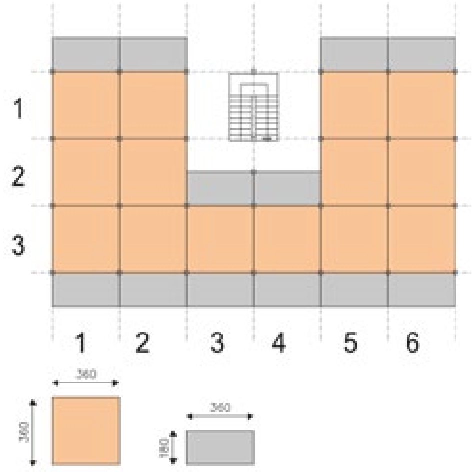


Fig. 108: The entire building structure can be devidied into large (3.60 x 3.60m) and small (3.60 x 1.80m) modules. They are organized around the public circulation area.

STEP 2: SETTING RULES

General building structure

The next question that had to be solved was, how and where to position these modules within the defined dimensional grid. The first step was to determine the position of access and public circulation area and group the planning modules around it. This led to a specifically defined building length of six and a width of three 3.60 m x 3.60 modules. These measurements are necessary to make the system work in general, but are - under certain circumstances - expandable.

Figure 108 shows how they are arranged around the public circulation area and where it is necessary to replace them with half-sized modules. On the building front and on the back it is also possible to add further 3.60 x 1.80 modules in order to increase design flexibility.

Permanent/ variable building parts

Then next focus was on defining further permanent building parts besides the public circulation. As it has been mentioned in previous chapters a smart position of service cores is very beneficial in terms of flexibility. In terms of cost-saving their number should be kept to a minimum and it is therefore advisable to service more than one unit with one core. For that reasons two permanent cores have been positioned in the middle of the building, usable for either one or two apartments.
Furthermore it is advantageous to group the main services rooms around these stacks; this is why the location of bathrooms and kitchens can be seen as given as well. All other areas of the building have been kept clear of permanent elements and can be designed and used differently.

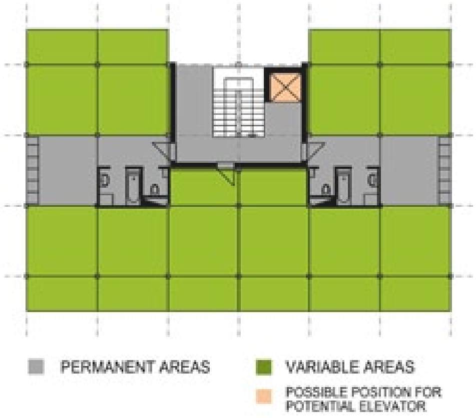


Fig. 109: Separation into permanent and flexible building parts

Fig. 110: The building is divided into several different zones to clarify the system. The different colours illustrate which zone is intended to be filled with which modules

Different zones

As it can be seen in figure 110 the distributional service zones which are logistically necessary for each unit, i.e. entrances and “wet-zones”, are located in the middle while the area which is intended to be filled with variable rooms is located in the front and in the back of the building. The green sections attached to the orange room modules can (but don’t have to) be used as a zone to extend the living units in width; they can either be filled with additional living space, balconies or nothing at all.

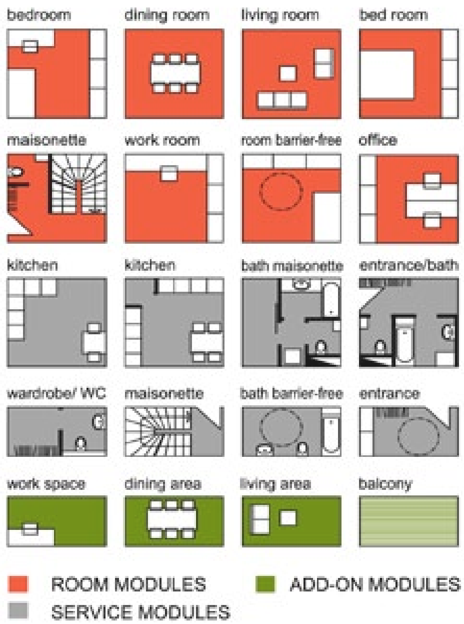


Fig. 111: Examples for planning modules which can be inserted into the generated framework

STEP 3. PROVIDING FLEXIBILITY

Before presenting specific unit layout that can be designed, it will be explained how flexibility and adaptability has been achieved and what kind of variations the proposed building system is able to generate.

1. On building level - adapability to different site conditions

As we all know, every building site is different. For that reason, one of the most important features of a universally applicable building system is its adaptability to varying site conditions. The proposed system is site-responsive in multiple ways:

Modular expandability

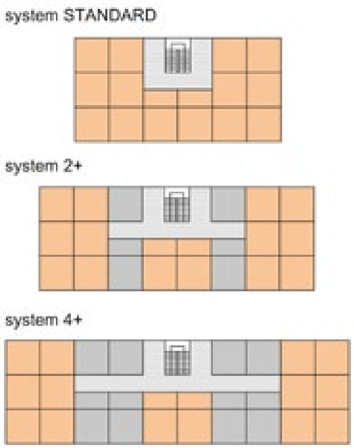


Fig. 112: The standard system can expand to up to four more modules if necessary

It can adapt to diverse lengths of building sites through modular expansion. The standard version of the building system which is lengthways composed of 6 modules can be extended by 2, or even 4 additional modules. The principle of expansion will especially come in useful when the site-length does not allow to arrange two standard sized buildings next to each other. The two extra types also particularly focus on providing units that can combine the functions of living and working within one apartment.

Horizontal connectivity

In any other case, the standard sized building can easily be connected on both ends with either the same type of building or with any other building. The possibility of horizontal connection is necessary to make the system usable not only in the green countryside but also in a high-density urban surrounding. In order to guarantee this connectivity, the living units must be provided with a sufficient amount of daylight without the position of any windows on the building edges. If the building is north-south orientated, this can be achieved by stretching the apartments from front to back. In case of an east-west orientation it can be enough to only orientate them in one direction, either to the east, or to the west. In both cases, a minimal building depth should be considered.

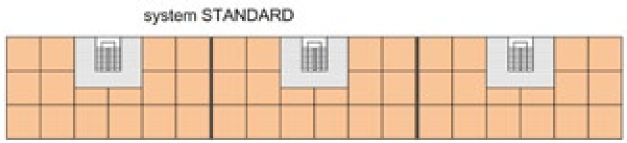


Fig. 113: The building can easily be connected horizontally because rooms are only oriented to the building's front or backside.

The apartments which are arranged on each building side can be stretched from front to back while the middle one is only oriented into one direction. The maximal room depth that has to be coped with is ca. 7 m. A further strategy to provide an apartment with light from more than one side is to design maisonette-units which range from front to back in the upper level. This principle was especially necessary to generate well-working unit layouts for the versions 2+ and 4+.

Vertical connectivity

Since it was one of the main goals to establish a system for multi-story building, of course the individual floor plans are vertically connectable as well. Theoretically, an infinite number of stories can be arranged on top of each other but practically there is a limitation of height determined by law and the load bearing capacity of the used materials. In Austria the maximal building height for a building constructed of timber is restricted to 4 stories, according to the “OIB-RICHTLINIE 2”.

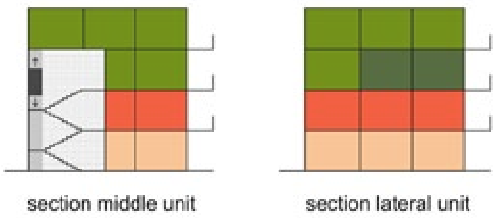


Fig. 114: This schematic section shows the vertical organization of the building. As many floors as desired can be arranged on top of each other. The last floor provides the possibility to replace the circulation area with a maisonette-unit

Orientation

While an east-west oriented building site generally does not imply an enormous challenge, it can be tricky to design the layouts for a building which is north-south oriented. I wanted the proposed system to be usable in either case and therefore had to find layouts that also make north-south units possible, paying particular attention to the fact that kids bedrooms are not supposed to be entirely oriented towards north. The system STANDARD can easily generate two, three and four-room units which are provided with a sufficient number of rooms facing south.

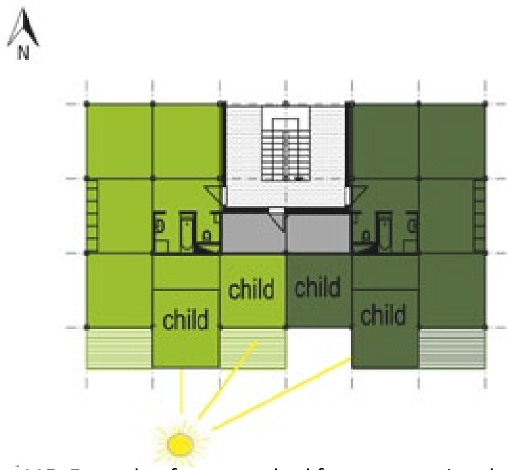


Fig. 115: Example of two standard four-room units; the kids bedrooms can both be oriented towards south

However, if maisonettes are desired too, the four-room maisonette type is problematic, because two of three bedrooms are north-oriented. This issue also counts for some of the maisonette-types of the system 2+ and 4+. I was able to overcome this this issue by making use of the “expansion zone” on the northern façade and simply extend the room with an add-on module which ensures daylight not only from the north but from east or west as well. This principle can be applied for any room where the lightning situation is difficult to handle.

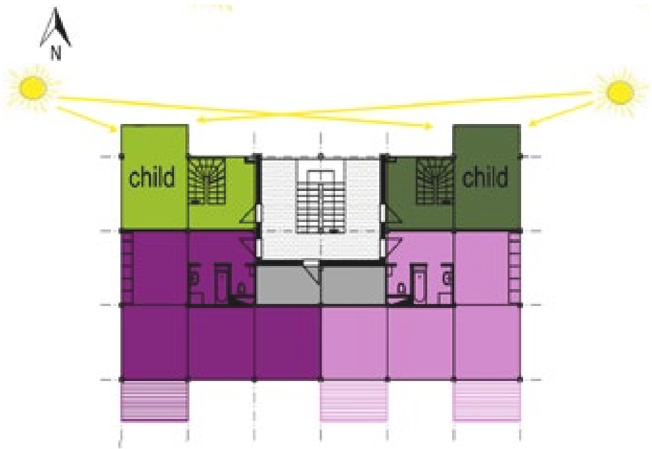


Fig. 116: In order to provide the north oriented room with daylight from either east or west it is extended with an additional cube-module

2. On unit level

Number of units per floor

While the basic dimensions of the building system can stay the same, the number of units per floor can vary from two to five, depending on the desired apartment sizes and types. When extending the system to version 2+ or 4+ the number of units per floor increases accordingly; at the most, seven apartments (including maisonette-types) can be accessed from one single floor.

In this context the importance of well-positioned circulation and entrance areas and service-cores becomes particular evident. While the staircase and corridors have to be situated in a manner that allows to access all inner building parts, finding the right position for the service cores can be difficult too, because many aspects have to be considered: They should be usable for as many units as possible, be vertically continuous and their location should not interfere with the design of well-functioning unit layouts.

The general strategy that has been chosen to enable a variable number of units per floor has been applied is not new: The position of one unit on each building side has been determined first. Their location is supposed to be the same in each floor; however, their size can vary thereby determining whether a third unit can be positioned inbetween or not.

There are following options to organize the units within one floor:

> **Option two units:** two large apartments (each with 4 rooms) which also occupy the zone in the middle of the building

> **Option three units:** the lateral apartments on each building side are smaller (3 rooms) and therefore do not make use of the modules in the middle. In this case an additional apartment can be positioned in between.

> **Option four units:** the same units release the modules on the buildings backside as well, which turn into the entrance level for the maisonette-type. The modules in the middle are again used by the lateral units.

> **Option five units:** combination of second and third option

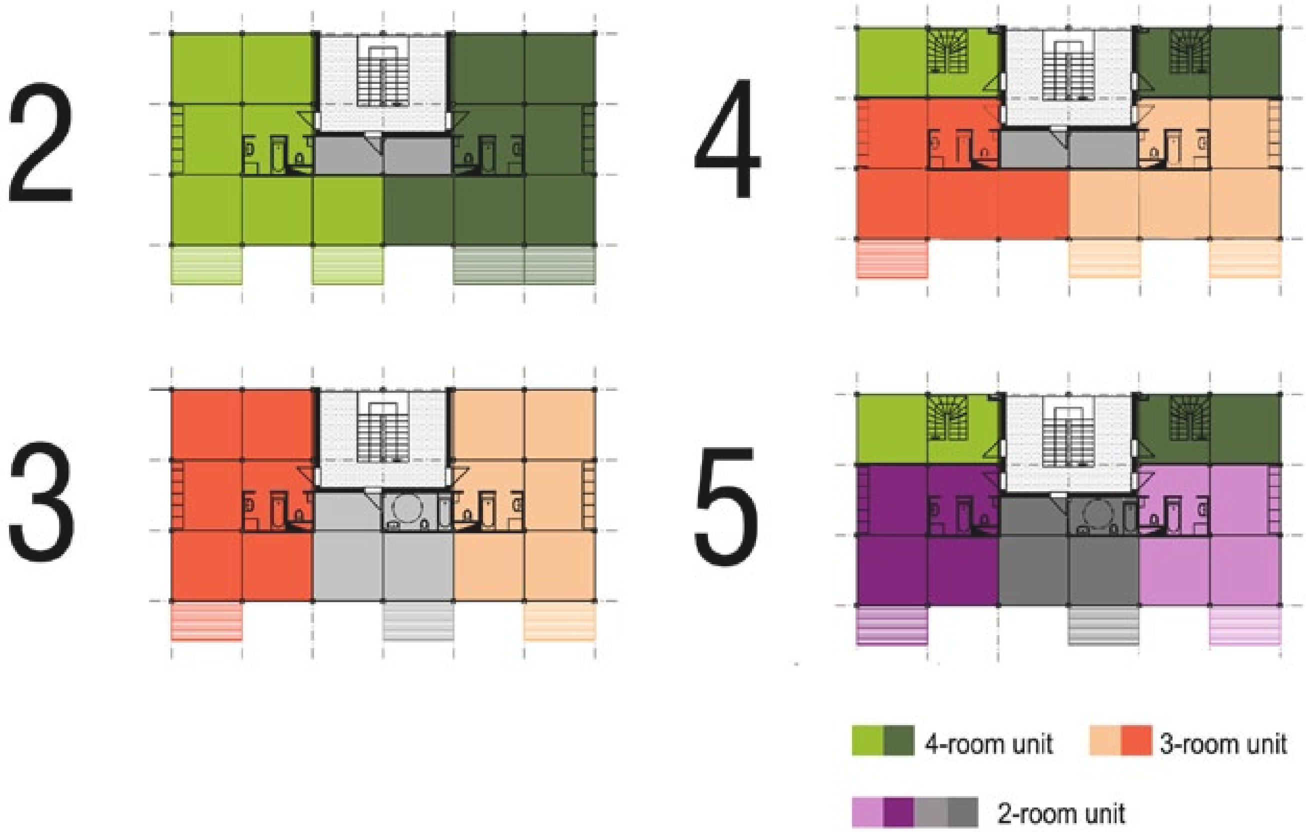


Fig. 117: Possible variations in terms of unit number per floor

Unit sizes and types

As the previous paragraph has shown, the building system allows the design of many different possibilities. It is very important that a residential building offers a great variety in terms of unit sizes and unit types in order to attract a broad spectrum of future occupants and thereby ensuring a well-balanced social mix.

The unit sizes have been determined according to commonly used sizes for 2, 3 and 4-room apartments. 2-room units typically offer an area of 45-50 m²; 3-room unit an area of ca. 75 m² and 4-room apartments usually have a size of ca. 90 m². Most of the proposed units are based on these sizes, but in order to increase the number of options and possible choices there is the possibility to generate sizes in between (for instance 40, 70 or 85 m²) or even special unit types - such combinations of living and working or units for more than one generation - which exceed or fall below standard unit sizes.

All these options should illustrate the system's manifoldness but its main focus lies on creating regular sized 2, 3 and 4-room apartments in order to make the system also applicable for social housing projects, which are publicly funded and intended for people with a low-income. To obtain these subsidies, the unit sizes are restricted to a certain amount of square-meters. According to §25 of the *Carinthian "Wohnbauförderungsgesetz 1997"* (which is decisive because the prototype of the building system will be tested in Carinthia) the maximal unit sizes that can be subsidized are:

> for one person 50 m²
> for two persons 65 m²
> for 3 persons 80 m²
> for 4 persons 95 m²
> and for 5 and more persons 110 m².

When determining the unit sizes, it was therefore of first priority not to exceed those limits.

But even though the units have standardized sizes, the system still offers a variety of types varying between horizontally organized apartments and maisonette types.

> Horizontal variation

If the system is composed of only two units per floor, there is not much room for variation. But the inclusion of a third unit in between results in a lot of options because its size is not pre-defined and can be individually determined, depending on the number of modules used. It can either only consist of the two middle modules, or be extended by a room module on the left, on the right, or on both sides.

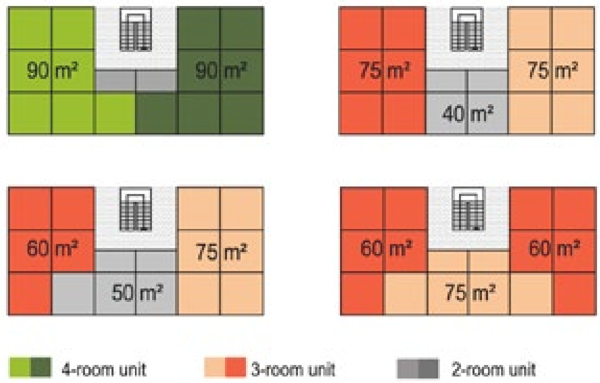


Fig. 118: Horizontal variation. The central modules of the building can be used in multiple ways

> Add-on modules/ expansion zone

In order to achieve even more types and sizes, there is also the possibility to make use of “add-on modules”. They can be positioned within the “expansion-zones” on the front and on the backside of the building. In the front this zone is mainly used for balconies, but it is also possible to extend the living space with additional modules, which measure 3.60 x 1.80 m. They give the future occupant the possibility to enlarge parts of the unit, such as the living room, or a bedroom. A further reason for their application is that they increase the accessibility of rooms (figure 119). If the building site is north-south oriented, they can be used on the building north-side in the back) for ensuring a sufficient amount of sunlight from the east or west, especially for kids bedrooms.

Fig. 119: Examples of customization possibilities that can be achieved by making use of the expansion zone

> Vertical variation

Almost every unit size can be generated on one or two levels: While the smaller two-room apartments are not designed as maisonettes but as barrier-free horizontal units, the ones with 3- and 4-rooms can either be regular single-story units or split up onto two levels, according to the developer/user’s desire. In order to guarantee enough sun and day lighted rooms the maisonette type stretches, similarly to the regular unit, from the building’s front to back in the upper floor.

A particular advantage is, that unit types can be modularly mixed and matched, meaning that if you arrange a maisonette on the building’s left side, the middle unit and the one on the far right is not influenced by this decision and vice versa.

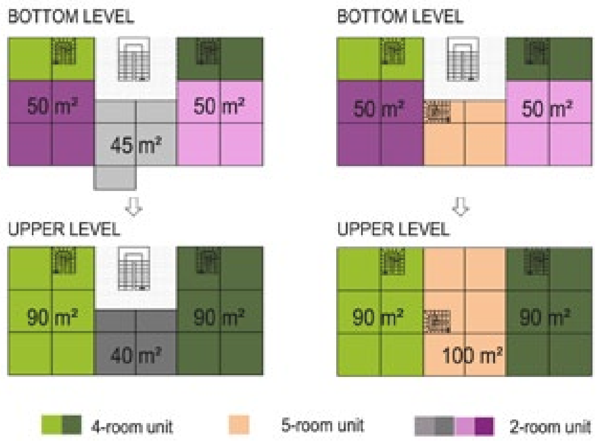


Fig. 120: Vertical variation. The lateral units as well as the middle one can be designed either as single-floor or as maisonette unit. This variation can be achieved without influencing the unit to the left or to the right.

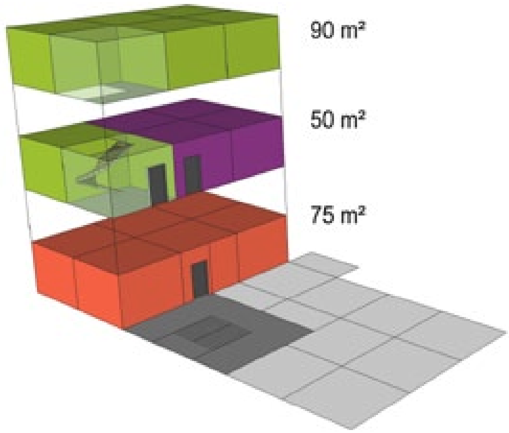


Fig. 121: Vertical variation. The units on each side of the building can either stretch from front to back (orange) or can be split up, thereby generating a smaller unit and a maisonette unit. These two possibilities can be achieved in every floor, independently from the other units

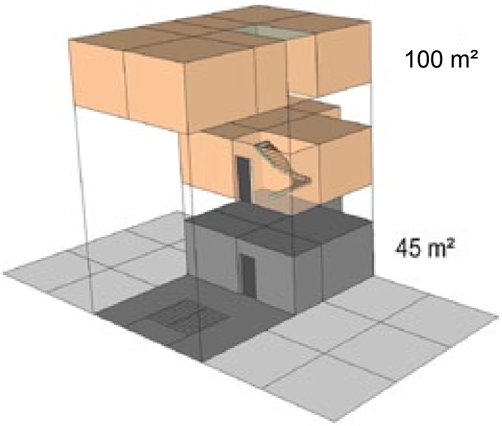


Fig. 122: Vertical variation. The middle unit is mainly intended to be oriented to the building's front, but can still generate small maisonette-units. In the last floor it is even possibe to design a large maisonette-unit when replacing the circulation area with living space.

3. On the user level

Flexibility within a living unit: multi-functional layouts and rooms

But not only the unit size and type can be individually determined. Another aim was to generate apartments which - even though they are equally sized - can be used in many different ways by their occupants.

Every one of us unique and therefore imagines his or her ideal living space differently. While some people prefer larger common areas over large bedrooms, others like the opposite; some favor east, some west-oriented rooms, some a larger kitchen, others larger living rooms, etc. Therefor it is a nice feature that occupants have the possibility to determine the function of each room individually.

As demographic structures change and different life patterns increase, it also seemed to me very important not only to provide units that are suitable for an average family but can accommodate various household constellations, such as a living community for students/singles, or can easily integrate a separately accessible home-office if one of the occupants works from home, or have the possibility to connect a barrier-free “granny flat” to the regular family unit.

Fig. 123: Examples of how a standrd sized unit (75 m²) can be used for different life patterns due to funcionally neutral rooms

Adaptability over time

While it is of course particularly important to have the possibility to design different sized units at the planning stage, in terms of sustainable building aspects it is also very advantageous if units can be adapted and changed post-occupation. This feature avoids that buildings become obsolete if the existing unit types or sizes are not in demand any more. Furthermore, the option to adapt a unit's size ensures that families that grow or shrink can stay in their apartment and don't have to leave their familiar surroundings. This adaptability can be achieved by joining or dividing entire units or simply add or remove individual room modules. Figure 124 shows exemplarily how the unit number, layout and can change over the years in order to adjust to different spatial requirements of their occupants.

Fig. 124: Examples of how one floor of the building can be adapted over the years when occupants or spatial needs change.

SYSTEM 2+

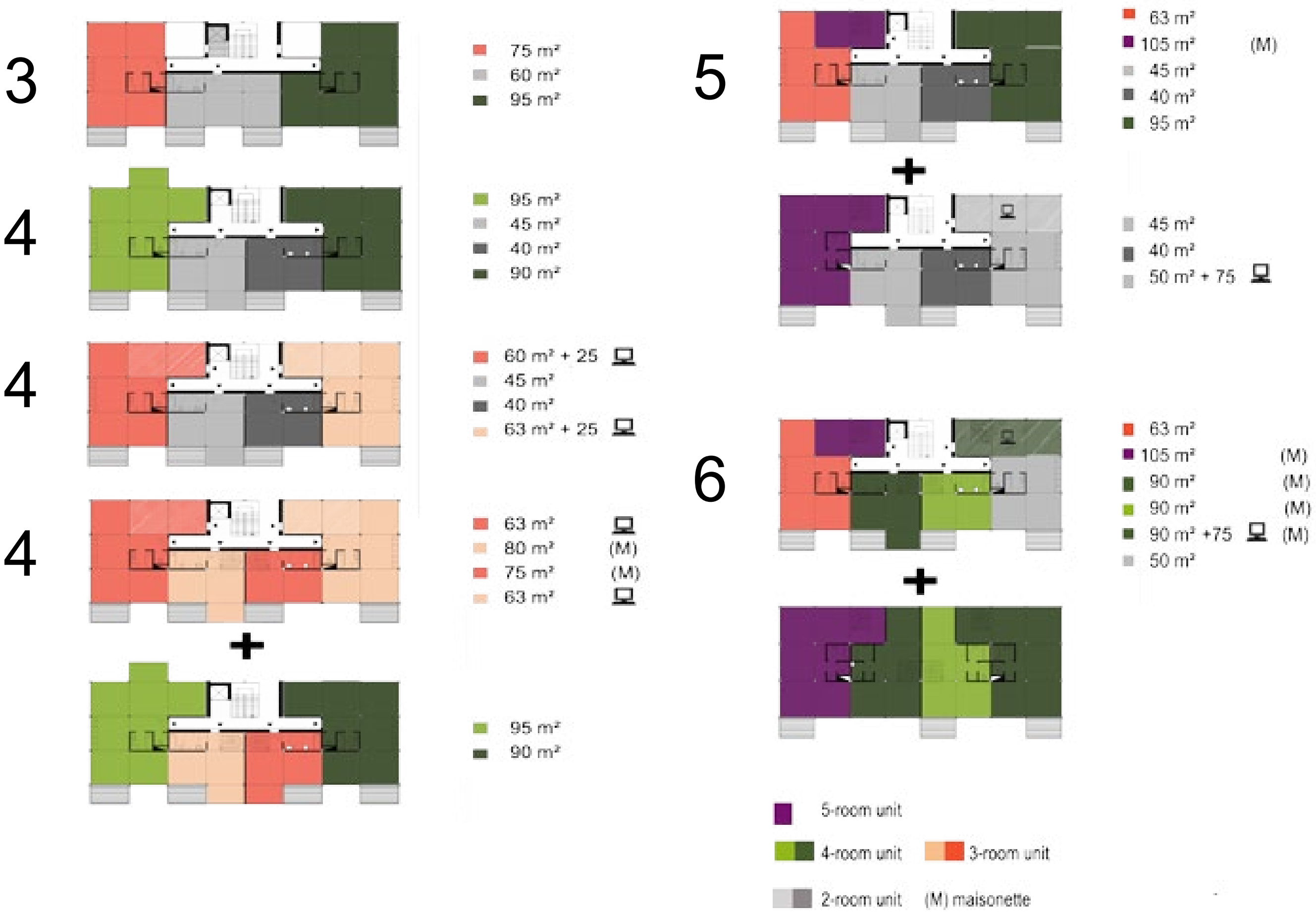


Fig. 125: Examples of unit sizes and layouts that can be achieved when making use of the SYSTEM 2+

SYSTEM 4+

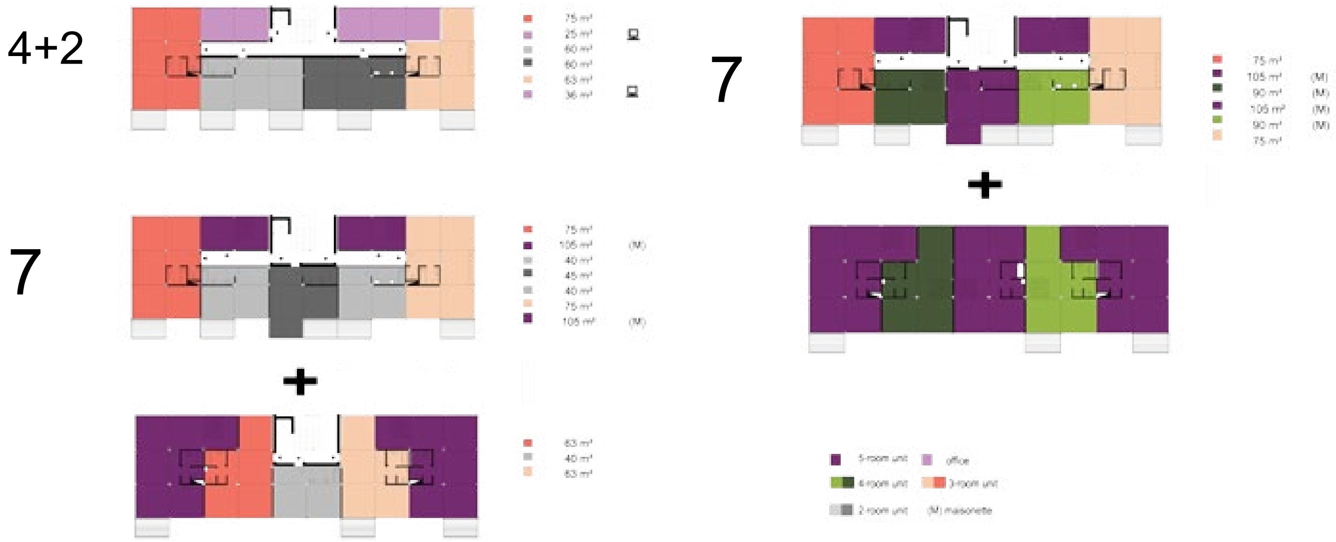


Fig. 126: Examples of unit sizes and layouts that can be achieved when making use of the SYSTEM 4+

4. Flexibility on the construction level

But all these different degrees of flexibility would not be possible without the right choice of the construction principle.

As already emphasized, the building structure which ensures the highest extent of flexibility is the frame because it is based on the idea of separating the load bearing structure from the building envelope and the internal fit-out. This allows endless possibilities in terms of configuration and adaptation of (living-) units because partition walls can be positioned or removed wherever desired.

Since the proposed building system focused on achieving a maximum degree of flexibility, a structural framework seemed to be an adequate choice.

Of course, before finalizing this decision I made sure that this principle also allows a reasonable application of the chosen construction modules (which will be further defined on the next pages).

Another helpful principle that was applied in order to achieve a flexible structure was to consider the building as a combination of various separated layers which should all be independently changeable. In this regards the skeleton structure also proved to be advantageous because it automatically separates a building into its main layers, i.e. load bearing and space-defining elements. Figure 127 shows the most imporant layers of the building system.

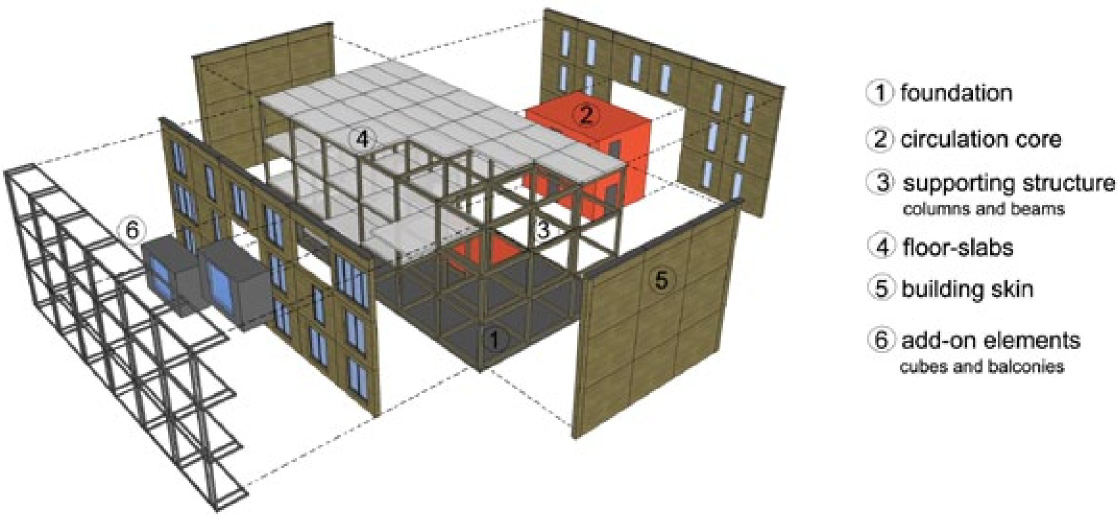


Fig. 127: Building structure separated into its most important layers. They can be understood as independent building parts. This independency of layers is an important aspect in terms of adaptability and flexibility of a building

STEP 4. DEFINING THE CONSTRUCTION PRINICPLES

Besides the achievement of a maximal degree of flexibility the most important aspect in terms of defining the system's construction principle was to ensure that it allows an efficient application of prefabricated construction modules. In this regards a structural framework also offers many possibilities, generally ranging from three-dimensional box-modules to two-dimensional wall and floor-slab modules that can be inserted into the generated framework.

Even though volumetric elements allow the highest extent of prefabrication and their assembly on site requires the least amount of time their application also brings disadvantages with it, such as:

> a costly production
> a costly transportation from the manufacturer to the building site because of oversized elements
> increased design restrictions
> constructional issues (double floor-slabs), etc.

Considering these aspects in combination with the aim of designing simple and universally producible elements it seemed to be more beneficial to make mainly use of two-dimensional modules.

The final decision was made in favor of a combination of all different module types - linear, planar and volumetric - with the idea of benefiting the most when using each of them according to their specific strengths.

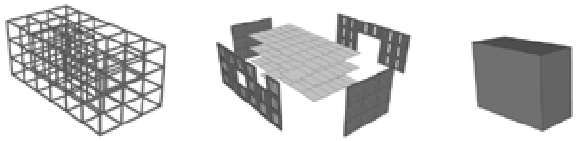


Fig. 128: Chosen construction modules (a) linear, (b) planar and (c) volumetric elements

1. Linear modules

The linear modules represent the lowest level of prefabrication and are commonly used in construction today. However, the columns and beams in this case can still be considered as modules in a broader sense because they are prefabricated and precut and only need to be assembled once they arrive on-site.

These linear elements play an important role within the system since they are responsible for the building's static stability. They generate the supporting framework which consists of columns and beams; crossbeams are not necessary because massiv timber decks which are mounted on top of the beams and the concrete circulation core provide the requried bracing of the system. Only along the framework's edges cross-beams are carried out to ease the attachment of the wall modules.

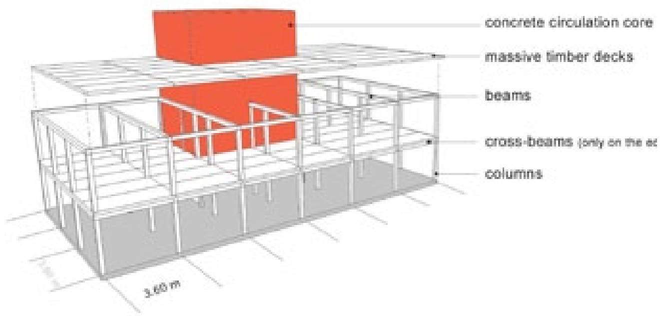


Fig. 129: Linear modules provide the supporting structure of the building

Even though the proposed building system could theoretically be realized in any kind of material, I chose timber due to ecological reasons for all building parts, including the supporting framework. The columns as well as the beams are constructed of laminated timber with quadratic dimensions of 0.20 m x 0.20 m. The column grid matches the 3.60 x 3.60 m dimensional grid which was used in the planning stage before and therefore enables easy room configurations on the buildings inside.

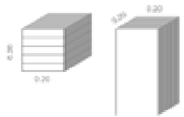


Fig. 129: Dimensions of beams and columns

2. Planar modules

Walls

Construction principle

The central modules of this system are the wall-elements. Their dimensions were chosen according to the column grid which has the same measurements of 3.60 x 3.60 m used for arranging the planning modules. Since a skeleton of columns and beams forms the building's load bearing system the wall modules are non-structural, following the principle of a curtain wall. This means that they are fixed onto the supporting skeleton framework and that their main function is to define the building's outer skin in order to keep the weather out and the occupants in.

To ensure a maximal degree of prefabrication, all necessary layers and parts (including windows and façade) are assembled by a manufacturer beforehand and the finished modules only need to be lifted into their final position by a crane once they are delivered on-site. This guarantees an easy and fast assembly which does not only save time, but also minimizes the impact on the environment tremendously and can further result in a reduction of costs.

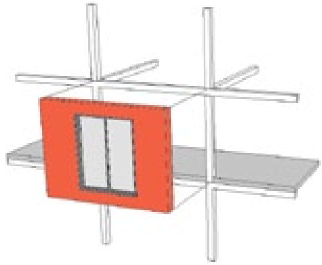


Fig. 130: Prefabricated wall-modules get fixed onto the frame

Dimensions

Lengthwise they range from one column axis to the next, which means that they have a specific length of 3.60 m. Their height is theoretically variable because it is dependent form the chosen story-height of the building, but in this particular case it was determined to 2.98 m for the ground floor and 3.10 m for every other floor. This height allows their transportation on a low-bed trailer without having to request a special permitment. They are attached onto the beam on their top edges and onto the timber columns sideways.

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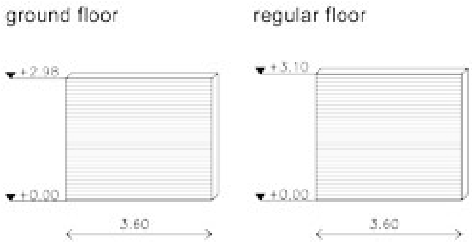


Fig. 131: Dimensions of the wall-modules

Material

Their main construction material is timber. Since they dont't have to take any loads, they constrcutional principle is based on a light-weight timber frame. In order to achieve a high termal quality, the cavities inbetween the timber studs are filled with 0.20 m of mineral wool. The cladding is designed as horizontal timber boarding.

Windows

Their design in terms of number and type of windows is customizable. The proposed system offers a great variety of different wall modules which can be chosen according to the user's taste or the conditions and orientation of the building site.

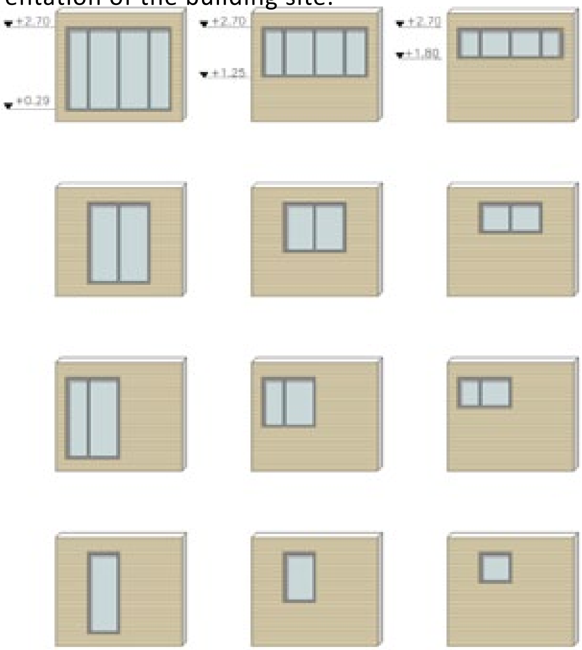
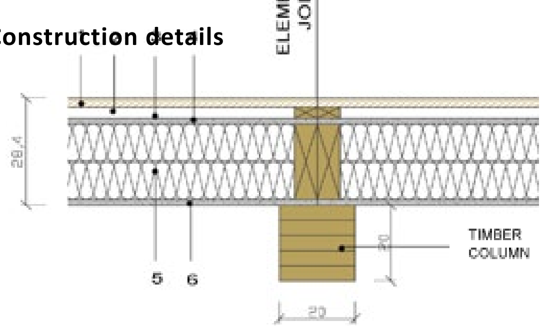


Fig. 132: The size and the position of the windows can be customized and offer a wide range of possibilities

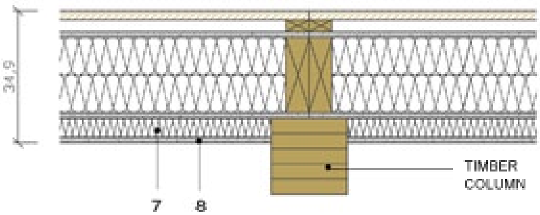
Outer corners and attic-elements

Further wall-elements that are necessary to complete the building's exterior skin are small modules for the building's outer corners and modules to generate the attic for the flat-roofed construction. Both of them are individual modules which are applied once the assembly of the main wall modules has been completed.

Construction details



1	horizontal timber boarding	24 mm
2	counter battens/ airspace	30 mm
3	wind-proof paper	-
4	gypsum fibre board	15 mm
5	mineral wool between timber frame 6/20	200 mm
6	OSB board (vapour barrier)	15 mm



7	installation layer	50 mm
8	gypsum fibre board	12.5 mm

Fig 133: Detail 01. Prefabricated wall-module; connection to the column | M 1:20
Fig 134: Detail 02. Only the installation and gypsum layer are attached on site | M 1:20

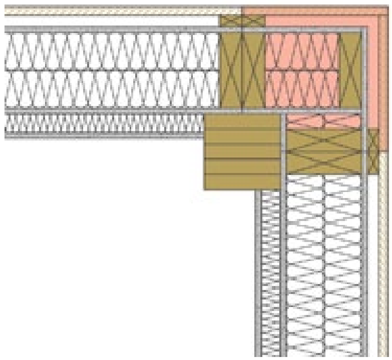


Fig. 135: Detail 03. Wall element for outer corners | M 1:20

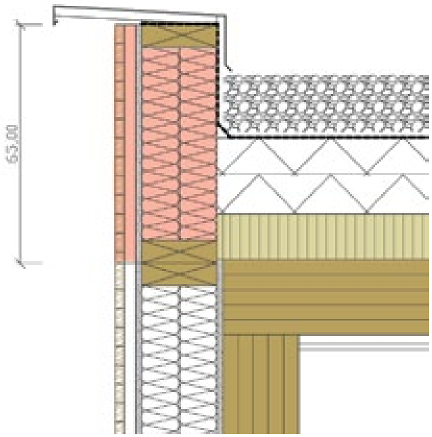


Fig. 136: Detail 04. Attic-element | M 1:20

Floor slabs

Construction principle

The second type of planar modules used for construction are the floor slabs. They also arrive on-site as pre-fabricated modules which only have to be lifted into their final position. By crane they are placed on top of the load bearing beams, on the one hand establishing the required bracing for the framework, on the other hand building the substructure for the floor construction.

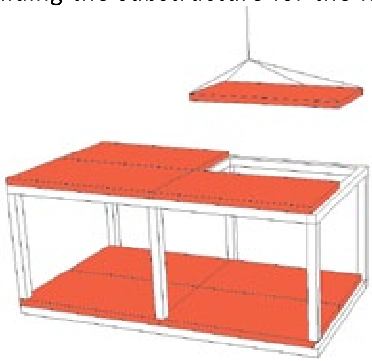


Fig. 137: The solid floor slabs are lifted onto the supporting beams by crane

Dimensions and material

Their lenght always has to be 3.60 m because they need to stretch from one to the next beam axis. Their width can theoretically vary, in this particular case they generally measure 3.60 x 1.80 m but these dimensions can slightly differ, depending if the floor module is situated somewhere in the middle of the building or on the outer edge, where the modules have to cross the axel line. In case of the application of an “add-on” cube, the affected floor slab needs to measure 3.60 x 3.60 m.

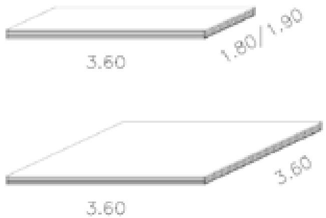
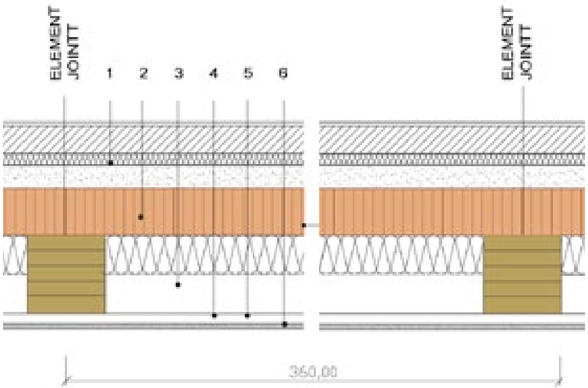


Fig. 138: Dimensions of the floor modules

Material

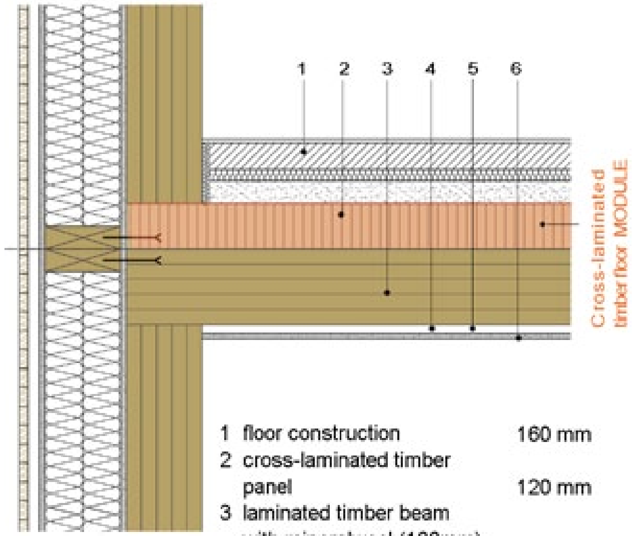
The floor modules are made of cross-laminated timber decks due to two reasons: (1) they are suitable to brace the skeleton structure appropriately and (2) their solidness and mass enhances the acoustic insulation quality of the party floors enormously. Sound insulation is a very important topic when designing housing projects made of timber, because this material does not automatically have such a great mass as for example concrete and it can be difficult to achieve the required numbers. As further measure to provide an appropriate acoustic insulation, the floor slabs are insulated from beneath with a layer of at least 10 cm of mineral wool. The thickness of the cross-laminated timber decks was determined to 12 cm.

Construction details



1	floor construction	160 mm
2	cross-laminated timber panel	120 mm
3	laminated timber beam with mineralwool (100mm) inbetween for acoustic isolation	200 mm
4	timber "sparschalung"	24 mm
5	resilient bars between "sparschalung	27 mm
6	gypsum fibre board	12.5 mm

Fig. 139: Detail 05. Ceiling construction | M 1:20



1	floor construction	160 mm
2	cross-laminated timber panel	120 mm
3	laminated timber beam with mineralwool (100mm) inbetween for acoustic isolation	200 mm
4	timber "sparschalung"	24 mm
5	resilient bars between "sparschalung	27 mm
6	gypsum fibre board	12.5 mm

Fig. 140: Detail 06. Connection wall-module and floor slab | M 1:20

3. Volumetric modules

Add-on cubes

Construction principle

While the so far introduced elements are essential to make the building work, the following module is optional and is only necessary if the position of add-on elements in the front or in the back of the building is desired. Those additional modules are designed to arrive as three-dimensional boxes on-site to avoid a complicated assembly process. Since their size is limited to 3.60 x 1.80 x story-height they can easily be transported on an ordinary truck (max. width in Austria is 2.55m). While their transportation was not so much of an issue, the more complex question was how to integrate them in this already existing system of wall-modules and floor-slabs without too much complication? In order to make this work, some aspects have to be considered:

1. the box replaces one wall module
2. the affected floor-slab needs to be constructed as cantilevering element
3. the box does not have a floor and therefore will be placed on top of the existing floor-slabs

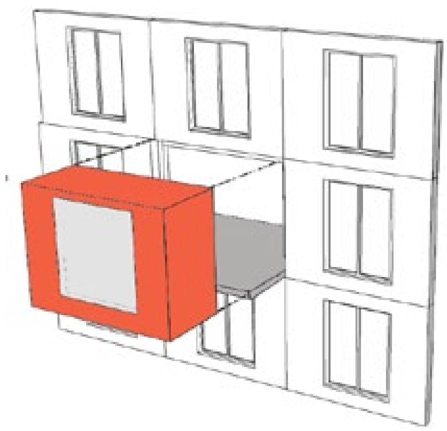


Fig. 141: Volumetric box is positioned onto cantilevering floor slab

Material

Similar to the floor slabs the cubes are made of cross-laminated timber as well. The timber cube will be manufactured off-site (including insulation and windows), delivered and positioned on top of the cantilevering floor slab. The thermal insulation on the box-underside will be applied once the cube is on its final position on-site.

Construction detail

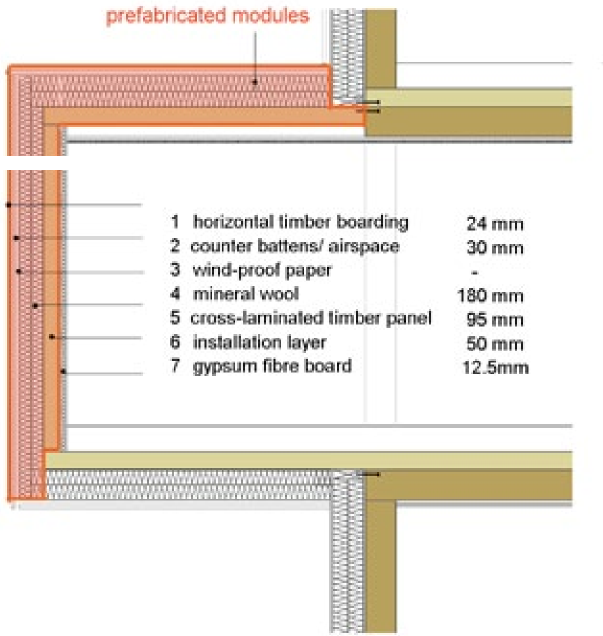


Fig. 142: Detail 07. Connection of the cube-module to the existing system of wall and floor elmenets

4. Further building elements

Exterior framework

In order to avoid a disruption of the building's thermal skin, the balconies are mounted onto a separated framework instead of directly connected to the supporting structure. This frame is made of aluminum columns and beams and completely stretches across the building's front façade which gives the future occupants the possibility to choose where exactly they want their balconies to be situated. This framework also integrates the "add-on"-cubes into it to generate a more homogeneously looking façade. If additional balconies or boxes are desired on the building's backside this framework can easily be duplicated.

To give occupants also the possibility to personalize their exterior living space this framework can be individually filled with different elements, such as blinds, vertical gardens,translucent elements, etc. This feature can also be used to avoid that every building that is based on the proposed system looks identically the same because there are various design possibilities, depending on what kind of add-on modules are chosen.

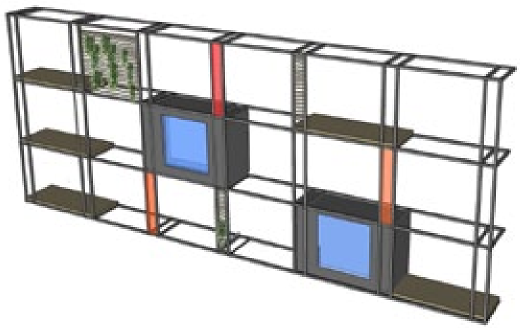


Fig. 143: Framework positioned along the front (or back) facade of the building; providing space for balconies, additional cubes and other customizable elements

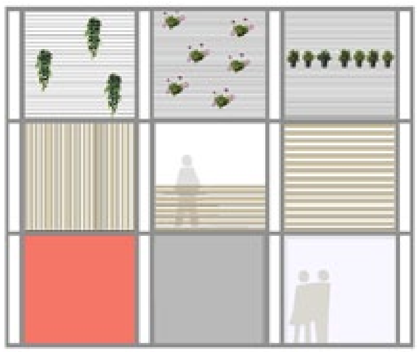


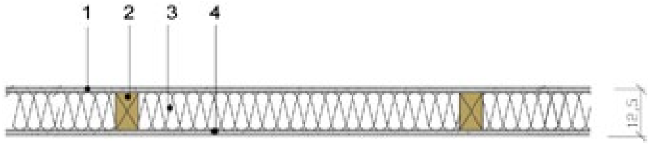
Fig. 144: Examples of add-on elements which can be inserted into this framwork

Party walls

As already emphasized the supporting structure of the building is provided by a framework and therefore neither the external nor the internal walls are load bearing. While the building skin is constructed of modular wall elements, the interior walls are not prefabricated and are ordinarily built on-site.

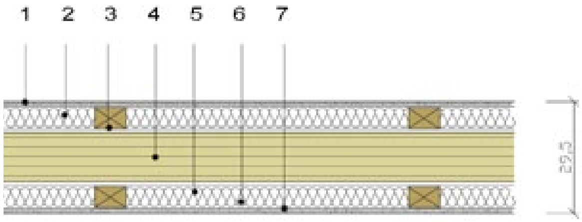
As in the case of party floors, a good acoustic insulation is required for unit party walls as well. The *"OIB-RICHTLINIE 5"* an Austrian regulation that deals with sound insulation refers to the *ÖNORM B 8115* which determines a minimal sound level difference of 55 db for party walls. But even if this number is achieved it is most likely that there is still soundpollution, a condition that is especially in terms of multi-unit apartments unfavourable. In order to make sure that the proposed building system guarantees an appropriate and not only the minimal noise insulation I decided on a solid timber construction for the party walls instead of using lightweight timber frames. Cross-laminated timber panels are positioned inbetween the columns and covered with insulation on each side. The construction was chosen based on party wall details developed by pro:Holz Austria.

The partition walls within one unit are carried out as timber frame constructions.



1 gypsum fibre board
2 timber frame 60/100
3 mineralwool
4 gypsum fibre board

Fig. 145: Detail 08. Partition wall within a living unit | M 1:20



1	gypsum fibre board	12.5 mm
2	timber studs on "schwingbügel"	70 mm
3	mineral wool	60 mm
4	cross-laminated timber	130 mm
5	mineral wool	60 mm
6	timber studs on "schwingbügel"	70 mm
7	gypsum fibre board	12.5 mm

Fig. 146: Detail 09. Party wall to another unit | M 1:20

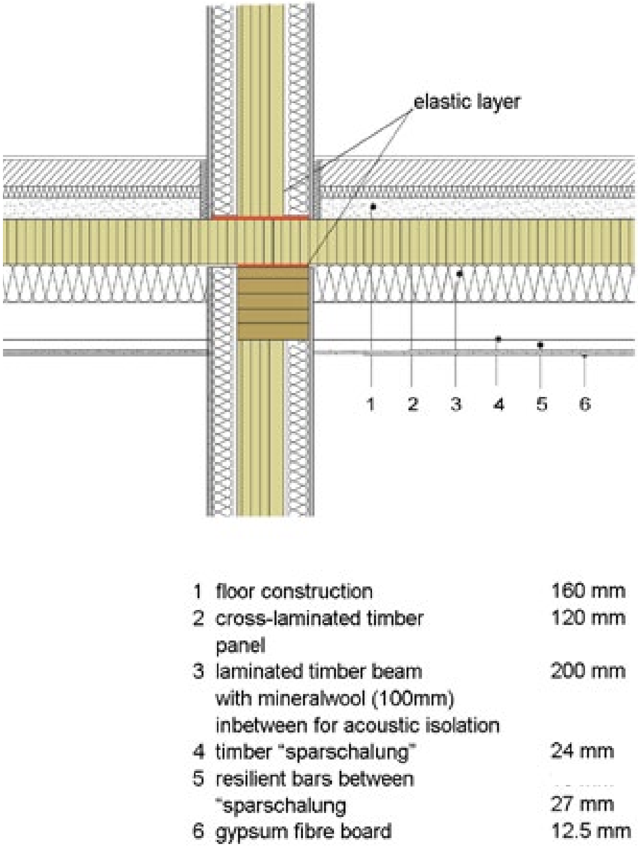


Fig. 147: Detail 10. Connection of party wall to beam and ceiling | M 1:20

Roof

The roof is a basic flat-roof construction which can - but does not have to - be prefabricated. In the proposed system it consists of the regular floor-slab modules and insulation and sealing layers which are fixed onto them on-site.

Foundation and circulation core

The last element of the system is the central circulation core which contains the staircase and the elevator (if one is required). Its second function is to provide the necessary bracing for the timber framework. For reasons of fire safety it is separated from the rest of the building and made of concrete. The core can either be constructed of precast elements or cast on site with in-situ concrete.

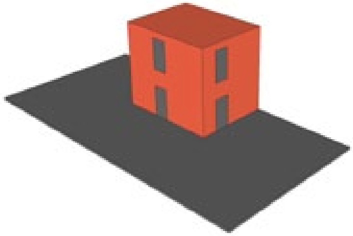


Fig. 148: Concrete circulation core

5. Assembly process step-by-step

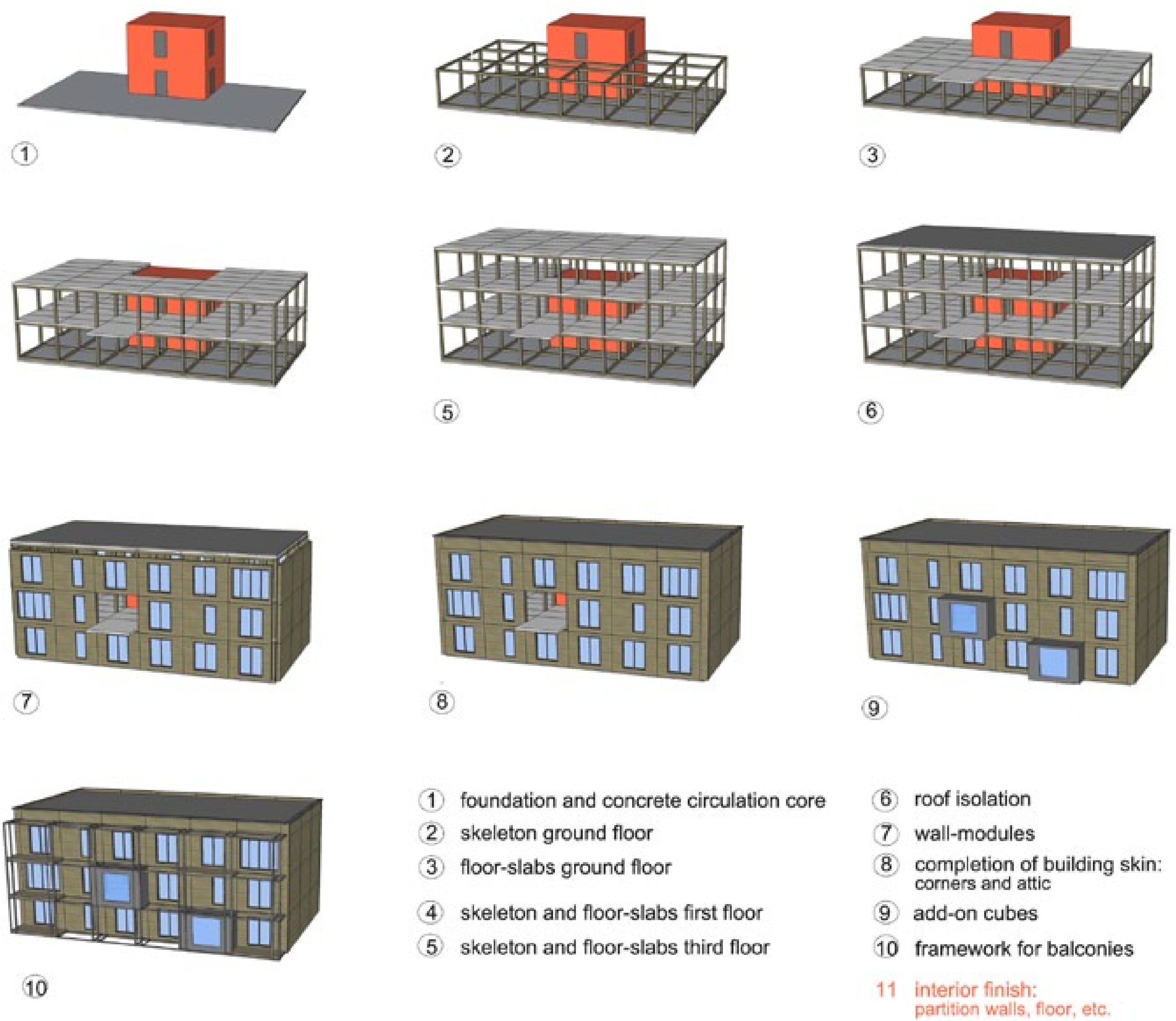


Fig. 149: Assembly process

PROTOTYPE

PLANNING CONDITIONS

As final and last part of my thesis I wanted to test the functionality of the proposed modular building system myself to make sure that it actually works and to show some more potential options which can be realized with it. Therefore I applied the system on a randomly chosen building site which is located in my hometown *Maria Saal* in Carinthia, a rather rural community with about 4,000 inhabitants. The building site itself is situated in an area of settlement that is mainly dominated by single-family houses but the future goal is to strongly focus on the development of housing projects that allow a higher density. These were good preconditions for the application of the building system because it is predestinated for providing an attractive alternative to the fatal single-family house culture. Due to the many different options a future occupant has in terms of determining his individual living space and the relatively low building costs, modular building systems in general and this proposed one in particular could be a smart solution to overcome the detached housing issue.

However, since this development is yet to come, it would not be appropriate to build a project in a striking large scale into this rural surrounding. But as the system is well-applicable in many different sizes, this was not a problem. After having consulted the local building authority I found out that I was limited to three storys anyways due to restrictions in the zoning plan. Other than that there were no further specific regulations that had to be considered during the design process. Even the orientation of the site is very convenient; it is oriented towards south-west, which provides the possibility for a wide range of layouts, because every kind of room can be oriented to both buidling sides (other than in case of a north-south orientation).

Fig. 150: Picture of the building site in *Maria Saal* showing its rather rural character

According to the building site's length and width I decided on using three standard sized buildings, each of them measuring approximately 21 x 11-13 m. To show how easily two buildings of the same kind can be connected horizontally, only one of them is carried out solitarily while the other two buildings are directly attached to each other, forming one large complex next to a smaller one.

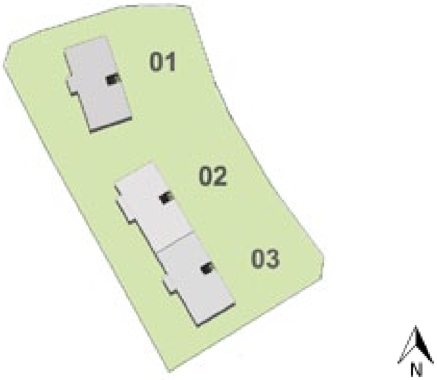


Fig 151: Three standard sized building complexes were positioned on the site

OUTCOME

As this is a fictional project and there were no future occupants who could determine their own specific floor plans, I had to define number, size and type of units myself. On the one hand I focused thereby on showing as many options as possible, on the other hand however, I always considered the real planning conditions and wanted to design units which would actually be needed and realistic in this community.

To combine both of these goals I assigned each of the three buildings with a specific focus:

While **building 01** rather concentrates on providing an alternative to single-family houses for families with more than one child, **building 02** focuses on elderly or handicapped people and their needs in terms of living space. Since the issue of overaging is becoming increasingly important I found it essential to provide units which are suitable also in this aspect. Therefore building 2 offers one barrier-free unit on each floor which can either be an independent unit or be connected to one of the units on each side as so called "granny flat".
Building 3 addresses the growing number of people who work from home and therefore want both functions - living and working - to be partly integrated, partly separable within one unit.

The result was 24 living units - 15 of them are designed differently, only a few types have been repeatedly used. Four units are barrier-free, and four integrate a home office, while the rest of the units are carried out as regular two-, three- or four-room (one even as five-room) apartments, ranging from 40 up to 105 m², always keeping in mind not to exceed the size limitations set by the "Wohnbauförderungsgesetz".

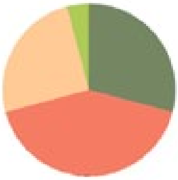
This great variety of units will guarantee a broad spectrum of potential occupants and a socially diverse structure, because even though each building has a specific focus, they still provide different units for different people.

In terms of exterior rooms the system provides nice features as well: Every apartment includes at least one standard balcony which can individually be extended by a second or third one. The units on the ground floor are equipped with private gardens. The framework which holds the balconies can be individually designed with vertical plants or shading-elements.
In between the two buildings there is a generous outdoor area which serves as playground for kids or as general social gathering place for the dwellers.

24 UNITS

CUSTOMIZABLE

MULTIGENERATIONAL LIVING



4 %	5-room units
25 %	4-room units
42 %	3-room units
29 %	2-room units

MULTIFUNCTIAL USE

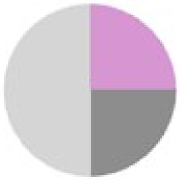
485, 00 m² PRIVATE GARDENS

ECO-FRIENDLY

ADAPTABLE STRUCTURE

10 SIZES

43 PARKING LOTS



50 %	living
25%	barrier-free living
25 %	living + working

15 DIFFERENT LAYOUTS

SOCIAL MIX

BUILDING DENSITY 0.54

gross floor area BUILDING 1	785,00 m²
gross floor area BUILDING 2+3	1568,00 m²
gross floor area TOTAL	2353,00 m²
building site	4368,00 m²

FAST CONSTRUCTION

SITE PLAN M 1:2000

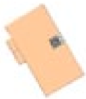
UNIT KEY

BUILDING 1 family living

focus on units for large families

2 x 50 m²
4 x 90 m²
1 x 105 m²

7 living units



BUILDING 2 barrier-free living

focus on units for elderly and handicaped people; multigenerational units

1 x 40 m²
1 x 45 m²
1 x 55 m²

2 x 63 m²
3 x 75 m²
1 x 85 m²

9 living units

BUILDING 3 living + working

focus on units with sperable offices

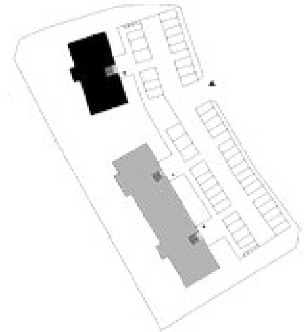
2 x 50 m² + 25 m²
1 x 63 m² + 12 m²
1 x 78 m² + 12 m²

1 x 45 m²
1 x 50 m²
1 x 63 m²
1 x 75 m²

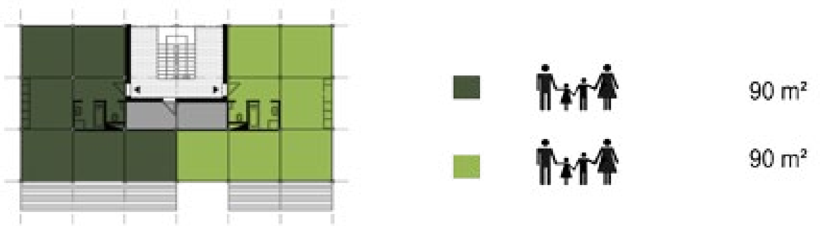
8 living units

SITE PLAN M 1:1000

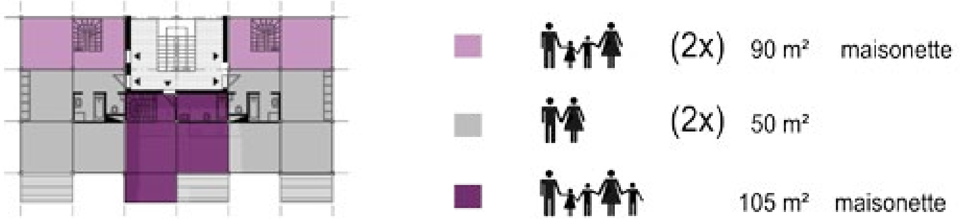
01 family living units



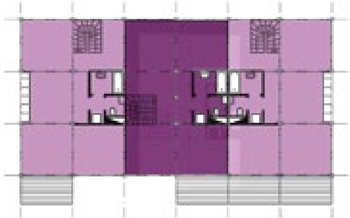
ground floor



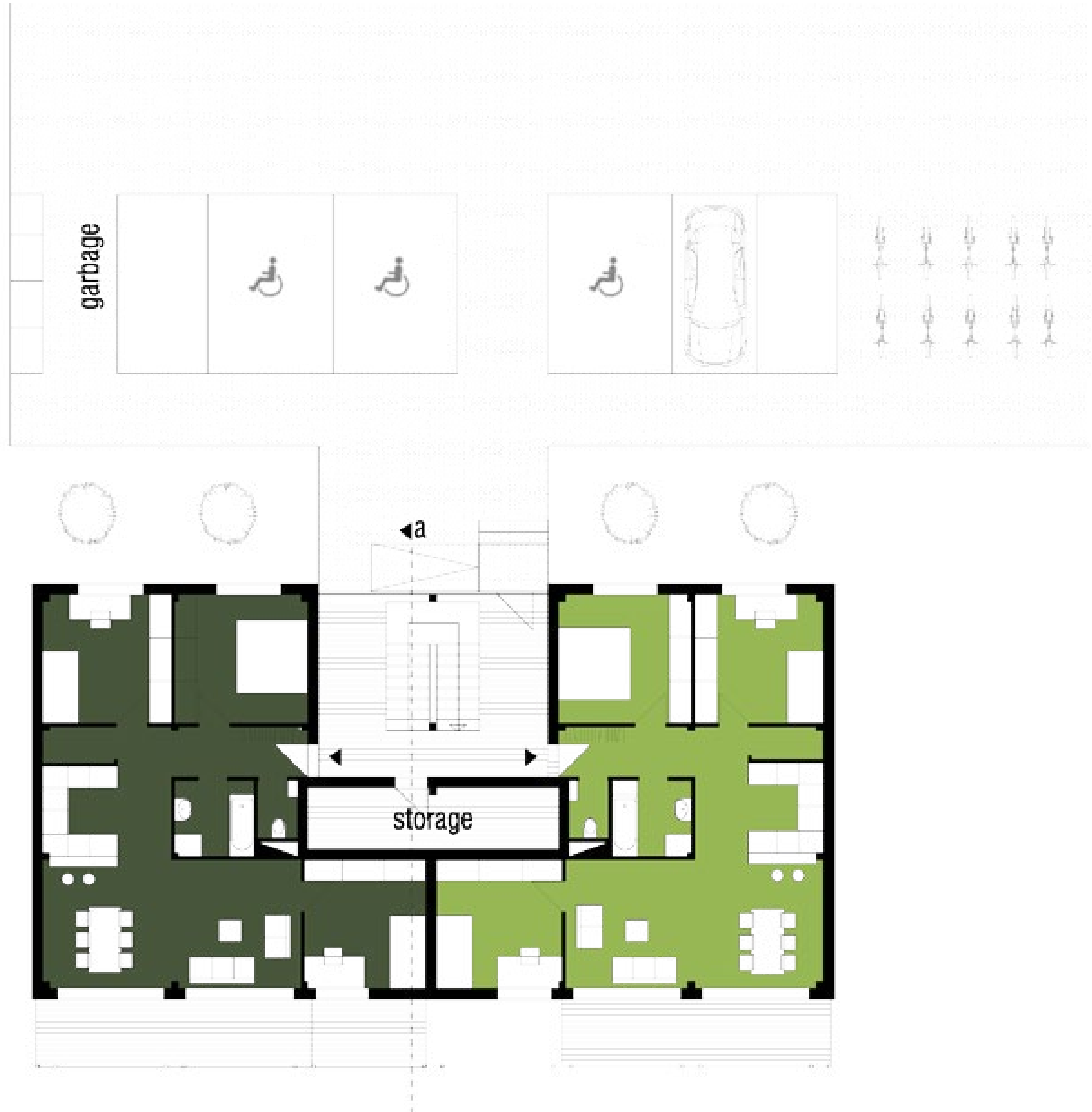
first floor



second floor



01 family living ground floor M 1:200

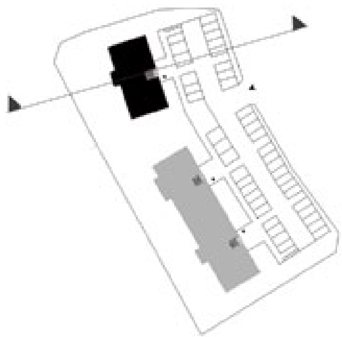


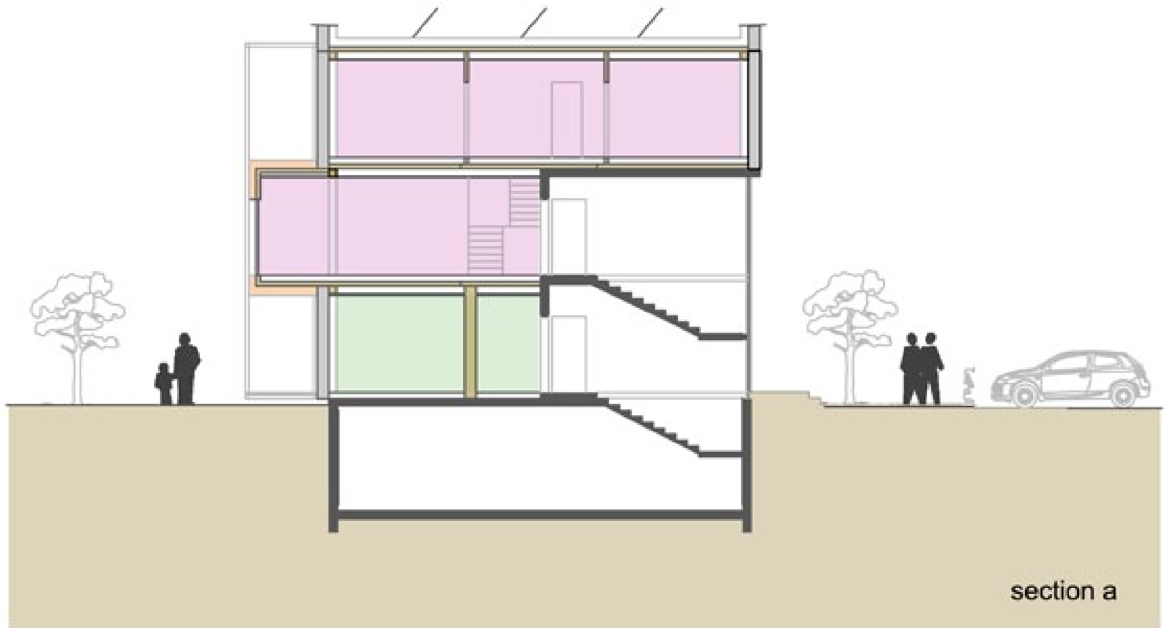
01 family living first + second floor M 1:200

1st floor

2nd floor

01 family living section M 1:200

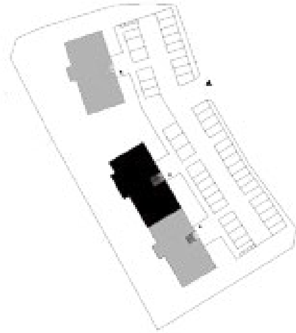




01 family living elevations M 1:200

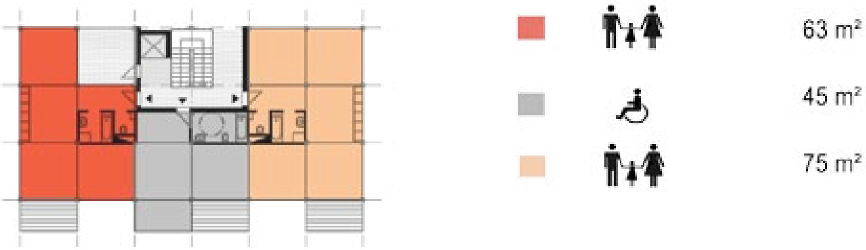
elevation south-west

elevation north-east

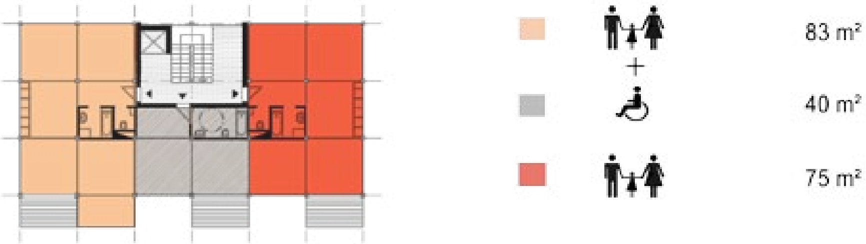


02 barrier-free living units

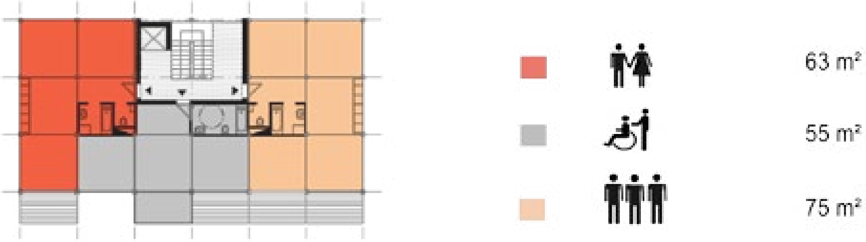
ground floor



first floor



second floor



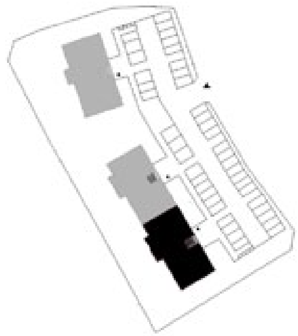
02 barrier-free living ground floor M 1:200

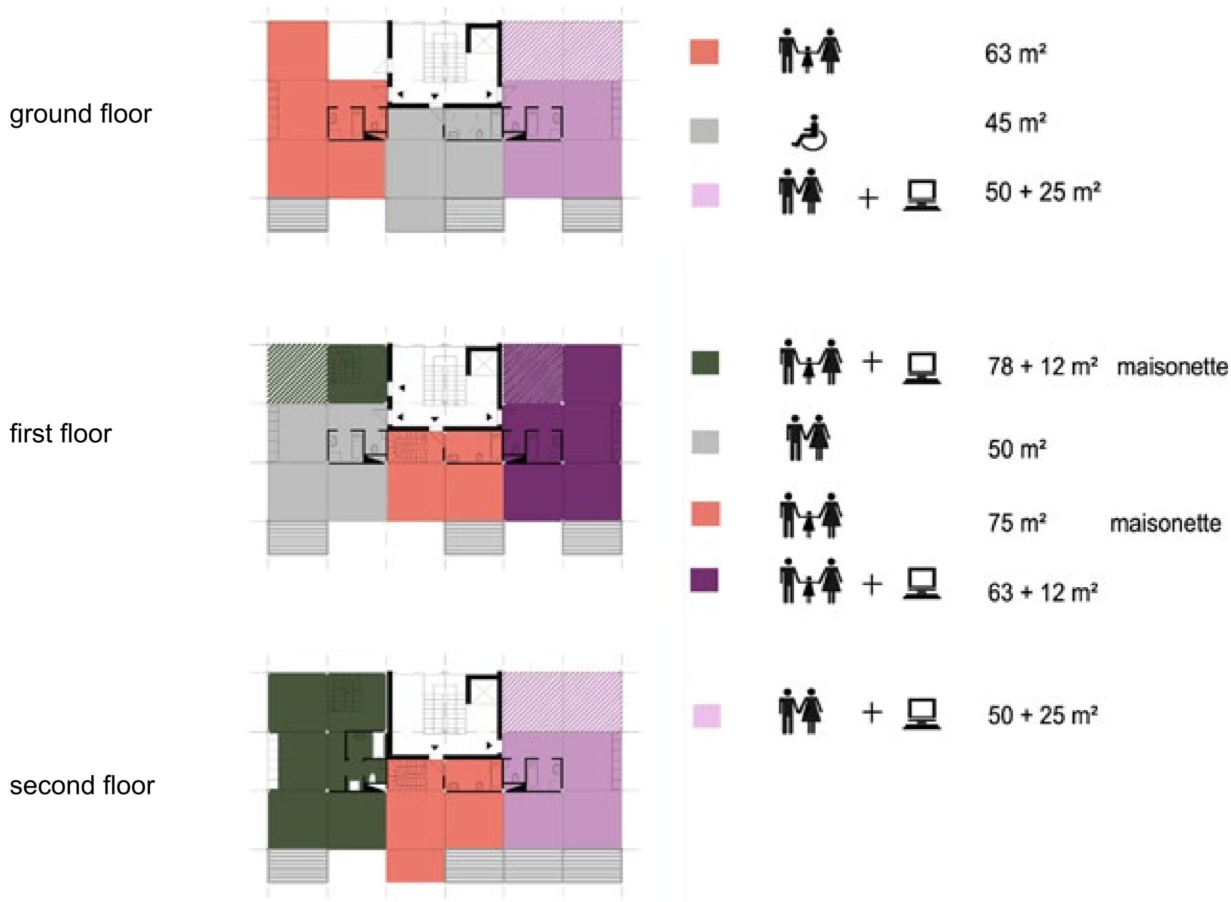
02 barrier-free living first + second floor M 1:200

1st floor

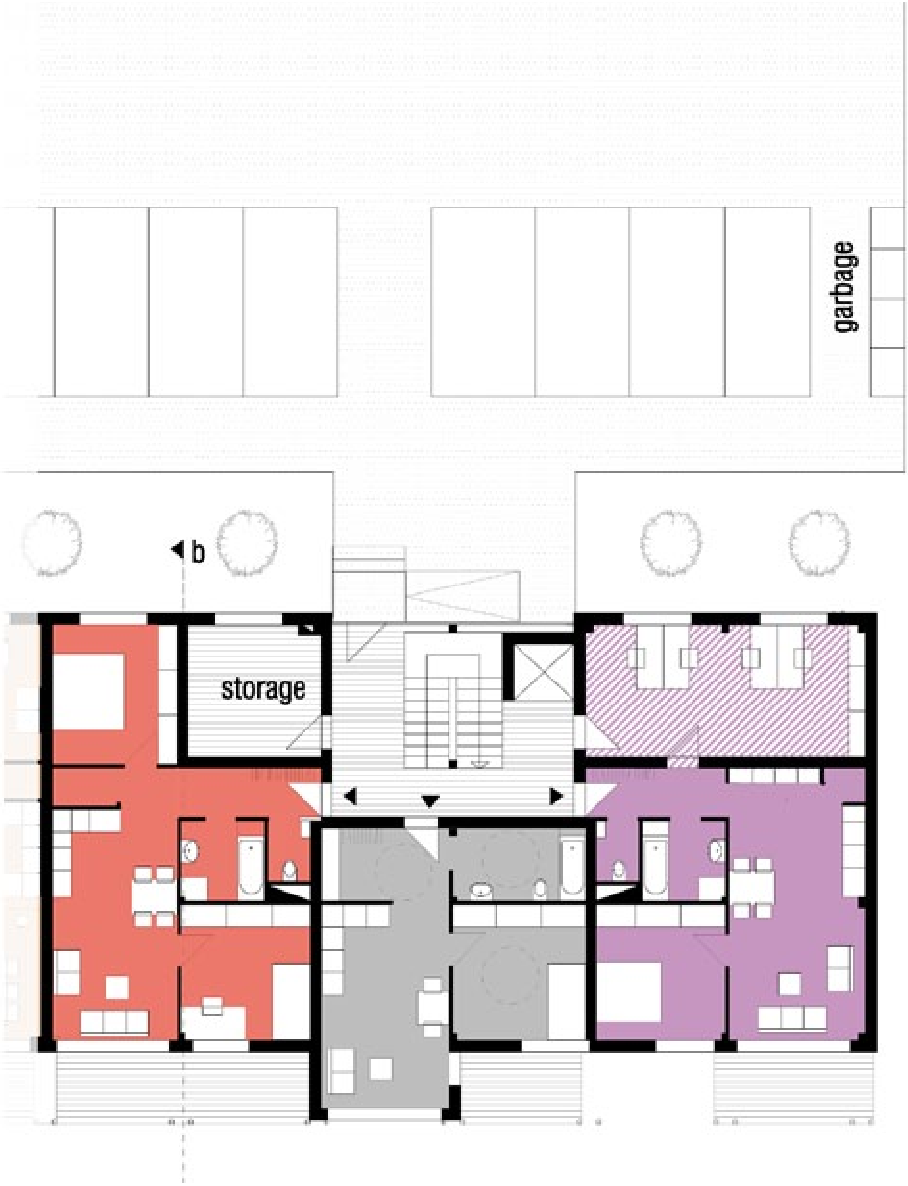
2nd floor

03 living and working units





03 living and working ground floor M 1:200

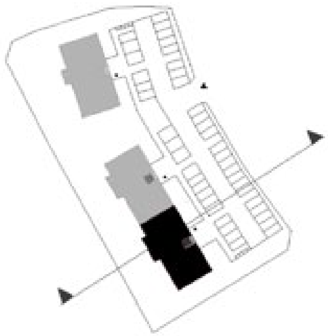


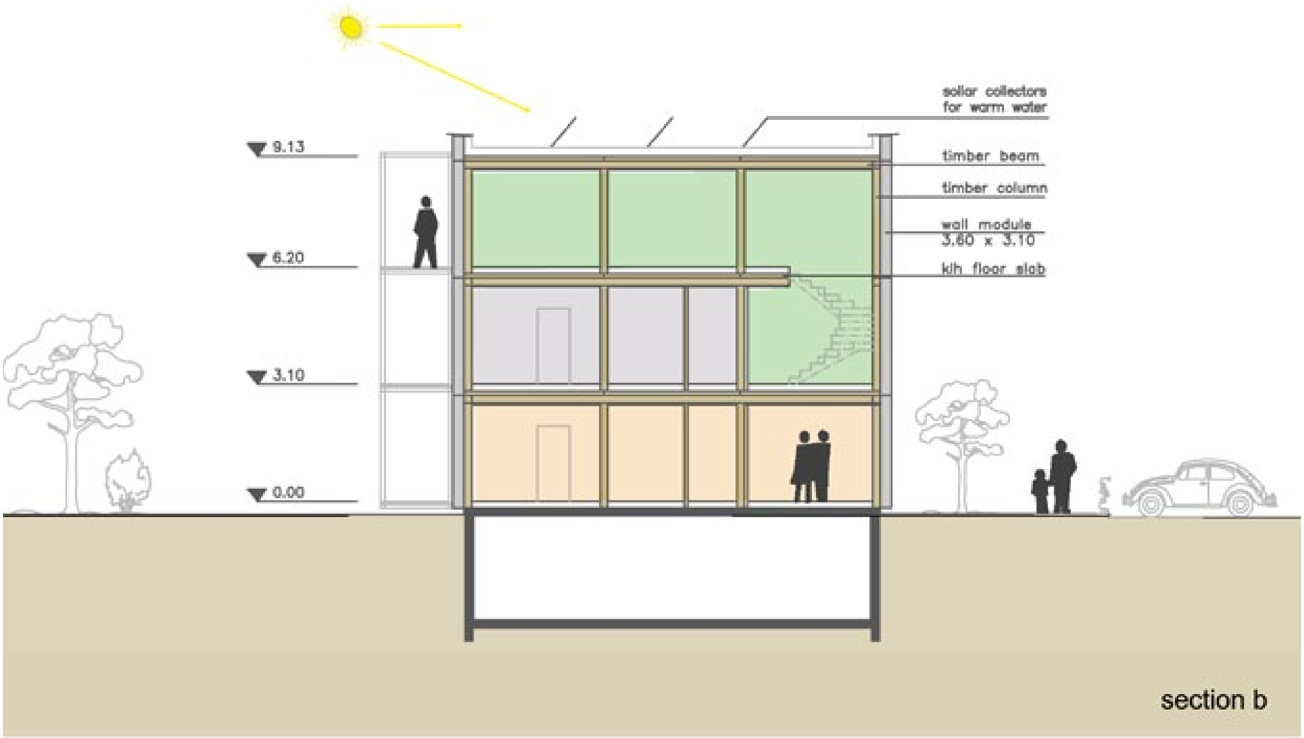
03 living and working first + second floor M 1:200

1st floor

2nd floor

03 living and working section M 1:200





02 + 03 elevations M 1:300

elevation south-west

elevation north-east

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FIGURES

Evolution

Fig. 1: Manning Portable Colonial Cottage
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Fig. 4: "Standardization, industrialization, taylorization"
Home Delivery, p. 17

Fig. 5: System Dom-ino, Le Corbusier
Home Delivery, p. 53

Fig. 6: Baukasten, Walter Gropius
Home Delivery, p. 57

Fig. 7: General Panel System, Gropius and Wachsmann
Components and Systems, p. 27

Fig. 8: The Wichita House, Buckminster Fuller
Components and Systems, p. 27

Fig. 9: Maison Tropicale, Jean Prouvé
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Fig. 10: Lovell Health House, Richard Neutra
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Fig. 15: Zip-Up House, Richard Rogers
Home Delivery, p. 148

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Fig. 17: Facades of different Plattenbauten
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Fig. 18: *Home Delivery*, p. 145

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Fig. 19: *Home Delivery*, p. 144

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Fig. 20: *Home Delivery*, p. 125

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Theory

Fig. 24: Main difference between closed and open systems
author

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Strategy

Flexibility

Sustainability

Trends

DESIGN