2011 – 2012

Catherine De Wolf

Life Cycle Design

How can interactions between buildings, components and materials support design for re-use through sustainable material management?

Applied to the renovation of residential building typologies in Brussels

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Masters dissertation submitted to the Faculty of Engineering, Vrije Universiteit Brussel, in partial fulfillment of the requirements for the degree of Master in Architectural Engineering

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By Catherine De Wolf

Acknowledgements

First of all, I would like to thank my supervisor Prof. dr. ir. arch. Niels De Temmerman for his dedicated time, unlimited support and incredible enthusiasm. I would like to express my deepest gratitude to my advisor dr. ir. arch. Wim Debacker for his availability, his sincere personal and professional involvement and the undeniable relevance of his feedback. I am also sincerely thankful for my advisor ir. arch. Pieter Herthogs for helping me with his precious remarks, encouraging words and eye for misspelling.
I would also like to thank my design studio supervisors Prof. dr. ir. arch. Jonas Lindekens and arch. Thierry Berlemont, for their intensive follow-up of my design, their critical point of view and their great advice.
For helping me develop a research topic that personally suited me best, I would like to thank my co-supervisor Prof. dr. ir. arch. Kristel De Myttenaere and arch. Steven Beckers.
Last but not least, I would like to thank my family and friends, especially my parents, for the unconditional love and for supporting me in every way to follow my dreams.

Abstract

English

In four-dimensional (4D) design, the "time" parameter, i.e. the complete life cycle of a building, is taken into account. Life Cycle Design of the built environment is generally studied on three levels: materials, components and building. However, the *interactions* between the levels are not yet implemented in design strategies. This dissertation analysed how interactions between the building, component and material levels can support design for re-use through sustainable material management.

The research was conducted in four steps. First an inventory of existing 4D design strategies (1) was made, focussing on three levels of the built environment, namely materials, components and buildings. This was followed by an analysis specifying the overlaps and gaps in existing strategies. Next, a study of existing urban residential typologies (2) was used to select a suitable case study: the social apartment block "Brigittinnen" in Brussels. Afterwards, a set of urban living scenarios (3) was developed and applied to the case study. Finally, the research by design in the "Brigittinnen" case emphasised the interacting aspects of life-cycle design (4). Based on the insights developed during the 4D design research, an analysis of the interactions between strategies on the material, component and building levels was applied. Further, adaptable connection details were designed and integrated. This led to a proof-of-concept of 4D design, through this practical case study.

Nederlands

In vierdimensionaal (4D) ontwerp, wordt eveneens de parameter "tijd", i.e. de volledige levenscyclus van een gebouw, in rekening gebracht. Levenscyclus ontwerp in de bouwomgeving wordt voornamelijk bestudeerd op drie niveaus: materialen, componenten en gebouwen. De *interacties* tussen de niveaus zijn echter niet voldoende geïmplementeerd in ontwerpstrategieën. Deze meesterproef analyseert hoe de interacties tussen gebouw-, component- en materiaalniveau het ontwerpen voor hergebruik kunnen ondersteunen aan de hand van duurzaam materiaalbeheer.

Het onderzoek is georganiseerd in vier stappen. Eerst werd een inventaris van de bestaande 4D ontwerp strategieën (1) uitgevoerd, met aandacht voor de drie niveaus van de bouwomgeving, namelijk materialen, componenten en gebouwen. Dit werd gevolgd door een analyse om de overlappingen en hiaten duidelijk te maken in de bestaande strategieën. Vervolgens leidde een studie van het bestaande stedelijke woonbestand (2) tot de keuze van een geschikte case study: het sociaal appartementsblok "Brigittinnen" in Brussel. Daarna werden een reeks stedelijke levensscenario's ontwikkeld (3) en toegepast op de case study. Tenslotte benadrukte het ontwerpend onderzoek in de "Brigittinnen" case de interagerende aspecten van levenscyclus ontwerp (4). Gebaseerd op de inzichten verworven tijdens het onderzoek over 4D design, werd een analyse van de interacties tussen deze strategieën op het niveau van materiaal, component en gebouw toegepast. Daarnaast werden aanpasbare verbindingsdetails ontworpen en geïntegreerd. Dit leidde tot het bewijs van de haalbaarheid van het 4D design concept, doorheen deze praktijkuitvoering.

Français

La conception en quatre dimensions (4D) intègre le paramètre « temps », c'est-à-dire le cycle de vie complet du bâtiment. La conception de cycle de vie dans le secteur de la construction a principalement été étudiée sur trois niveaux : les matériaux, les composants et les bâtiments. Les *interactions* entre ces niveaux ne sont cependant pas encore implémentées suffisamment dans les stratégies de conception. Ce mémoire analyse comment les interactions entre le niveau du bâtiment, des composants et des matériaux peuvent soutenir la conception d'habitations pour leur réutilisation à travers une gestion soutenable des matériaux.
La recherche est organisée en quatre étapes. D'abord, un inventaire des stratégies existantes de conception (1) a été effectué, en accentuant les trois niveaux du secteur de la construction, c'est-à-dire les matériaux, les composants et les bâtiments. Ceci est suivi d'une analyse des points communs et des lacunes des stratégies existantes. Ensuite, une étude des typologies métropolitaines et résidentielles du patrimoine immobilier actuel (2) a conduit au choix d'un cas d'étude approprié : les appartements sociaux « Brigittinnes » à Bruxelles. Après, des scénarios de vie urbaine ont été développés (3) et appliqués au cas d'étude. Enfin, la recherche par la conception dans le cas des « Brigittinnes » s'est concentrée sur les aspects interagissant de la conception de cycle de vie (4). Basée sur les perceptions faites durant la recherche sur la conception 4D, une analyse des interactions entre les stratégies au niveau des matériaux, des composants et du bâtiment a été appliquée. Des détails de connexion adaptable ont été conçus et intégrés. A travers cette mise en pratique, la faisabilité du concept de design 4D est démontrée.

Keywords

Life Cycle Design – 4D design – adaptability – time-based design – level interactions – building layers – sustainable development – building, component, material

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Lexicon

Transformable

Latin: transformare = change shape; The (construction) system (cfr. system theory[1]) or shape can change, significant alterations can take place through constructional interventions [KRONENBURG, 2007, p 145].

Adaptable

Latin: adaptare = fit, matching; Able to answer to new functions or uses, fitting to occurring changes within the same system, for example open landscape offices. [KRONENBURG, 2007, p 114] The definition given by Schmidt (2010) is *capable to accommodate effectively the evolving demands of its context, thus maximizing value through life* [PADUART, 2012]. According to Friedman, adaptability can be defined as "*providing occupants with forms and means that facilitate a fit between their space needs and the constraints of their homes*" [FRIEDMAN, 2002, p 1].

Versatile

Latin: versatilis = turning easily; many-sided, multifunctional within a static building, for example polyvalent spaces.

Flexible

Latin: flexibilis = bending, curving; flexible architecture adapts, transforms, is motive, interacts with its users [KRONENBURG, 2007, p 11] in order to give the building a longer useful life. The term "flexibility" needs to be defined in the context as it can be defined in many different ways (in latitude, subdivision, load, services, expansion, function, etc.) [HEIJNE et al, 2005, p 76, W. Spangenberg].

Changeable

Able to change forms or functions for unknown future needs; more general term.

The relation between the definitions above is illustrated in Figure 1.

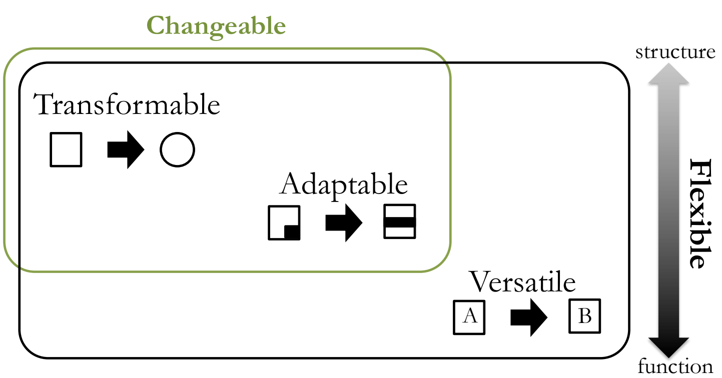


Figure 0.1: Definitions flexible, changeable, transformable, adaptable, versatile

[1]i.e. science of system properties, analysing the intern structure and functioning as well as the relation between the system and the environment [GWPE, 1984, p 401]

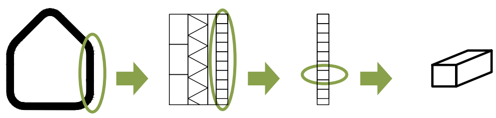
Buildings Man-made supporting structure or shelter assembled using various components.

Components An element having one or more functions. The prefixes 'sub' and 'super' define the level of the system under study. (See Table 1) An assembled element becomes a (sub)component since it receives a meaning [DEBACKER, 2009].

Basic elements A basic element is the smallest entity of a building or construction system, a single element processed out of a material. In this dissertation, a basic element can consist of a *material* or a *composite material*. If a specific purpose is given to a basic element, it becomes a (sub)component (see Table 1) [DEBACKER, 2009].

Materials A distinction must be made between raw and processed materials. In this dissertation, when interactions between buildings, components and materials are concerned, 'materials' refers to 'processed building materials'. In most cases, the processed material is also the basic element of a component.

The definitions of 'building', 'component', 'basic element' and 'material' used in this dissertation are in continuity within the habits of the research group at the Vrije Universiteit Brussel. Other definitions exist, such as defined in SuFiQuaD (Sustainability, Financial and Quality evaluation of Dwelling types). To clarify the further use of this terminology, Table 1 illustrates the difference between the definition in this dissertation and SuFiQuaD [ALLACKER et al, 2012].



Definition	Building	Component	Subcomponent	Material Basic Element
SuFiQuaD		Element	Processed material	Material

Table 1: Definitions building, component, material

Restoration Reconstruction of a building with value as a monument

Refurbishment Renewal, improvement of buildings; in this dissertation synonym to **renovation**.

Type *Greek: typos = model, matrix, impression, mold, relief;* A classifying tool for families with common characteristics [DE ZEEUW et al, 1997, p 133].

Typology	**Study of types**; Abstraction of characteristics in order to classify into principles or types. *Analytical typology* enables researchers to name different elements of buildings in order to compare them to each other. *Generative typology*, according to Philippe Panerai, offers designers a standard solution to generate a new design [DE ZEEUW et al, 1997, p 132].
Scenario	Synthesis of a series of events; in this dissertation possible households and chronological (unknown) future needs in residential buildings.
Sustainable development	Defined by the Brundtland Commission as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [UNCSD, 2007, p 1].
Cradle to Cradle	Model inspired by nature in which a positive attitude towards products, materials, buildings, etc. is adopted through endless life cycles: at the end of their useful life, technical materials are recycled and biodegradable materials are composted or consumed. W. McDonough en M. Braungart define three principles: waste equals food (1); use current solar income (2) and celebrate diversity (3) [BRAUNGART & MCDONOUGH, 2002].
Four-dimensional design	In architecture, a distinction is made between design attitudes, strategies, approaches and principles. "Four-dimensional design" is a design **attitude**, whereas "Design for Reuse" is a design **strategy** within the field of adaptable architecture. "Design for Reuse" can be divided in "Design for Dismantling" (on material level), "Design for Deconstruction" (on component level) and "Design for Adaptability and Versatility" (on building level). Next to this, design **approaches** exist on the different levels: Cradle to Cradle on the material level, Hendrickx – Vanwalleghem Design Approach on the component level and the Stichting Architecten Research on the building level. Finally, the design **principles** are for example "waste equals food" within the Cradle to Cradle approach [Int. Debacker, 2012].

Attitude	4D design	
Strategy *DfRe-use*	DfDismantling	Material level
	DfDeconstruction	Component level
	DfAdaptability/Versatility	Building level
Approaches	C2C	Material level
	HVDA	Component level
	SAR/Open building	Building level
Principles	e.g. "Waste equals food"	

Table 2: Design Attitude, Design Strategy, Design Approach, Design Principle

0. Introduction

Sustainable and adaptable architecture is gaining importance in urban housing management because of growing environmental awareness, increasing living costs due to a rapidly increasing urban population density, urgent renovation needs for a large part of the existing building stock and a proliferating waste management problem.
This dissertation studies Life Cycle Design, the act of designing in such a way that the building, its components and its materials are redirected into closed reuse and recycling loops. The goal of this research is to integrate the interactions between a building, its components and its materials in order to support design for re-use, with the aim to evolve towards sustainable resource management.

Problem statement

The state of the art in research on Life Cycle Design of buildings is generally studied on three[2] different levels: the building itself, its components and the materials they are made from.

On the building level, Brand [1995] considers the "time" parameter on top of the space parameters. Defining five building layers, he emphasizes different rates at which different aspects of a building (like the skin, services, space plan, etc.) change over time, from an ecological point of view. The Stichting Architecten Research (SAR) introduced the "support and infill" concept, which is user-oriented with a focus on self-determination: the collective frame supports the individual filling [HABRAKEN, 1961]. The Industrial, Flexible and Demountable method (IFD) on the building as well on the component level is more economically oriented [DE TROYER & KENIS, 2003]. Leupen [2006] extended the layers of Brand and defined the concept of "frame and generic space", where one layer is permanent and the others changeable.

On the component level, the Hendrickx – Vanwalleghem design approach (HVDA) is based on a user-minded set of design guidelines for compatible components that can be disassembled, comparable to a 'Meccano' building set [HENDRICKX & VANWALLEGHEM, 2002]. In addition, Durmisevic [2006] defined the Open Systems approach, a dynamic top-down process departing from an open structure and independent sub-systems.

On the material level, Braungart and McDonough [2002] reinvented the industrial process, inter alia in a more ecological way, in "Cradle to Cradle: Remaking the way we make things". The main principle is "waste equals food", which aims to prevent 'down'-cycling, i.e. turning recycled waste into less qualitative resources than the initial resources. Two spheres are defined: the biosphere, where natural materials are completely biodegradable, and the technosphere, where the non-natural materials can be recycled or 'up'-cycled.

In four-dimensional (4D) design, the "time" parameter, i.e. the complete life cycle of a building, is taken into account. However, what is lacking in the existing 4D design strategies, are the *interactions* that exist between the material, component and building level.

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[2] The neighbourhood or district can be seen as a fourth level, but is out of scope in this dissertation, which focuses on the building itself. In further research, the fourth level could be integrated.

There is a need for an integrated total strategy in which the four-dimensional design tools and principles of the various approaches on different levels are combined. By listing the boundary conditions for Life Cycle Design and material re-use, parallels and possible interacting and overlapping ideas can be uncovered.

As you can see, the concept of four-dimensional architecture has already been analysed using different and diverse theoretical methodologies. However, to this day, the number of adaptable buildings that has been built is insignificant compared to more conventional buildings. Nevertheless, examples do exist (a more detailed discussion of examples can be found in chapter 1, section 1.4). However, applying life cycle design on the building level, the component level and the material level – in this case a renovation of a complete static building – will prove that the theoretical methodologies can be put into practice for the static building stock as well. This could have a larger impact and could be implemented more generally than only considering new buildings. Designers need a methodology that enables them to offer guidelines on transformable reconversion during design. The designers need tools that help them to construct buildings based on integral loop-closure and sustainable use of materials, components and buildings. This dissertation will be the starting point for the development of such four-dimensional design tools, more specifically focussed on post-war high residential buildings, which is the most ubiquitous urban building typology in Belgium.

Overview

This dissertation is divided in four main parts: the first three parts (chapter 1 to 3) describe a theoretical study and the last part (chapter 4 and 5) is a practical application.

The **first** part consists of a literature study of the existing "four-dimensional" strategies for each level (building, component, material). All four-dimensional strategies includes one or more design approaches, each of which being composed of design principles and tools. The literature study is followed by a synthesis on all levels and an analysis of possible overlaps or gaps between different approaches.
The **second** part defines the existing building typologies in a metropolitan city. The aim is to create an overview of different types that occur in the existing building stock. The most representative type, i.e. the most common and the one with the most urgent need for renovation, will be selected for the practical case study in part four. The choice will lead to a social housing building block.
The **third** part analyses typical living/dwelling patterns in order to define plausible scenarios that will allow testing the adaptability in residential architecture. A particular scenario will be developed for social housing, as base for the practical case study in part four.
The **fourth** part uses the level interactions discussed in the first part for an in-depth design of a selected practical case study. The challenge will be changing static architectural heritage for the better, while still enabling it to comply with our unknown future needs. Part four is divided in two chapters. Chapter 4 gives an introduction to the building selected for the case study and illustrates the four-dimensional design attitude, integrating the design tools of Chapter 1 through the interactions between the building, component and material level. Chapter 5 has an in-depth focus on the connection details, as these are a key factor in adaptable re-design. It describes a series of existing connection examples for each building part, which are then applied to the practical case study.

The general approach of this dissertation is illustrated in Table 0.1, with the expected results, which will be filled in during the conclusion of this dissertation.

The result of this research will be a proof-of-concept integrating the interactions between building, component and material design levels, through the application of four-dimensional design tools and principles on a practical case study.

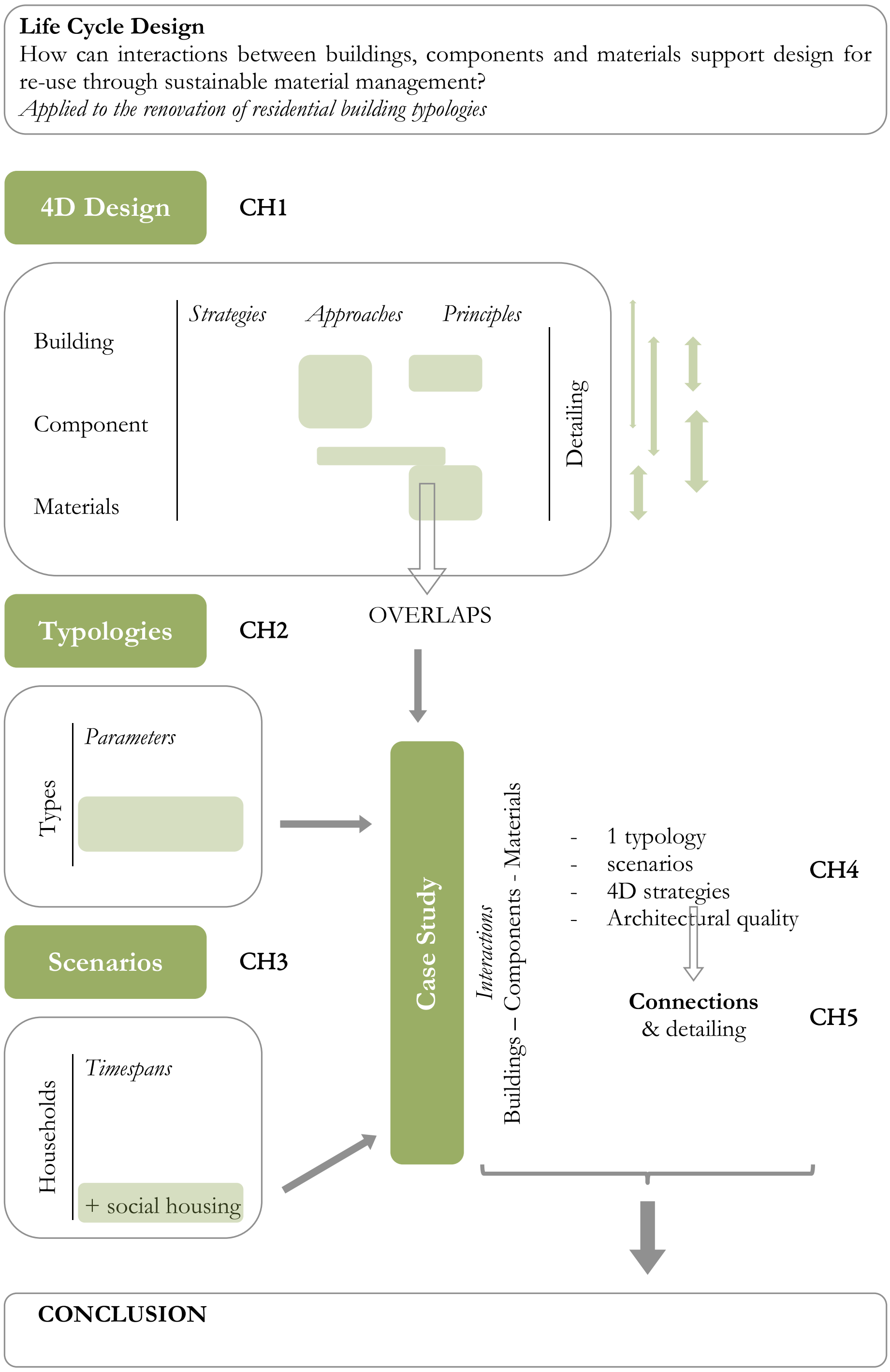


Table 0.1: General Approach of this dissertation

1. Four-dimensional Design

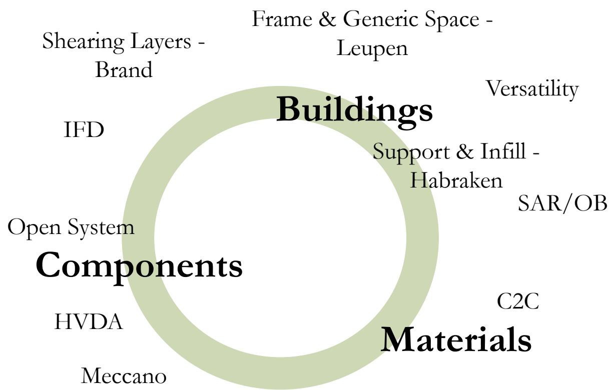
"Human beings are flexible creatures. We move about at will, manipulate objects and operate in a wide range of environments. There was a time, not too long ago in evolutionary terms, when our existence was based on our capacity for movement and adaptability; indeed it is to this that we owe our survival as a species. Most cultures now lead a more or less sedentary life, but it could be that flexibility is once again becoming a priority in human development and that technological, social and economic changes are forcing, or at least encouraging, a new form of nomadic existence based on global markets, the world wide web and cheap, fast transportation." – Robert Kronenburg [KRONENBURG, 2007, p10]

In this chapter the basic principles of the existing four-dimensional design strategies and approaches in literature are explained. The fourth dimension consists of the 'time' parameter. The "Transformable Structures" Research Group (Vrije Universiteit Brussel) investigates designing methods and element detailing in order to respond to the need for change in the future. Life Cycle Design takes into account unpredictable future needs or changes. For the time being, four-dimensional design strategies include the evolving processes in life and society into the design methods on four levels: urban fragments, *buildings, components and materials*. In the following chapters, the *interactions* between these levels will be discussed. A holistic approach is crucial: loop closure must not stand in the way of transmitting inheritance in architecture [DE MYTTENAERE, 2006].

Architecture based on a four-dimensional design approach is analysed with different theoretical methodologies, but hardly put into practice. Looking at the interactions instead of breaking down into levels enables a holistic approach necessary for life cycle design. The *interactions* are the missing links between the different four-dimensional design attitudes, strategies, approaches and principles. In order to clearly analyse these interactions, an inventory of the existing design strategies and approaches on each level is developed, in this chapter.

The four-dimensional concepts are often developed for new projects. Nonetheless, in developed countries, only 1.5 to 2% of the existing building stock is composed of new buildings [DEBACKER, 2009, p 339]. If the aim is to replace the existing building stock with new buildings which take life cycle design in account, the process would take up to one hundred years. Therefore, the challenge is to *retrofit* the existing static architecture into dynamic constructions [DEBACKER, 2009]. Demolition processes are an important factor in the construction waste. This is why rethinking the renovation approach of existing buildings is crucial. Sustainable development is only efficient if the existing, static architecture can be reused and reorganised as adaptable and transformable buildings. Design strategies for adaptive reuse of the existing Flemish (social) housing stock has been done by Paduart [2006]. In her PhD thesis, Paduart [2012] also investigated a "four-dimensional renovation approach towards a dynamic and sustainable building stock", in order to develop a re-design for change method [PADUART, 2012].

The discussed four-dimensional design approaches in the following chapter are illustrated in Figure 1.1 in relation to the level(s) they apply to. The explanations and definitions of the terms and abbreviations will be clarified during this chapter.



DfV/A Buildings	*DfDe Components*	*DfDi Materials*
Versatile **SAR/OB** **Leupen**		
IFD		
	HVDA **Open Systems**	
		C2C

Figure 1.1: Four-dimensional designs and the three levels[3]

Design for Reuse (DfR) can be divided as follows (based on [DEBACKER et al, 2007, lines 216 - 243], [DEBACKER, 2009] and [PADUART, 2012, p 45]):

- *Design for adaptability (DfA)*
  The *buildings* can adapt when constraints change, by reuse for the same or another function, a flexible and versatile re-design or a moderate refurbishment.
- *Design for deconstruction (DfDe)*
  The building *components* can easily be disassemled and are designed to prevent damage.
- *Design for dismantling (DfDi)*
  The building *materials* can easily be separated in order to recycle technical materials and bring the biodegradable materials back into the natural cycle.

Each of these *Design for X* concepts have their own design approaches. These will be discussed in the following paragraphs. In Figure 1.1, several of these approaches to four-dimensional design are illustrated according to the three levels.

In architecture, a distinction is made between design attitudes, strategies, approaches and principles. "Four-dimensional design" is a design **attitude** where the designer must be aware of, whereas "Design for Reuse" is a design **strategy** within the field of adaptable architecture. "Design for Reuse" can be divided in "Design for Dismantling" (on material level), "Design for Deconstruction" (on component level) and "Design for Adaptability and Versatility" (on building level). Next to this, design **approaches** exist on the different levels: Cradle to Cradle on the material level, Hendrickx – Vanwalleghem Design Approach on the component level and the Stichting Architecten Research on the building level. Finally, the design **principles** are for example "waste equals food" within the Cradle to

[3] All Figures without reference are personal drawings by the author.

Cradle approach. Next to design principles, some approaches also define design **tools**, such as "modular coordination" [Int. Debacker, 2012].

1.1 *The building level: design for adaptability and versatility*

Design for adaptability and versatility is a strategy for designing buildings in a flexible way. *Three main categories* can be defined for design approaches on the building level (Table 1.1). Firstly, we can make the building *versatile*: without adjustments; spaces (for example the rooms in residential buildings) can be used for various activities. The building can be designed in a multifunctional way, so that another usage is possible with little or no change. Secondly, we can construct *partially permanent and partially changeable*. For example a permanent structure can be filled in with adaptable objects. Finally, in *semi-permanent* buildings, the used components can be completely disassembled [PADUART, 2012].

Shearing Layers Brand	**Versatile building**	
	Permanent vs. changing building layers	Support & Infill - Habraken Frame and Generic Space - Leupen
	Semi – permanent building	IFD

Table 1.1: Building level

Before elaborating on the building level design approaches illustrated above, a clear definition of building 'layers' is needed. Brand [1995] defined five 'shearing layers', explained in the following paragraph.

1.1.1 Shearing Layers – Brand

The layers discussed in this paragraph are not a design approach. They define the theoretic link between the building and component layers. The Layers of Brand are nevertheless discussed in this section on building level, to understand the following design approaches.
Brand [1995] considers the building in *time* instead of in space. Applying the "shearing layers of change", he emphasizes the different rates of changes.
Brand decomposes architecture in six layers, which are an expansion of the four S's defined by Francis Duffy[4] [BRAND, 1995]. These layers have different lifespans:

- The *site* is timeless;
- The *structure* (foundations and bearing elements) is difficult and expensive to change. The lifespan holds between 30 and 300 years;
- The timespan of the *skin* ("*Skin is mutable*") is considered 20 years to keep up with fashion or technological mutations;
- The electrical and communications wiring, the heating, ventilation and air conditioning, the sanitary zones and the elevators/escalators, in other words "the *services*", need replacement every 7 to 15 years;
- The *space plan* or the interior layout has a change rate varying between 3 and 30 years depending on the function the building shelters;
- The furniture or "*stuff*" moves daily or monthly.

[BRAND, 1995]

[4] Brand refers to: DUFFY F., "*Measuring Building Performance*", Facilities, May 1990, p17

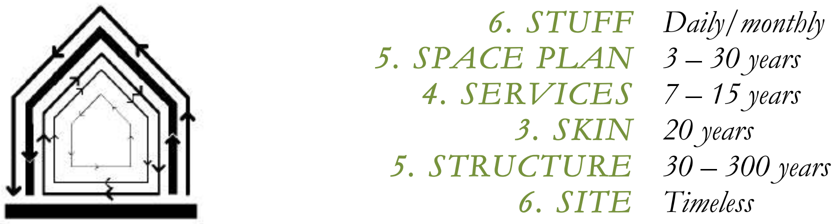


Figure 1.2: Shearing Layers of Duffy and Brand, based on [BRAND, 1995, p 13]

Brand also makes a distinction between so called "low road" and "high road" buildings. The first buildings should be easy to adapt to new needs. The second ones are more difficult to change, but have an important place in the public life, such as buildings with a governmental or monumental value.

1.1.2 Versatile buildings

The first four-dimensional design approach within the building level is (re-)designing versatile buildings. Little or no radical adjustments are needed to adapt the building to different functions. Multi-functional spaces are an example of versatility. In residential buildings, this means the rooms can shelter different activities without important destructions. A building is versatile when the spatial configuration of its rooms can support several non-similar living patterns. However, this approach is more suitable for industrial or commercial buildings [PADUART, 2012].

The Van Nelle factory in Rotterdam (see Figure 1.3) is an example of the versatile buildings. The building was initially designed in 1931 for coffee factory. Today, the factory is transformed to an industrial monument sheltering small offices. The versatile buildings are not always designed with the intentions of four-dimensional design, but have inherent characteristics that permit new functions with little or no radical changes.

Figure 1.3: Van Nelle factory in Rotterdam, source: [DEBACKER, 2009, p 27]

1.1.3 Support and Infill or the SAR approach – Habraken

The second four-dimensional building design approach, is called "Support and Infill" and was introduced by Habraken.
For the Stichting Architecten Research (SAR) and for Open Building (OB), the participation of the dwellers into the design process is crucial [DEBACKER, 2012]. SAR developed three main ideas towards a four-dimensional approach in buildings.

The *first idea* can be summarized as a 'supporting' structure, in which the elements can be 'filled' [DEBACKER, 2012]. The support belongs to the community, whereas the infill belongs to the individual.

Habraken stated that our homes participate in two spheres: the interior reflects and responds to the needs of the individual environment and the exterior belongs to the community environment [LEE, 1971].
An illustration to understand this division is the street: the street belongs to the community, whereas the car belongs to the individual [DE TROYER & KENIS, 2003].

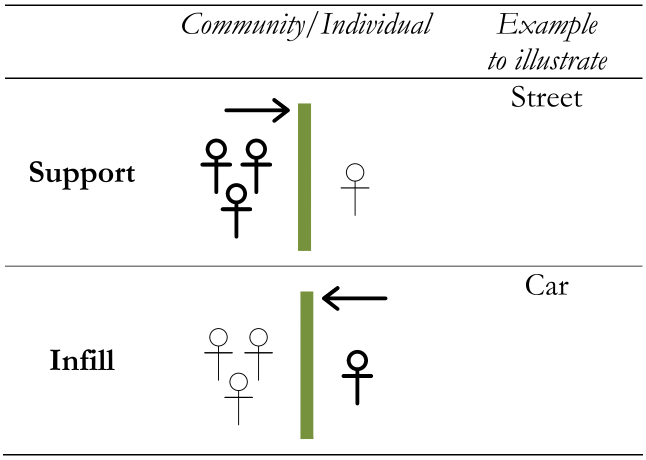


Figure 1.4: Two spheres of our homes: community vs. the individual, based on [LEE, 1971, p22]

Also, the built environment is in continuous (part by part) transformation and is a never ending design process instead of a final product [KENDALL & TEICHER, 1999]. In "De dragers en de mensen, het einde van de massawoningbouw" (or "Supports: an Alternative to Mass Housing,"), Habraken combined the industrial housing construction with the participation of the inhabitants by defining a collective 'support' wherein the individual could 'infill' as desired. In this concept, the designer has the role to accommodate the collective and the individual to one another [GALLE, 2011].

The *second concept* is the use of a modular dimensioning system to ensure the compatibility between the elements. In both plan directions, two measures, 10 and 20 cm, are used in combination to form preferably a grid of 30 cm. The 20 cm distance is used for bearing elements and fluid conducts. The 10 cm distance is used for non-bearing elements and electrical wiring [BOSMA et al, 2000], [GALLE, 2011].

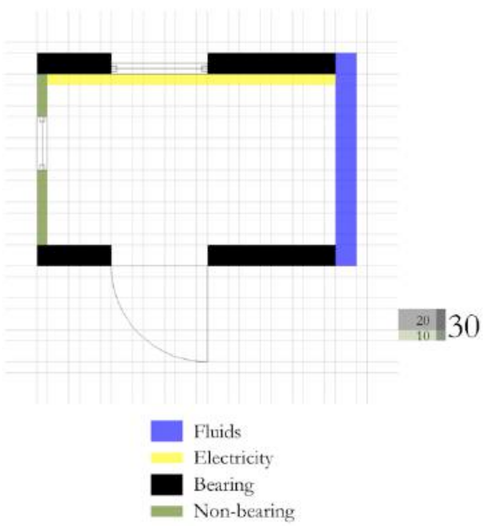


Figure 1.5: Dimensioning system

The *last aspect* is the definition of different types of 'zones', separated by 'margins' with the characteristics of both adjacent zones. This principle is illustrated in Figure 1.6. The zones contain the living spaces or circulation. The margins are utility spaces or transitions.

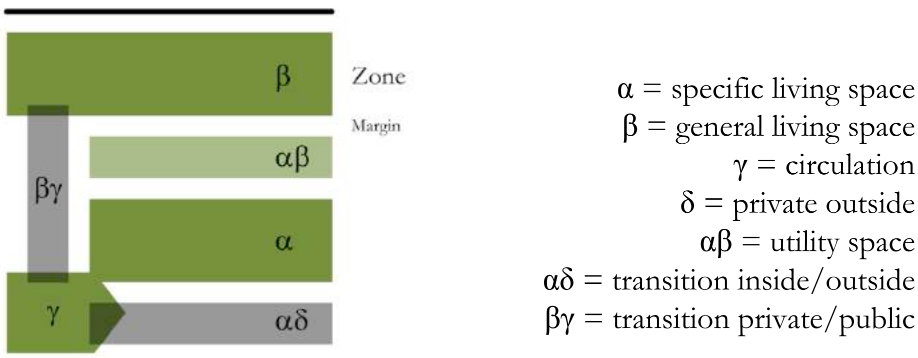


Figure 1.6: Zone and margins, based on [DEBACKER, 2009, p 38] and [GALLE, 2011, p 22]

The SAR or OB approach can be summarised as "Support and Infill", with a 30 cm grid dimensioning system and differentiation between zones and margins.

1.1.4 Frame and Generic Space – Leupen

Leupen [2006] defines three ways to design for adaptability/versatility: make buildings versatile; make buildings partially permanent and partially changeable; and make buildings permanent. To apply this on existing building structures, the outdated parts are removed and the remaining part forms the permanent base for a dynamic retrofitting design [PADUART, 2012].

In "Frame and Generic Space – A study into the changeable dwelling *proceeding from the permanent*", Leupen [2006] considers the frame as a permanent departure-point for change through the means of a generic space. To understand this concept he defines, in accordance with Brand, five layers (Table 1.2) by their function instead of their architectural elements: Structure, Skin, Services, Scenery (equivalent to Space Plan) and Accesses (considered instead of furniture in de layers defined by Brand) [LEUPEN, 2006]. The layers are illustrated in Figure 1.7.

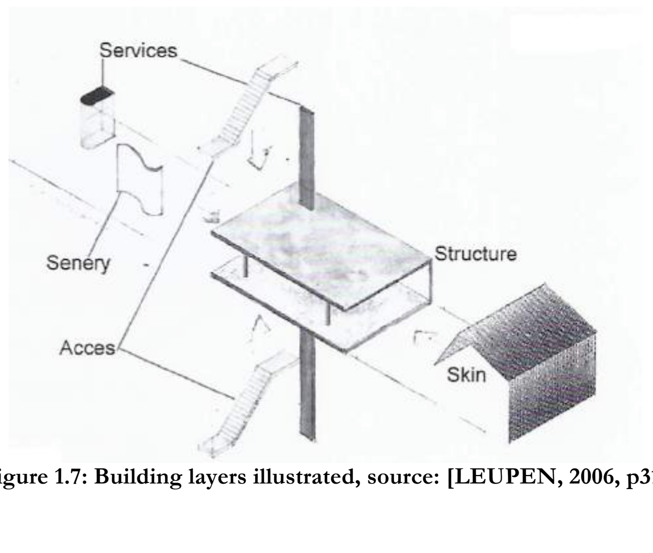


Figure 1.7: Building layers illustrated, source: [LEUPEN, 2006, p31]

The structure transmits the loads to the ground. The skin is the separation between the inside and the outside, but also the representation of the building to the external context. The scenery defines the space plan via the wall partitioning and finishing. The role of the services is to regulate the supply and discharge of water, energy and air. Finally, the access is considered. The accessibility of the spaces or individual homes is defined by the circulation modes [LEUPEN, 2006].

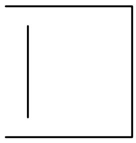
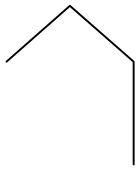
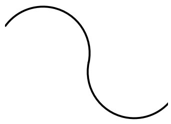
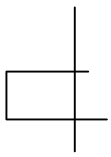
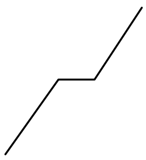
	**Structure**	Transmits the *loads* to the ground	▪ Columns ▪ Beams ▪ Load-bearing walls ▪ Trusses ▪ Structural floors
	**Skin**	Separates *inside and outside* + Represents the building *externally*	▪ Façade ▪ Base ▪ Roof
	**Scenery**	Defines the *space plan*	▪ Cladding ▪ Internal doors ▪ Internal walls ▪ Finish of floors, walls and ceilings
	**Services**	Regulate the *supply and discharge* of water, energy and air	▪ Pipes and cables ▪ Appliances ▪ Special amenities
	**Access**	Takes care of *accessibility* of spaces/individual homes	▪ Stairs ▪ Corridors ▪ Lifts ▪ Galleries

Table 1.2: Layers based on [LEUPEN, 2006, p 32]

One of these layers becomes a *frame* when it makes another layer free. The frame stays permanent for the entire building life cycle. Each of the layers defined in Table 1.2 can constitute a frame, on the condition it can be *disconnected* from the other layers. The border on which the disconnection takes place are marked by *excision* (see Figure 1.8) The freedom in the other layers to evolve and be frequently updated is summarised as the *generic space*. The changeability of the generic space is divided in 'alterability', 'extendibility' and 'polyvalent spaces'.

- in *alterable* spaces, a layer can be changed;
- in *extendable* space not all sides are bordered; or
- in *polyvalent* spaces different uses are possible.

[LEUPEN, 2006]

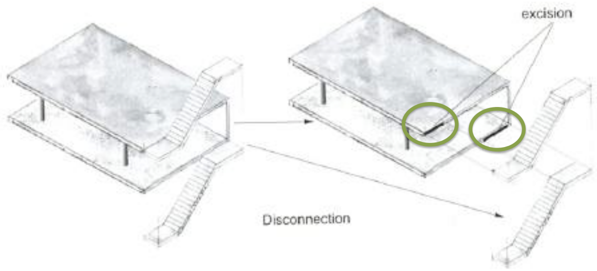


Figure 1.8: Disconnection and excision illustrated, source: [LEUPEN, 2006, p34]

1.1.5 Industrial, Flexible and Demountable – De Troyer, Kenis

Industrial, Flexible and Demountable (IFD) tends to build flexible and demountable based on industrialisation. Where the SAR approach is a system, IFD is a concept more than an approach. The IFD concept does not involve rules and systems such as seen in the SAR approach. However, the industrial aspect demands standardisation of measures. Initially, IFD was a program launched to stimulate prefab constructions. The program resulted in flexible principles.

The support or the shell work belongs to the community. The infill or the finishing belongs to the individual. Table 1.3 illustrates this division, with the example of the street/car mentioned in paragraph 1.1.3 [DE TROYER & KENIS, 2003].

			Example to illustrate
Support	Community	Shell	Street
Infill	Individual	Finishing	Car

Table 1.3: IFD based on Support and Infill, based on [DE TROYER & KENIS, 2003, p 17]

The *industrial* aspect stands for the assembly of prefab elements. The advantages of prefabrication are the weather-independent production of components, the quality of detailing and less construction waste.
The *flexible* concept gives the building a longer useful life. The first user receives freedom in choices, but further we can alter these initial choices. The change of functions is possible with little or no modifications by decoupling components with different use cycles.
The *demountable* part stands for the reconversion of a building or component and material recycling. The limitation of waste during the construction process and entire life cycle of the building is also crucial [PUTZEYS & VAN DESSEL, 2004].

Industrial	Mountable Project development Weather independent
Flexible	Freedom of choices Adaptability Decoupling
Demountable	Reconversion Recycling Less demolition waste

Table 1.4: What is IFD?, based on [PUTZEYS & VAN DESSEL, 2004, p3]

Five important concepts are practiced by IFD [DE TROYER & KENIS, 2003]:

- Industrial and user-oriented design
- Support and infill
- Flexibility based on modular grid connections
- Freedom of choices
- Dry joints and indirect[5] connections

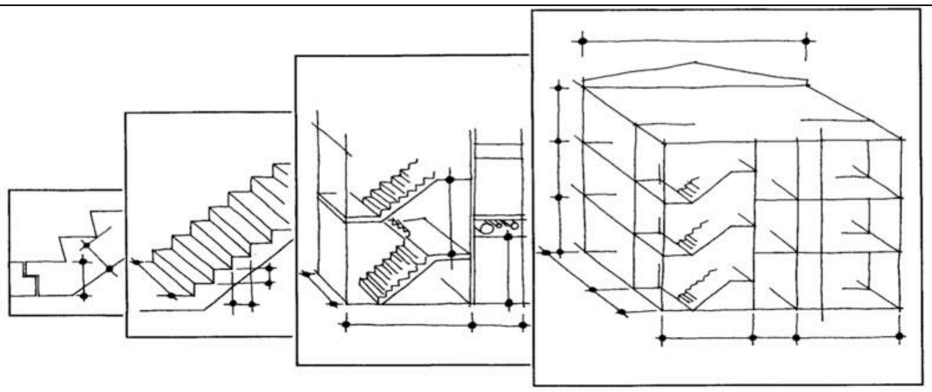


Figure 1.9: Grids and modulation on different levels, source: [DE TROYER, 2002, p4]

1.1.6 Summary of the building layers

Different authors defined the layering of buildings. The different lifespans of these building layers connect the materials, the components and the buildings to each other. In Table 1.5, the different definitions are listed.

Habraken[6] (1961)	**Rush[7] (1986)**	**Duffy (1990)**	*Brand (1995)*	**Slaughter[8] (2001)**	*Leupen (2005)*
			Site		
Support	Structure	Shell	*Structure*	Structure	*Structure*
Infill	Envelope		*Skin*	Exterior enclosure	*Skin*
	Mechanical	Services	*Services*	Services	*Services*
					Access
	Interior	Scenery	*Space Plan*	Interior Finish Systems	*Scenery*
		Set	*Stuff*		

Table 1.5: Building layers in literature based on [AUSTIN et al, 2009, p1] and [PADUART, 2012, p51]

The different layers are now defined on building level. Certain interactions between building, component and material are linked to specific layers. The type of change can also differ from layer to layer. Versatile buildings are multifunctional. Adaptable buildings are able to answer to new functions or uses, fitting to occurring changes within the same

---

5 "*Indirect connections are usually easier to deconstruct; they are interchangeable and independent from adjacent components.*" – [DEBACKER, 2009, p56]

6 Support and Infill are not considered as temporal layers. However, they are an indication of not-adaptable/adaptable.

7 Richard D. Rush and the American Institute Of Architects defined these layers in [RUSH, 1986].

8 Professor E. Sarah Slaughter is President and CEO of MOCASystems Inc. and did research in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology. Source: [SLAUGHTER, 2001].

system [KRONENBURG, 2007]. In transformable buildings, the (construction) system (cfr. system theory[9]) or shape can change, significant alterations can take place through constructional interventions [KRONENBURG, 2007]. This type of change (versatile, adaptable, transformable) is brought in relation with the layers defined by Leupen [2006] in Figure 1.10. The illustration represents the three levels (building, component, material) wherein the different layers (structure, skin, scenery, services, access) are most likely to be re-designed for change (darker green colour). The layers of Leupen were taken as base, since this recent division takes into account Access instead of Stuff, which will be important in the case study in chapter 4.

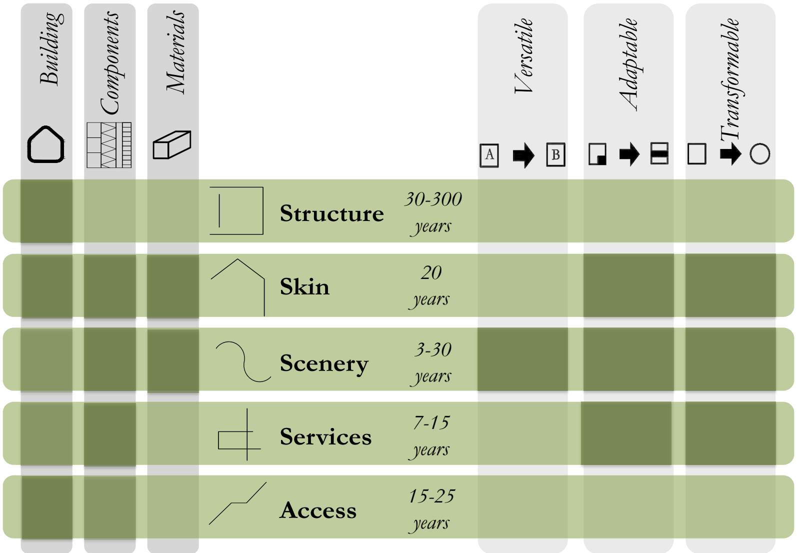


Figure 1.10: Link between building, component and material through the layers of building

This section discussed the design approaches on the building level: versatile buildings, the Support & Infill principle of SAR and the Frame & Generic Space principle of Leupen, and finally the IFD projects. These approaches enable design for adaptability or versatility through different ratios of permanent and changing building layers. In the following section, approaches will accentuate the component level.

1.2 The component level: design for deconstruction

After elaborating different design approaches on the building level, this section clarifies the approaches on the component level. The term 'component' is used for an element that has one or more functions. The prefixes 'sub' and 'super' define the level of the system under study. An assembled element becomes a (sub)component since it receives a meaning [DEBACKER, 2009].

In Design for Deconstruction (DfDe), the building components should be easy to reuse and therefore disassembled technically. For reuse purposes, damage should be prevented as much as possible through the design of the components, with eventually inexpensive and simple maintenance processes [DEBACKER et al, 2007]. This paragraph discusses the

[9] i.e. science of system properties, analysing the intern structure and functioning as well as the relation between the system and the environment [GWPE, 1984, p 401]

Hendrickx-Vanwalleghem Design Approach and the Open Systems approach. The Industrial, Flexible and Demountable approach will also be applied to the component level.

DfDe	**Meccano®**	HVDA – Hendrickx & Vanwalleghem
	Sub-systems	Open Systems - Durmisevic
	Demountable	IFD - De Troyer & Kenis

Table 1.6: Component level - DfDe approaches

1.2.1 Hendrickx – Vanwalleghem Design Approach or the Meccano® building – Hendricks and Vanwalleghem

The Hendrickx – Vanwalleghem Design Approach (HVDA) integrates *compatibility* of components in the design for deconstruction strategy. The approach includes design guidelines for adaptable and reusable constructional components, which are all compatible to one another. The compatibility is comparable to a Meccano® or LEGO® toy building set: the components are standardised so that different configurations are possible by adding/removing/reassembling the components. A generating system is created with a minimum number of basic elements (per construction kit) and a set of combination rules. The combination of this limited number of basic elements leads to more complex entities. The connections between the elements and components can be undone, so that different configurations are possible with the same set of basic elements [HENROTAY, 2008].

The HVDA provides two tools: the development of a *generating form and dimensioning system* and *design catalogues* [PADUART, 2012].

Any basic element can be composed of *basic forms*, with *basic dimensions*. The basic forms can be reduced to the square, its diagonals and the inscribed circle. To enable compatibility of the elements and components, the measurements of the elements need to be defined on the same matemathical sequence, which is 2^n for the HVDA. The basic dimensions are obtained by doubling or halving the value of a basic unit. This fractal model can be applied to linear, planar and volumetric elements (see Figure 1.11 and Figure 1.12) [HENROTAY, 2008]. The fractal dimensioning system, using a single operator (divide or multiply by two), makes it possible to connect the elements within a modular system, theoretically avoiding problems at the intersections of the gridlines [DEBACKER, 2009].

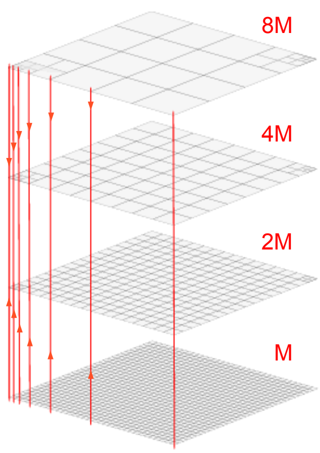


Figure 1.11: Fractal model, source: [DEBACKER, 2009, p48]

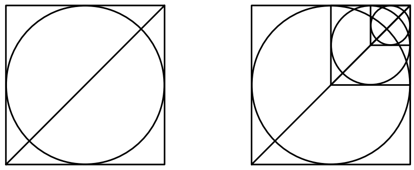


Figure 1.12: fractal model, basic forms, based on [HENROTAY, 2008, p 121], [HENDRICKX & VANWALLEGHEM, 2002, p8]

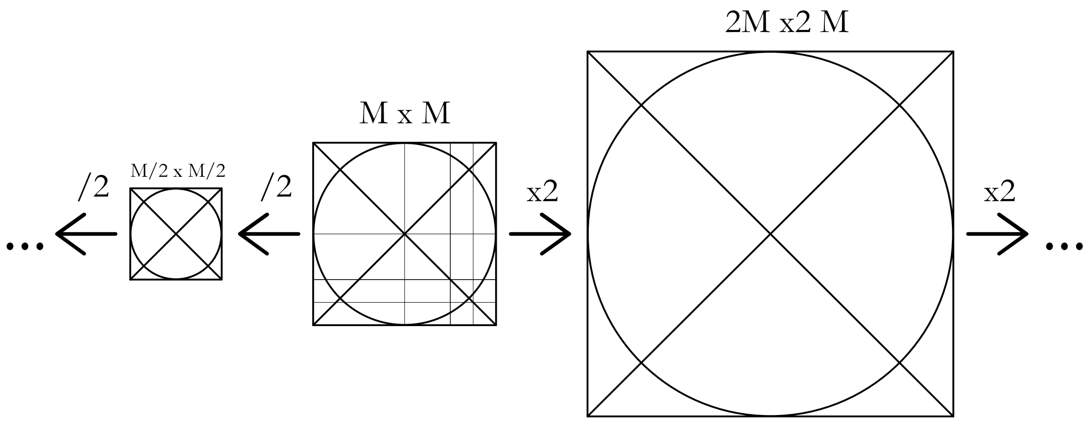


Figure 1.13: Fractal model, dimensioning, departing from 10 cm, based on [HENROTAY, 2008, p 121], [HENDRICKX & VANWALLEGHEM, 2002, p8] and [PADUART, 2012, p 56]

The solution for nodes joining the basic elements are illustrated in Figure 1.14 and Figure 1.15. The challenge is the integration of tolerances required by the construction industry.

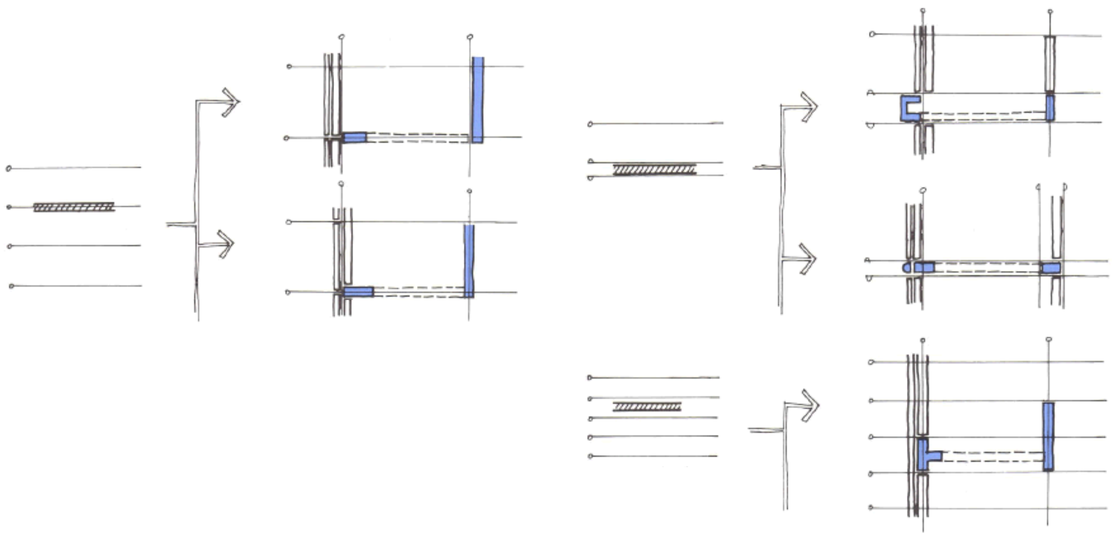


Figure 1.14: Integration of nodes in the grid, source: [HENROTAY, 2008, p117]

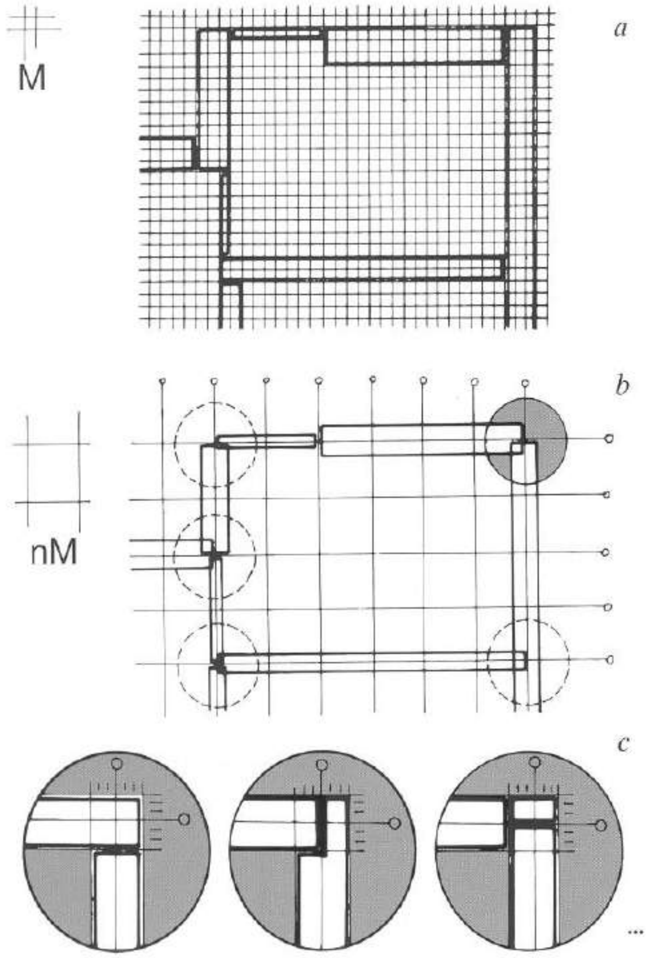


Figure 1.15: Nodes, Source: [DE TROYER, 2002b, p8]

For making the connection of basic elements possible, standardisation rules are necessary. Theoretical design catalogues can form a basis for a form of practical catalogue of elements with the according properties [PADUART, 2012].

The HVDA approach departs from basic forms and dimensions to develop basic elements. This development is based on a generative grid. The elements can be elaborated in specific catalogues for practical use.

1.2.2 Open systems approach - Durmisevic

The open systems approach, developed by Elma Durmisevic, is a dynamic top-down process. The principle departs from an open structure. Independent sub-systems can be integrated in this open structure. The aim of this system approach is to separate or decouple sub-assemblies with a different function and life cycle expectancy [DURMISEVIC, 2006, p151-152].

The systematisation of building components introduces a hierarchy of independent subsystems facilitating the maintenance and replacement of parts. The considered subsystems are not 'material entities', but are defined by the tasks they fulfil [DURMISEVIC, 2006, p152-153].

These are the principles of the open systems building approach:

- Separation of functions;
- Open assembly;
- Flexible production processes with no restriction in size and shape;
- Standardisation on sub-assembly level, which connect the use of small sized components to mass production.

The main aspects of open systems are accessibility, variation, reuse, replacement, reconfiguration and recycling. The functional, technical and physical decomposition are necessary for a dynamic system [DURMISEVIC, 2006, p153-155].

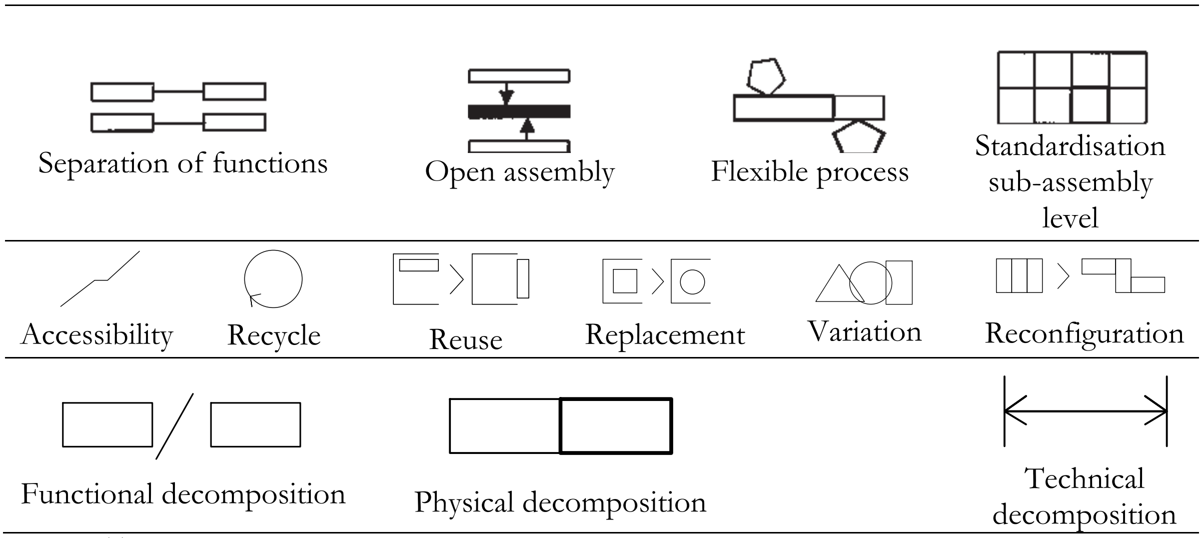


Table 1.7: Principles and concepts Open Systems Building, based on [DURMISEVIC, 2006, p153]

1.2.3 Industrial, Flexible and Demountable – De Troyer and Kenis

The industrial, flexible and demountable building approach can also be considered on the component level, since it considers the possibility of total disassembly of the building into its components. The same principles as illustrated in paragraph 1.1.5 can be applied to components.

1.2.4 Summary: component level

The summary of the component design approaches discussed in this paragraph, is illustrated in Table 1.8.

DfDe	**HVDA** *Hendrickx, Vanwalleghem* (2002)	Basic elements/forms/dimensions → fractal grid Design catalogues
	Open systems *Durmisevic* (2006)	Open structure + independent sub-systems
	IFD *De Troyer, Kenis* (2003)	Modulation: mountable, prefab

Table 1.8: Summary DfDe approaches on the component level

The HVDA approach defines basic elements with a fractal grid or generating form and dimensioning system and in design catalogues. The Open Systems approach considers an open structure with independent sub-systems. The IFD approach uses prefab components, which are demountable thanks to dry jointing.

This section discussed design for deconstruction through the HVDA, the Open systems approach and IFD projects on the component level. The next section will deepen the material level with a design approach within the design for dismantling strategy.

1.3 The material level: design for dismantling

Following the design for dismantling strategy, building materials should easily be separated according to their waste or reinvestment treatment. After selection technical material can be recycled – downcycling should be avoided. Biodegradable material can be brought back into the natural cycle. This will be explained in the Cradle to Cradle (C2C) paradigm.

1.3.1 Cradle to Cradle approach – McDonough and Braungart

William McDonough and Michael Braungart reinvented the industrial process in "Cradle to Cradle: Remaking the way we make things". The main idea is the loop closure of material and product life cycles. The paradigm departs from a positive attitude aiming to increase the ecological gain. This positive message motivates more industries towards sustainable material management than the negative idea of 'decreasing our waste', which they summarise as "*Less bad is no* good" [Int. BECKERS, 2012], [BRAUNGART & MCDONOUGH, 2002].
Two spheres exist in man-made materials: the biosphere, where natural materials are completely biodegradable, and the technosphere, where the non-natural materials can be recycled or even 'up'-cycled [BRAUNGART & MCDONOUGH, 2002].

Figure 1.16: Biosphere and technosphere, source: [LE ROY & STOUTHUYSEN, 2009, p 10]

The Cradle to Cradle concept is inspired by nature. The three 'Cradle to Cradle principles' are deducted from nature:

- "*Waste equals food*": Every product or material waste is food for another system or product. Life cycles have no endpoint, but are followed by new life cycles. Materials are not 'downcycled'.
- "*Use renewable energy*": In nature, the sun is our primar source of energy.
- "*Create diversity*": Nature is composed of a multitude of "solution"; each of them plays a role in the bigger eco system.

The eco-effectiveness is a crucial notion: materials should not only have an ecological added value, but also an economic and societal positive impact [BRAUNGART & MCDONOUGH, 2002], [VANDENBROUCKE, 2011, lexicon], [DEBACKER, 2009, p342].

Note that Cradle to Cradle is not only a four-dimensional design approach on the material level. The guiding principles are also applicable on the building level [BRAUNGART & MCDONOUGH, charter]. However, a 100 % Cradle to Cradle building does not yet exist.

The Openbare Vlaamse Afvalstoffenmaatschappij (OVAM) (English: Public Flemish Waste Company) is thinking about a way to use materials in the most efficient and ecological way. Instead of managing waste, they try to look at the source to look how to use materials efficiently, in order to close the loop before waste appears. Instead of calling it "sustainable waste management", they talk about "sustainable material management" [OVAM, 2012]. The OVAM consequently implements the positive message from the Cradle to Cradle paradigm: instead of decreasing waste ("less bad"), they aim at reviewing a sustainable resource management ("good").

1.3.2 Summary: material level

In design for dismantling, the separation of materials is possible due to the recycling of technical materials or composting of biodegradable materials. The main design approach on material level is the Cradle to Cradle paradigm. Life Cycle Assessment (LCA) can evaluate the four-dimensional aspect of materials and will be discussed in the next paragraph. The Openbare Vlaamse Afvalstoffenmaatschappij (OVAM) is looking for means to manage material resources in a sustainable way.

1.4 Application examples

Although a complete existing building combining different four-dimensional approaches is difficult to find, several applications are already developed. Two examples are illustrated in this section.

1.4.1 Application – Henrotay's shelter for disaster relief (HVDA)

Henrotay [2008] applied the combination of basic components to shelters for disaster relief. Following the HVDA principle she designed a minimum of basic elements. The linear and planar elements could then be connected to each other in different configurations [HENROTAY, 2008]. The principles and basic elements are illustrated in the conceptual drawing below (Figure 1.17) and in the representation of the linear elements and their connections (Figure 1.18).

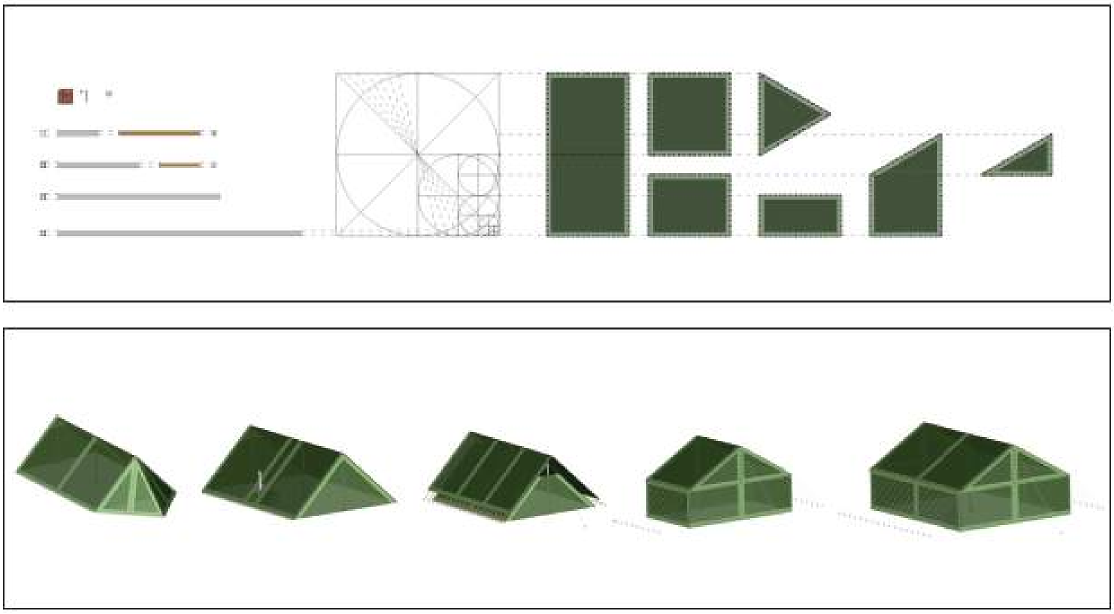
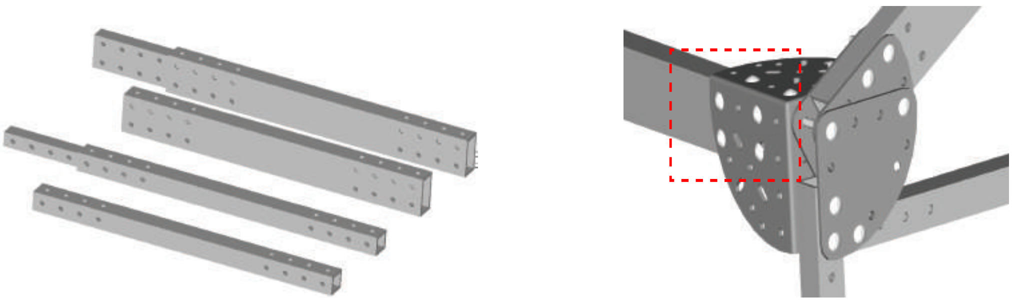


Figure 1.17: Construction systems and HENROTAY's emergency shelter kits, source: [DEBACKER, 2009, p 42]



(a) (b)

Figure 1.18: (a) Linear elements of the shelter kit [HENROTAY, 2008, P 419]; (b) Connection elements of the shelter for disaster relief, source: [HENROTAY, 2008, p 424]

1.4.2 Application – Debacker's PSO kit (HVDA & C2C)

Debacker [2009] worked on the structural design and environmental load assessment of multi-use construction kits. He designed temporary constructions for peace supporting operations (PSO). These PSO kits consist of versatile and compatible (sub)components that are combined in different configurations for various and diverse applications (inter alia a container for transport or storage of the elements). He also works with a minimum number of basic elements. The construction kit is composed of bearing frames and girders, enclosing or dividing panels and dry and reusable connections [DEBACKER, 2009].

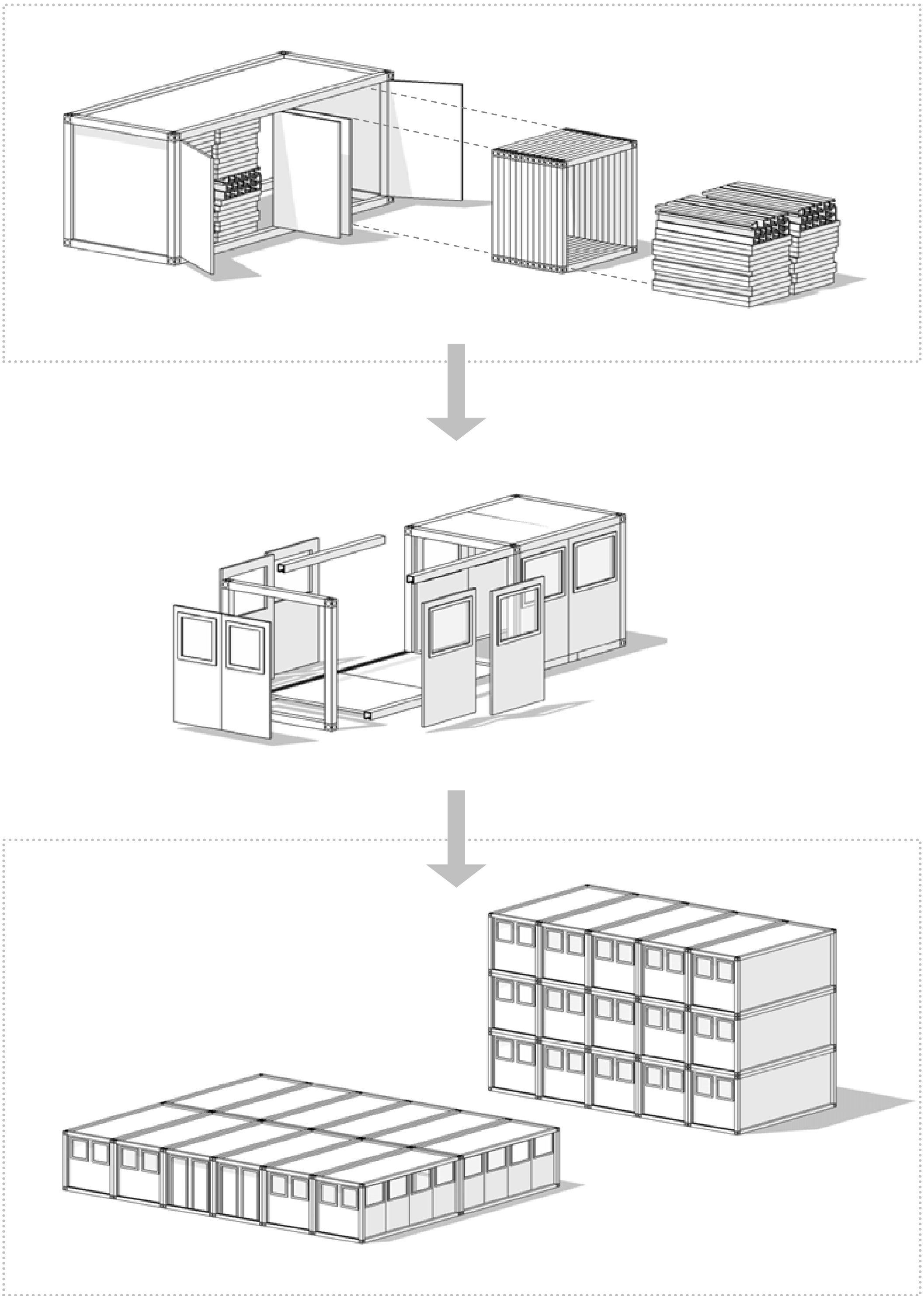


Figure 1.19: Conceptual drawing of multi-use construction kit, source: [DEBACKER, 2009, p118]

The PSO kits can be extended to multi-use construction (MUC) kits, illustrated in Figure 1.19. The HVDA is consequently not only used for disaster relief and humanitarian situations.

1.5 Life Cycles of the three levels – Debacker

The three levels discussed above – building, component, material – come together during the use of the building. However they are separate before the construction and dismantled afterwards [DEBACKER, 2012]. Debacker defined seven (plus one) ‘paths’ that can be followed after the use of a construction [DEBACKER et al, 2007b, p1-2], [DEBACKER, 2009]:

- Path I. *Land filling*. Components are buried, which costs energy (for transport and burying) and causes water and soil pollution or erosion.
- Path Ibis. *Composting*. Regenerate new organic materials by assimilating biodegradable materials.
- Path II. *Combustion*. Components are burned, which creates ashes and greenhouse emissions, but also recovered heat.
- Path III. *Feedstock recycling*. Sorted components are converted into building material feedstock, which demands a high amount of energy (and produces green house gasses).
- Path IV. *Material recycling*. Separated components become building materials, which also demands a lot of energy (and produces green house gasses).
- Path V. *Reuse of components*. Sorted components are used as the same components in another configuration, if the maintenance procedures are cheap and not too labour-intensive.
- Path VI. *Renovation or restoration of the artefact*. The renovation or restoration involves the implementation of a small amount of new elements.
- Path VII. *Reuse of the artefact*. The artefact undergoes only minor maintenance operations, but remains standing.

[DEBACKER et al, 2007b, p2-3]

Path I. *Land filling.* Path Ibis. *Composting.* Path II. *Combustion.*	(Partially) disassembled or demolished	Components/materials out of cycle
Path III. *Feedstock recycling.* Path IV. *Material recycling.* Path V. *Reuse of components.*		Components/materials receive second life
Path VI. *Renovation/restoration artefact.* Path VII. *Reuse of the artefact.*	Building remains standing	

Table 1.9: Seven Paths after dismantling of the building, based on [DEBACKER, 20009, p18]

In Figure 1.20, Debacker [2009] illustrates the life cycle model.

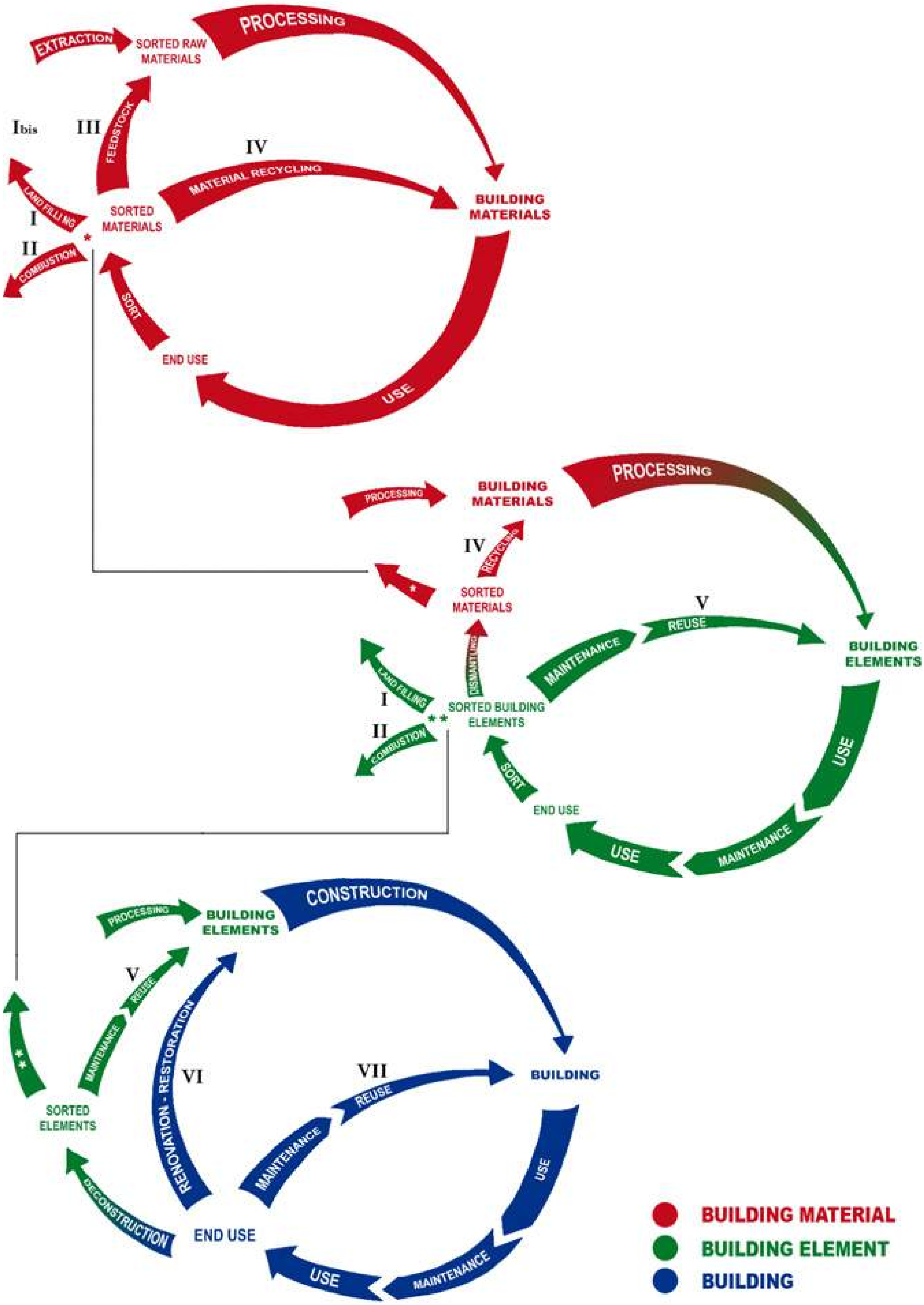


Figure 1.20: Life cycle model of building material, building component (element) and building, source: [DE BACKER, 2009, p 20]

1.6 *Discussion of the 4D design approaches – goals, ideas, tools*

1.6.1 Comparative analysis

Table 1.10 summarizes the characteristics of the 4D design approaches. These approaches are grouped in design strategies. The approaches working on the building level are brought under the *design for versatility* strategy (Versatile buildings, mainly industrial) and the *design for adaptability* strategy (SAR/OB, the layers of Leupen, for residential buildings). The Open Systems approach however is an application of *design for adaptability* (building level) as well as *design for deconstruction* (component level). The *design for deconstruction* strategy assembles also the IFD concept and HVDA. IFD buildings are defined by their components and the building itself; HVDA projects are defined by the components and materials. Finally, the Cradle to Cradle paradigm is mainly working on the material level in the *design for dismantling* strategy.

	Goal	*Level*	*Design Strategy**	Main idea	Design Tools or Principles
Versatile buildings	Little radical adjustments[10]	*Buildings, industrial*	*DfV*	Polyvalent building, flexibility	Flexible design
SAR/OB	Participation of dwellers into design process	*Buildings, residential*	*DfA*	Support and Infill	▪ Support & Infill ▪ Modular coordination ▪ Zone and margins
Leupen	Changeable dwellings proceeding from the permanent	*Buildings, residential*	*DfA*	Frame and generic space	▪ 5 layers ▪ Disconnection of the layers ▪ Excision
IFD	Participation of the individual and the community	*Buildings / components*	*DfDe*	Modulation of (de-) mountable prefab components	▪ Industral, user-oriented ▪ Support & Infill ▪ Flexibility: modulation & grids ▪ Freedom of choices ▪ Demountable joints/nodes
HVDA	Dynamic artefacts supporting individual, social, environmental and economic changes	*Components / materials*	*DfDe*	Compatibility (construction kits with basic elements)	▪ Generating grid (basic shape and basic dimensions) ▪ Design catalogues

[10] Not every versatile building is designed with the intetion to change in the future, but these (often industrial) buildings posess this quality.

Open Systems	Dynamic top-down integration of life cycle expectancy differences	*Buildings / components*	*DfA / DfDe*	Open structure + independent sub-systems	▪ Separation of functions ▪ Open assembly ▪ Flexible production processes ▪ Standardisation on sub-assembly level
C2C	Positive impact: eco-effectiveness	*Materials*	*DfDi*	Inspired by nature	▪ Waste equals food ▪ Use renewable energy ▪ Create diversity

**DfV = Design for Versatility; DfA = Design for Adaptability; DfDe = Design for Deconstruction; DfDi = Design for Dismantling*

Table 1.10: Summary of 4D design approaches, based on [DEBACKER, 2009, p 62] and expanded by the author

A lot of overlaps are perceptible. In the goals for example, the SAR/OB and IFD projects both accentuate the participation of the individual infill and the collective support, which also sets the basis for the HVDA. The overlaps are also translated in the design tools and principles, as a modular coordination grid is a recurrent design tool (modular coordination for SAR/OB, modulation & grids for IFD, generating grid for HVDA, standardisation for Open Systems). Another overlap can be observed in the ideas: support and infill of SAR/OB and IFD is comparable to the concept of "frame and generic space" defined by Leupen or the concept of "open structure and independent sub-systems" from Open Systems.

Next to these overlaps and comparisons, combinations of design tools from different design approaches can potentially be developed. For example, the design catalogues of the HVDA can take the biosphere and technosphere principles of the Cradle to Cradle paradigm as a starting point.

On the opposite, some approaches have divergent goals. The versatile buildings aim at little radical adjustments, where the HVDA approach for example supports dynamic artefacts enhancing changes on a social, environmental and economic point of view. However, they both result in adaptable architecture.

An important factor, which will be discussed in chapter 5, is the detailing. The interactions between different levels are only possible if the connections are properly designed in order to enable dismantling and deconstruction.

The most important conclusion, when looking at the issues and opportunities of each existing 4D approach and the interaction between different scale levels, a clear overlap exists. The reuse on all scale levels, researched through a design case study in chapter 4 and 5, is therefore a simplification of the discussed approaches of this chapter.

1.6.2 Synthesis

In this paragraph, a synthesis of the overlapping design tools and principles, listed in Table 1.11, will lead to a simplified total design approach, illustrated in Figure 1.21. The recurrent 4D design principles and tools are for example "support & infill", "modulation and grids" and "assembly sequences". Through all levels, detailing remains a key factor to 4D design.

DfV/A		*DfDe*	*DfDi*
Versatile			
SAR/OB			
Support & infill	Modular coordination		
Collective - individual			
Leupen			
Frame & generic space			
	IFD		
	Modulation & grids		
		HVDA	
		Generative grid	
		Design catalogue	
		Open Systems	
		Assembly sequences	
			C2C
			Waste = food
			Biosphere/technosphere

Table 1.11: Synthesis of overlaps in 4D design strategies

The interactions between the building level, the component level and the material level integrate the overlapping 4D design ideas. The building leads to a frame and a generic space, wherein a generative grid can be integrated, based on the existing building measures. Departing from this grid, the components, composed of basic elements, are designed while selecting materials, which can be brought back in the natural or technological cycle. The connections are designed and detailed to create adaptable components, materials and consequently buildings.

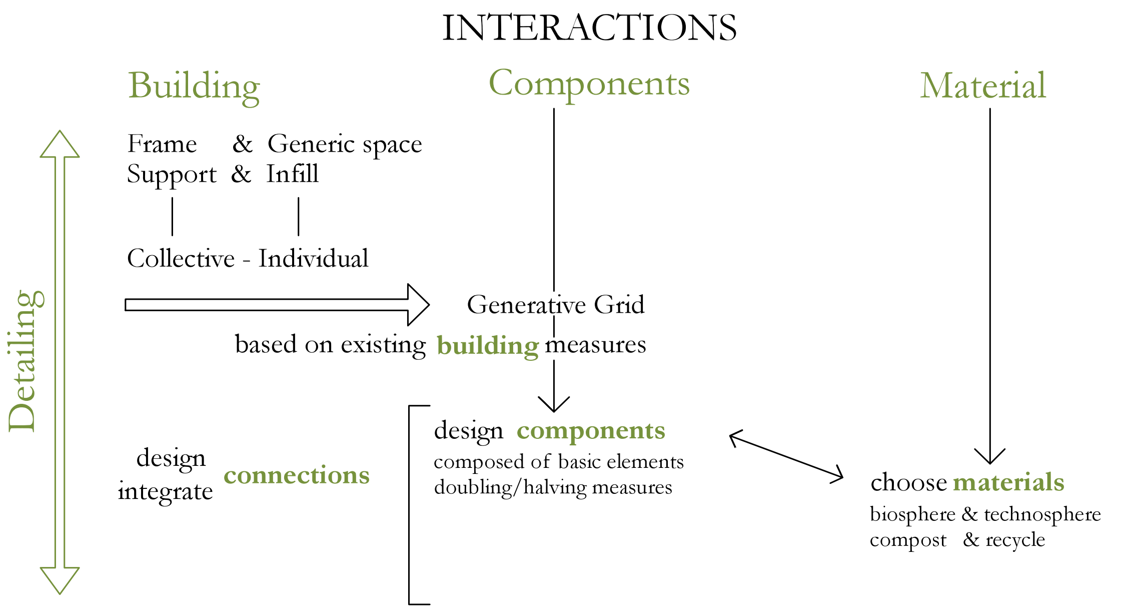


Figure 1.21: Synthesis of 4D design

2. Typology

"Nothing, in any genre, comes from nothing, and this must apply to all of the inventions of man." – Quatremère de Quincy [DE ZEEUW et al, 1997]

In this chapter, an analysis of various parameters (functions, age-groups, material combinations and compositions, free-standing walls, structures) will permit the definitions of types. The occurrence per type is listed, based on the existing definitions, such as SuFiQuaD (Sustainability, Financial and Quality evaluation of Dwelling types) [ALLACKER et al, 2008]. The statistical data used for this typology are focused on the Brussels Capital Region and Flanders. The resulting types are therefore context-specific, but can also be generalised with new data to context-independent types.

2.1 Parameters

Various parameters can be considered when defining a building typology. These parameters are abstraction of building characteristics that will allow the classification of these buildings into different types. The resulting analytical typology will enable us to compare different buildings to each other. Based on the occurrence of the types, a generative typology can be developed to offer designers a standard approach to generate a transformable design.

The relevant parameters are listed in Table 2.1. The first parameter is the building's **function**. Within the scope of this dissertation, only the residential function is studied. This focus on dwellings is pertinent, since 85% of all buildings in Belgium are residential [STATISTICS BELGIUM].
The construction methods, used materials and building compositions change according to the construction period. Therefore, the **age** is an important factor, especially when analysing the renovation of buildings. The division in different construction periods shown in Table 2.1 is based on [ALLACKER, 2010], [ALLACKER et al, 2011]. The oldest houses, build before 1945, lead to the highest life cycle costs if no renovation is undertaken [ALLACKER et al, 2012]. Before the end of World War II, buildings were not insulated. After 1945, the postwar economic boom led to new construction methods and philosophies. Another drastic change in conception and construction is noticeable in the 1970s, explained by the economic recession, particularly increasing oil prices, leading to more energy-efficiently and –conscient building. Finally, the contemporary buildings are more and more defined by new needs and environmental and financial sensibilisation. Also the social awareness becomes more important, but is not dominant.
Since the interactions between buildings, components and materials are analysed, it is evident that properties of the **materials** that were used, are taken into account. Therefore, the way they are assembled, combined and composed are important as well.
The **structure** tranfers all loads to the foundation and is consequently an important part of the building. However the insulation and finishing materials will have a bigger impact on the life cycle environmental cost in renovation cases [ALLACKER et al, 2012]. This can easily be explained by a longer lifespan of the structure, which remains with little changes in most of the renovation cases.
Next to this, the **size** and **type of occupants** define different types. Buildings with ample floor space offer other opportunities than those with little, for example. Owners and tenants do not have the same approach and rights concerning the renovation of their houses. Moreover, the renewal of **technical services** is necessary in certain cases. This is

strongly linked to the age of the building. Furthermore the **space plan** of the building will define different types. A spacious loft offers other possibilities than an appartment divided in rooms by massonery walls.
Walls demand a different approach when they are external, free-standing or when they are division walls between two dwellings. This finally leads to a division in **dwelling types** such as free-standing, semi-detached or terraced houses and high or low apartments.

Function	*Residential* Commercial Offices Education Recreation Industrial	Private, Social, etc.
Construction period (Age)	*Different construction periods*	<1919 1919 – 1945 (WW) 1945 – 1970 1970 – 1990 1990 – contemporary
Material	Material combinations	
Structure	Concrete Masonry Metallic Wooden Combinations	Reinforced concrete
Size	Surface, Height	
Occupancy	Ownership / tenancy	
Technical services	Space heating Domestic hot water Ventilation Cooling Lighting etc.	Production, distribution, emission, controlling, type
Space plan	Rooms, box-in-box etc.	
Dwelling type	Houses Apartments	Freestanding, semi-detached, terraced High, Low, Lofts, Flats, etc.

Table 2.1: Defining Parameters (first column: general parameter, second: different options per parameter, third: specific division of the options)

2.2 Typological analysis according to construction period – Blum and Gruhler

In "*Typologies of the built environment – An approach for inventory, benchmarking and monitoring towards sustainability*", Blum and Gruhler define a division in construction periods (see Figure 2.1). They differentiate houses for one or two families from the multifamily housing [BLUM & GHRULER, 2009]. This example is, as will be seen in the next paragraph, similar to the housing typology in Belgium.

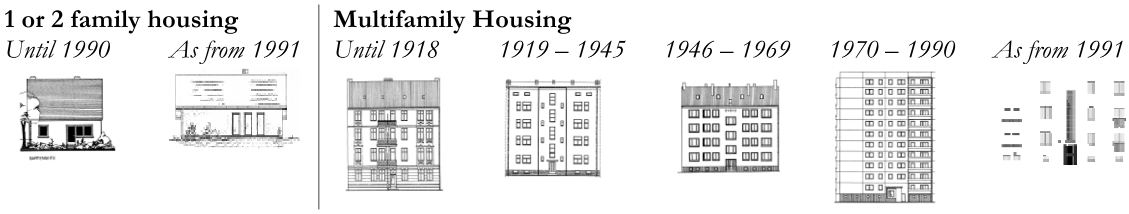


Figure 2.1: Construction periods [BLUM, 2009, p 3], with reference building type

In Table 2.2, the relation between urban structures and building types (listed in Figure 2.1) is shown: for example, a one family home built before 1990 is more likely to be found in a context of detached and semi-detached houses or in a neighbourhood of terraced houses with a garden yard, rather than in a urban structure of enclosed blocks. We can observe that a distinction is made between houses for one or two families and multifamily housing. The detached, semi-detached and terraced houses are used for one or two families, whereas the enclosed blocks, linear developments, open structure apartments and partially enclosed low density blocks are multifamily housings. Linear developments are most common in the period between 1919 and 1969, whereas the open structure apartment blocks have increased in number since the 1970s.

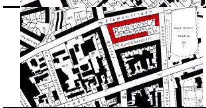
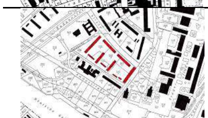
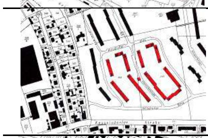
		1/2 Family		*Multi Family*				
		Until 1990	*As from 1991*	*Until 1918*	*1919 – 1945*	*1946 – 1969*	*1970 – 1990*	*As from 1991*
	Detached and semi-detached (single / two families' homes)	■	■					
	Terraced houses with garden yard (single / two families' homes)	■	■					
	Enclosed Blocks			■				■
	Linear developments with different density				■	■		■
	Open structure apartment blocks						■	■
	Partially enclosed low density blocks			■				■
	Heterogeneous open developments	■	■	■				■

Table 2.2: Relation Urban Structures and related Building Types [BLUM, 2009, p 3]

2.3 *Dwelling type – SuFiQuaD*

The research projectSuFiQuaD (Sustainability, Financial and Quality evaluation of Dwelling types) investigated the Belgian building stock in order to pave the way towards sustainable dwellings. The research is part of the Science for a Sustainable Development (SSD), a collaboration between the ASRO department of the Katholieke Universiteit Leuven, the Belgian Building Research Institute (BBRI) and the Flemish Institute for Technical Research (VITO). SuFiQuaD selected representative dwelling types in Belgium. Based on statistics and literature study, they listed the characteristics of the building stock in the Flanders, the Walloon Region and in the Brussels Capital Region. The common parameters in different typological studies of dwellings were summarised as follows:

- *Type*: freestanding houses, semi-detached houses, terraced houses, apartments;
- *Age*: different construction periods exist such as the pre-war period, between the two world wars, 1946-1960, 1961-1970, 1971-1980, 1981-1990, and 1990-now.
- *Size*: adaptability also depends on the total surface or number of rooms;
- Characteristics of the *occupants*: the ratio ownership / tenancy is an influencing factor for possibilities in reconstruction.

Other aspects are the needs for renovation, the technical infrastructure and the materials (especially insulation) [ALLACKER et al, 2008, p 10-12].
Table 2.3 summarizes the most important parameters in the research of SuFiQuaD.

	<1919	*1919-1945: WW*	*1945-1960*	*1960*	*>1970*
Freestanding house	Rural	Villages			Within town surroundings
Terraced house	Type 'mansion'	Towns (working class)			Social dwellings
Semi-detached house			Within agglomeration		
Apartment				Within agglomeration	Small, social dwelling

Table 2.3: Typologies (based on [ALLACKER et al, 2008])

2.3.1 Housing stock in the Brussels Capital Region

In "Technisch-economische analyse van de rendabiliteit van energiebesparende maatregelen" (i.e. technical-economical analysis of the profitability of energy saving measures) in the Brussels Capital Region, a difference is made between terraced houses and apartments for the existing building stock. The apartments are divided in large and small buildings with smaller and larger flats. Within each typology, the analysis considers newly built separated from the renovated dwellings [DE CONINCK & VERBEEK, 2006].

Statistical data of the housing stock in the Brussels Capital Region is illustrated in Table 2.4. To understand the names of the different types, the legend is given below. The table gives the occurrence of different types, ordered in four categories: freestanding houses, semi-detached dwellings, terraced houses and flats. A percentage is stated for the most recurrent construction period and surfaces for each category. The results show that flats are the most common dwelling type. The flats (f) between 1919 and 1970 (b2-b3-b4) are the most representative. The surfaces are mostly around 55 – 84 m2 (o3).

Brussels Capital Region							
Top 5 freestanding		*Top 5 semi-detached*		*Top 5 terraced*		*Top 5 flats*	
%	Type	%	Type	%	Type	%	Type
0,1120%	o-b3-o3	0,3566%	h-b3-o3	3,5513%	g-b1-o3	4,9164%	f-b2-o3
0,0954%	o-b2-o3	0,3283%	h-b2-o3	2,5346%	g-b1-o2	3,8994%	f-b3-o3
0,0799%	o-b3-o2	0,2545%	h-b3-o2	2,4171%	g-b1-o4	3,5089%	f-b2-o2
0,0762%	o-b3-o4	0,2427%	h-b3-o4	2,3460%	g-b2-o3	3,3463%	f-b2-o4
0,0681%	o-b2-o2	0,2343%	h-b2-o2	1,7048%	g-b1-o1	3,1613%	f-b4-o3
Sum: 33,2%							

Legend Types:

o: freestanding	*b1*: <1919	*o1*: <35 m^2
h: semi-detached	*b2*: 1919-1945	*o2*: 35-54 m^2
g: terraced	*b3*: 1946-1961	*o3*: 55-84 m^2
f: flat	*b4*: 1962-1970	*o4*: 85-104 m^2
	b5: 1971-1989	*o5*: 105-125 m^2
	b6: 1981-1990	*o6*: >135 m^2
	b7:1991-1995	
	b8: 1996-2001	
	b9: 2002-2007	

Table 2.4: Top 5 dwelling types in Brussels Capital Region, based on cross-relation between dwelling type, age and surface [ALLACKER et al, 2008, p 22]

The equivalent data are also available for the Flanders, the Walloon Region and Belgium in [ALLACKER et al, 2008]. To give an idea of the differences between metropolitan and general typologies, we can compare statistical data from Belgium with data from the Brussels Capital Region, in Figure 2.2.

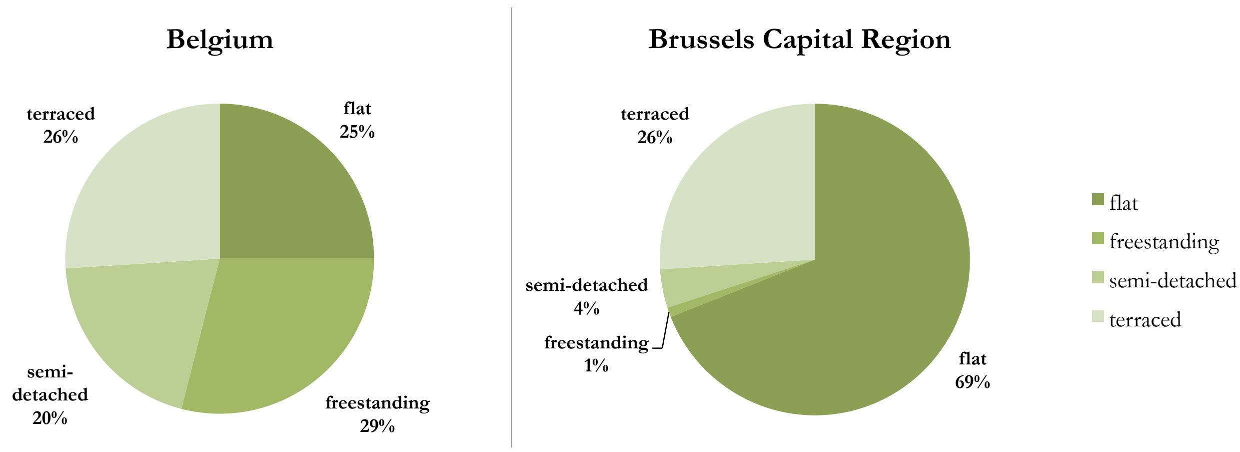


Figure 2.2: Distribution of dwelling types according to region [ALLACKER et al, 2008, p 23]

The comparison between the distribution of dwelling types in Belgium and Brussels shows, as expected, that apartments are much more common in the capital than in the rest of Belgium. A quarter of the dwelling types are terraced houses, in both cases.
In the Brussels city, the most represented dwelling types are single housing units within a multi-residential building (flats). For the single-family houses, the terraced houses are the most common dwelling type.

2.3.2 Renovation measures

In the SuFiQuaD research project, the cost reductions of renovation measures for the typologies are analysed.
In a comparative study between renovated, not renovated and newly built houses, the oldest type without renovations gave the highest life cycle costs. The renovation of these houses would give the lowest (environmental and financial) life cycle costs. Renovation of the buildings from the period between 1971 and 1990 would also lead to a reduction of the environmental life cycle cost as well as the financial life cycle costs, if a prolonged lifespan of 120 years is taken into consideration [ALLACKER et al, 2012, p 4].

2.4 Building components

The different materials used for each type play a part in the adopted renovation methods. The insulation thickness differs from one construction period to another. The insulation, for example, determines the design approach for the renovation.
The structure materials, the façade composition (ventilated, prefabricated, etc.), the used materials and connections in the partitioning and internal walls, the integration of technical installation in separating floors, the roof insulation possibilities and waterproofness are all determining components for the adaptable design of a renovation of each type.

In [ALLACKER et al, 2011], two types are detailed with material used for different components, as summarized in Table 2.5.

	Terraced dwelling (<1945)	**Detached dwelling (1971-1990)**
Component	*Materials*	
Exterior wall	• Brick • Gypsum plaster • Paint	• Brick • Air cavity 3 cm + ties • Rock wool cavity insulation 2 cm • Loadbearing brick • Gypsum plaster • Acrylic paint
Windows	• Wooden frame • Single glazing • Aluminium or steel spacer	• Wooden frame • Standard double glazing • Aluminium or steel spacer
Roof	*Inclined* • Purlins • Arrises • Tile laths • Ceramic roof tiles	*Flat* • EPDM • Rock wool 6 m • PE vapour felt – glass fibre reinforced • Sloping concrete • Precast hollow slab – reinforced concrete • Gypsum plaster • Acrylic paint • XPS edge insulation

Technical installations	• Non-condensing oil boiler • Oil storage tank • Cast iron radiators • Manual valves and room thermostat • Separate hot water storage vessel	• Gas burner • Galvanized steel pipes • Circulation pump and expansion vessel • PP sanitary drainage pipes • Shallow-walled steel pipes for heat distribution • Standard panel radiators • Thermostatic valves and room thermostat

Table 2.5: Example for material use in terraced dwelling (<1945) and in detached dwelling (1971-1990) [ALLACKER et al, 2011, p 62 and p 69]

The differences in material use for the various types can be categorized by building component: façade, partitioning wall, internal wall, separating floor, roof and windows.
For the structure, most used materials are masonry, concrete and steel. For façades and windows, wood is also a recurrent construction material. Different insulation materials offer other renovation possibilities.

In older typologies (mainly free-standing, semi-detached and terraced houses), masonry will often occur. In apartments, especially post-war higher buildings, concrete will be used more. In the example of Table 2.5, differences from one type to another in insulation and material use are illustrated.

From the analysis of the material use in the reference cases for each dwelling type, a summary of the building elements is given in Table 2.6. This summary gives a general overview and does not represent a detailed construction.

Masonry, concrete, steel, wood, several insulation kinds	*<1945*	*1946-1970*	*1971-1990*	*>1990*
Structure	Masonry	Masonry Concrete	Concrete Steel	Concrete Steel Wood
Façade	No insulation Masonry	No insulation Masonry	Little insulation Concrete	Insulation (Steel) Wood
Internal and partition walls	Masonry	Masonry	Masonry Concrete	Masonry Wood
Roof	Wood	Wood	Concrete	Concrete (Steel)
Separating floor	Wood	Wood Concrete	Concrete	Concrete

Table 2.6: Material use typology

2.5 Conclusions on typological study

In this dissertation, the name '**dwelling typology**' will define the division in *freestanding* houses, *semi-detached* houses, *terraced* houses, *terraced apartments* (*low-density*), stand-alone *apartment blocks* (*high-density*) and open structure apartments or *lofts*. This simple division allows a clear difference between the types for every case.
The **age** of the dwelling is not context-independent, but crucial to the understanding of the building elements, material compositions (for example the use of asbestos) and structures (prefab, masonry, etc.). The construction period also determines the design attitude and philosophy. This factor has to be taken into consideration, in every typological study.
The '**building components** define the materials used (Table 2.6) and their combination for insulation, structure, interior walls and façades. This is a more precise way of dividing into typologies. These building components can be made of wood, concrete, metal, etc. Especially the presence and thickness of the insulation is important for renovation.
Table 2.7 shows the final proposed typologies.

The size of the dwelling will not define the typological study in this case, since it does not have a major impact on the used materials or components. An economic or feasibility study requires taking the characteristics of the occupants into account, but this is out of scope for this dissertation. Furthermore, the quality state and needs for renovation are difficult to define objectively within the scope of this dissertation and will therefore not be considered. Next to this, the present technical systems and facilities will be in function of the dwelling types, sizes, ages, etc. Moreover, the heating system is very important for energy balance, but less for sustainable material management. These parameters are taken into account for further typological studies, but are not necessary for the analysis made in this dissertation.

In the Brussels Capital Region, the most common dwelling type is an apartment, with a surface between 55 and 84 m^2 per family. The most representative construction periods are 1919 – 1945 and 1945 – 1970. In further research, terraced houses (25% of Brussels dwelling stock) and apartments (70% of Brussels dwelling stock) should be analysed first.

In this dissertation, a case study of a social housing block in the Marollen (i.e. a neighbourhood in the centre of Brussels) will illustrate the time-based design principles on the apartment typology just before the 1970s, where no insulation is present. Since apartments are the most common typology in metropolitan cities, the case is representative and will permit to focus on one of the types and analyse the application of four-dimensional design in depth.

Period			*<1945*	*1946-1970*	*1971-1990*	*>1990*
Types	**Houses**	**Freestanding**				
		Semi-detached				
		Terraced				
	Apartments	**Terraced** **Low density**				
		Blocks **High density**		**Marollen** **Brigittinnen**		
		Lofts **Open structure**				

Table 2.7: Proposed typologies and case study

3. Scenarios

"Other family compositions began to emerge in the later decades of the twentieth century. With changes in moral values and the acceptance of nonfamily unions and same-sex marriages, the definition of family was expanded." – Avi Friedman [FRIEDMAN, 2002]

3.1 Objective of defining scenarios

The aim of this chapter is to list current changes and have a better view on possible changes in urban life structures. Adaptable buildings need to respond to demographic, economic and cultural shifts in society as well as to life-cycle changes due to aging, disability or new family growth and living patterns.

Firstly, living scenarios will be developed for the present and future needs. Secondly, the scenarios will be connected to corresponding timespans in order to define the needed degree of transformability of residential buildings.

According to Friedman, adaptability can be defined as "*providing occupants with forms and means that facilitate a fit between their space needs and the constraints of their homes*" ([FRIEDMAN, 2002, p 1]). Unfortunately, the space needs are linked to changing human lifestyles whereas constraints of homes are often static. Houses designed today constitute an unchangeable physical environment with permanent boundaries. However, the evolving requirements specific to human lives demand 'life cycle' houses where spaces can adapt to, for example, the birth of children, the fact children 'leave the nest', the take-in of elderly family members or the new need of home offices [FRIEDMAN, 2002].

In fact, the housing habits of human being changed continuously since settling after our nomadic existence, when permanent walls became boundaries for our homes. In the agrarian lifestyle, different generations of a family lived in one house. After the Industrial Revolution, families moved to cities, where only one family lived in a house. After the end of the Second World War, the emergence of the automobile brought the development of the suburbs. Also, the introduction of birth control made the sizes of families decrease and consumerism changed the home life. In the end of the 20th century, the change of moral values led to a different kind of families than the classical 'working father and mother caring for the children' [FRIEDMAN, 2002].
Forecasting future space requirements and demographic evolutions is a difficult task, but it is certain that housing will need to be adaptable more than ever. Different scenarios will therefore be defined so that these can be tested in design cases.

3.2 Demographical statistics

3.2.1 Demographical statistics of the Brussels Capital Region

Before "predicting" future tendencies for space needs and family compositions, the current demography will be analysed. As base for the projections on demography in the Brussels Capital Region, [SURKYN & WILLAERT, 2008] will be used.

Firstly, Figure 3.1 and Figure 3.2 give an idea of the age group, gender and nationality that prefers to live in the capital and the evolution in the past 20 years.

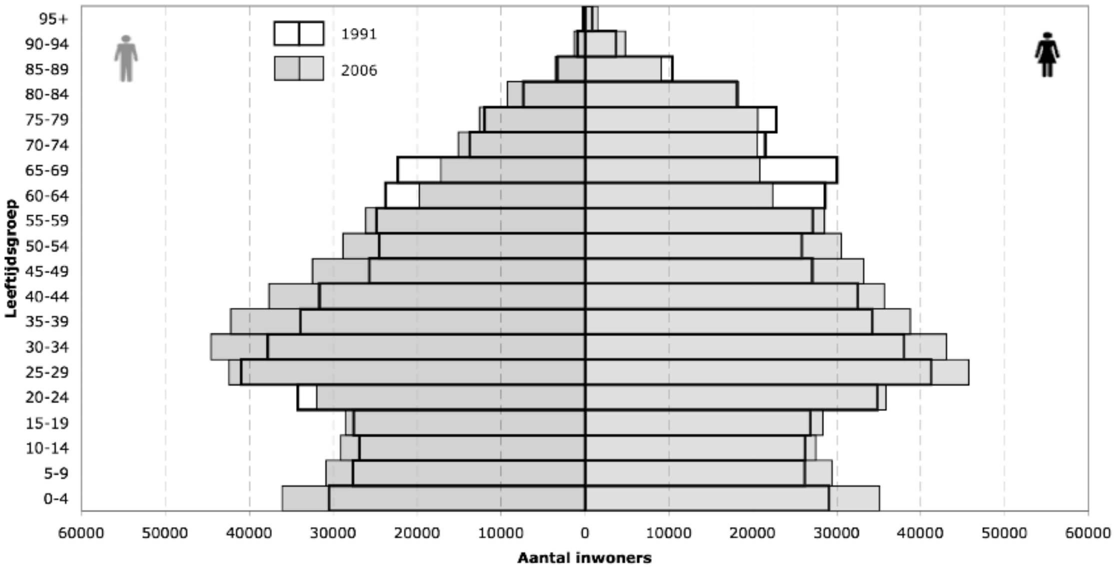


Figure 3.1: Age Pyramid, Brussels Capital Region, 1/3/1991 and 1/1/2006, *Source: Algemene Directie Statistiek en Economische Informatie, volkstelling 1991 en Rijksregister* **[SURKYN & WILLAERT, 2008, p 3]**

As shown in Figure 3.1, the *increasing population groups of Brussels are mainly young children and adults between 30 and 50 years old.* This can be explained by the tendency of non-European parents with children, which constitutes the opposite of the suburbanisation trend. We can observe that young adults in the peak between 25 and 45 years old prefer to live in the capital [SURKYN & WILLAERT, 2008].

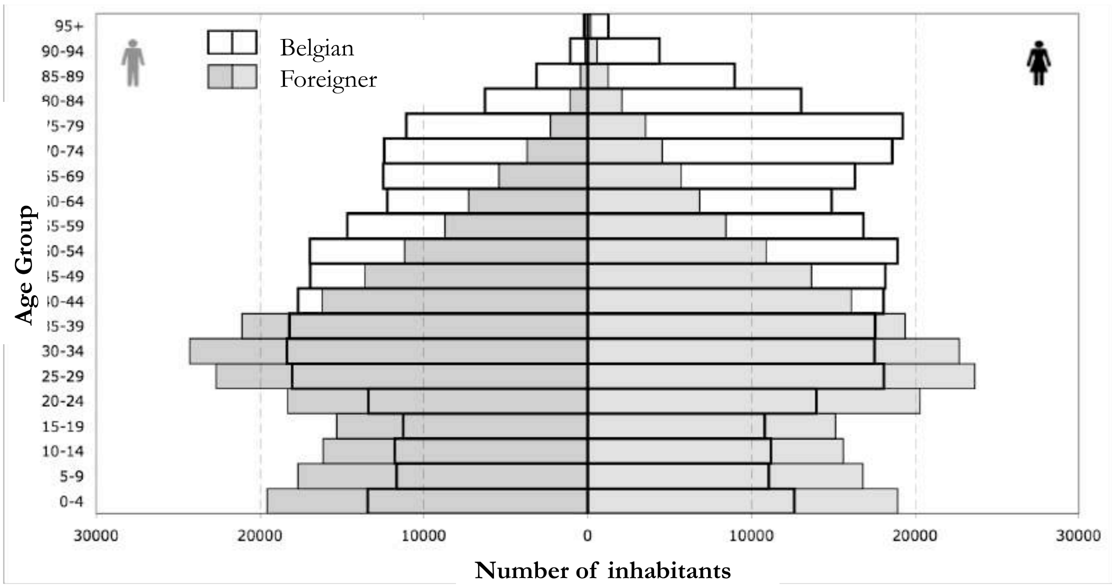


Figure 3.2: Age pyramid, Brussels Capital Region, Belgians and foreigners (current and original nationality), 1/10/2001, *Source: Algemene Directie Statistiek en Economische Informatie, volkstellingen 1991 en 2001, Rijksregister* **[SURKYN & WILLAERT, 2008, p 4]**

In Figure 3.2, we can see that *Brussels has more young foreigners than young Belgians and more old Belgians than old foreigners.* In Brussels, we can find the following division of the population [SURKYN & WILLAERT, 2008, p 4-5]:

- people under 18 years live (mainly foreigners) mostly in the zone around the town centre;
- young adults live mostly in the city centre;
- elderly people live mostly outside the city centre.

Secondly, Figure 3.3 illustrates the evolution of the demographic growth since 1988. The recent growth of the population is due to the *extern migration balance*, the *natural growth of population* and the *statistical changes* (changes in the course of a given year to the data of previous years) or register changes (from waiting register to National register). We can observe that the intern migration (from the city to the Flanders and the Walloon Region) is still important, cancelling out the foreign immigration. The peak in 2001 and 2002 is due to a regularisation of illegal immigrants [SURKYN & WILLAERT, 2008].

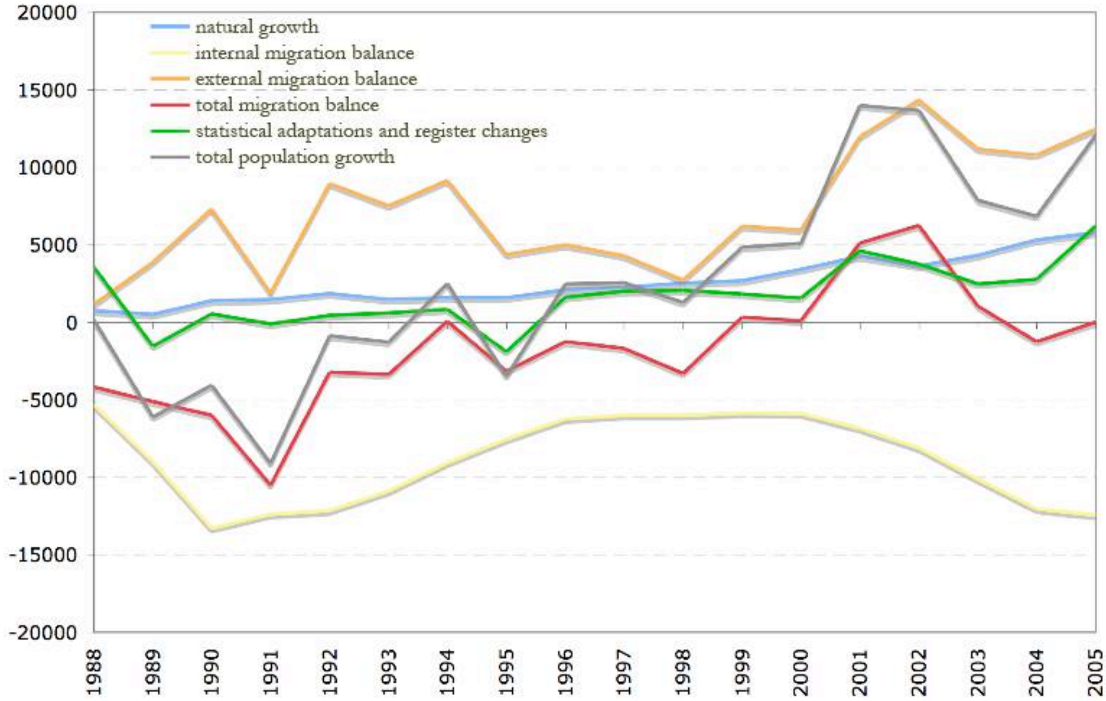


Figure 3.3: Evolution components of the population growth, Brussels Capital Region, 1988-2005, *Source: Algemene Directie Statistiek en Economische Informatie, Rijksregister* **[SURKYN & WILLAERT, 2008, p 13]**

We can conclude that, while older people tend to move to the suburbs, parents with young children are more and more settling in the city of Brussels, mainly due to the growing foreign immigration.

3.2.2 Building stock in the Brussels Capital Region compared to profile group of inhabitants

Table 3.1 compares the percentages of total dwellings by type and number of bedrooms and the percentages of 'adequate occupancies'. These adequate occupancies are based on social housing standards (i.e. one room for a couple, two children younger than 9 or two children of the same sex between 9 and 12 years old and one room per person in other cases), so that each household has a dwelling that is just sufficiently large to fit its needs. These standards are the minimum needed for decent housing [SURKYN & WILLAERT, 2008].

Type*	1		2		3		4		5+		Total	
	All dwellings	Adequately occupied	All	Adequately	All	Adequately	All	Adequately	All	Adequately	All	Adequately
O1+	1,0	1,9	2,8	1,6	5,4	2,1	4,6	0,9	4,8	0,9	18,5	7,3
O10	0,6	1,0	1,1	0,7	1,2	0,6	0,8	0,3	0,6	0,4	4,3	3,0
Oa+	1,1	2,1	1,6	0,8	0,8	0,2	0,3	0,0	0,1	0,0	3,9	3,2
Oa0	3,7	7,6	7,7	3,8	3,2	0,9	0,6	0,1	0,2	0,0	15,5	12,3
T1+	0,6	1,1	1,0	0,7	1,6	0,8	1,0	0,2	0,8	0,1	4,9	3,0
T10	1,3	2,3	0,9	0,7	0,4	0,2	0,2	0,1	0,1	0,1	2,9	3,3
Ta+	3,5	6,8	2,2	1,7	0,7	0,3	0,2	0,0	0,1	0,0	6,7	8,9
Ta0	*23,0*	*44,9*	15,6	11,9	3,8	2,0	0,6	0,2	0,1	0,0	43,2	59,0
Tot	34,8	67,6	32,9	21,9	17,2	7,1	8,3	1,8	6,8	1,7	100,0	100,0

Number of sleeping rooms in the dwelling

* O=ownership; T=tenancy; 1=one family; a=apartement;+with garden; 0= without garden

Table 3.1: Percentage of dwellings by house type and number of bedrooms: comparison between the total stock (all dwellings) and the profile of the group with a housing according to the standard of social housing (adequately occupied.), BCR, ***Source: Algemene Directie Statistiek en Economische Informatie, Algemene socio-economische enquête 2001*** **[SURKYN & WILLAERT, 2008, p 49]**

We can observe that the most recurrent dwelling is the *rental apartment of one bedroom without garden (23,0%)*, but still with ideal adequate occupancy, the *city of Brussels would need almost the double (44,9%)*. A general trend is the *strong decrease of small dwellings and an abundance of dwellings with more rooms than needed for the social housing standards*. These statistics are of course a simplification and can only be used for deducting a general trend.

3.3 Connecting scenarios and timespans

Different types of families need different housing transformations. A definition of different scenarios includes the *classical* family (married + children), the *stepfamily*, the '*travellers*' (for example employees of the European Commission in Brussels, Immigrants), the *one-person* family or the *couple*. Evolutions from one type to another should be made possible through the transformation capacity in renovation projects.

3.3.1 Existing definitions

Households

To have an idea of the composition of the population in Belgium, statistics of [BOULANGER et al, 2009] will be used. The authors defined a classification in LIFestyle PROjections (LIPRO) to evaluate eight household-types and twelve individual household positions (see Table 3.2 and 3.3).

1.	Singles
2.	Married couples without children (+ eventually other residents)
3.	Married couples with children (+ eventually other residents)
4.	Unmarried couples without children (+ eventually other residents)
5.	Unmarried couples with children (+ eventually other residents)
6.	1 parent households (+ eventually other residents)
7.	Others
8.	Collective households

Table 3.2: Household-types, based on [BOULANGER, 2009, p 73]

CMAR	Child of (with) MARied couple
CUNM	Child with UNMarried couple
CIPA	Child in a 1 Parent household
SING	SINGles
MAR0	MARried, 0 children
MAR+	MARried, plus children
UNM0	UNMarried, 0 children
UNM+	UNMarried, plus children
HIPA	Head of a 1 Parent household
NFR	Non-Family Related
OTHR	OTHeRs
COLL	Collective households

Table 3.3: Positions in households, based on [BOULANGER, 2009, p 73]

In Brussels, two opposite tendencies are observed:

- More singles, one parent households and unmarried couples with children, in case of Belgian households
- Traditional patterns with married couples with (relatively a lot of) children for the foreign households

Brussels has consequently a complex development of household patterns [BOULANGER et al, 2009].

Existing scenario definitions

A. Friedman defines possible household scenarios to state the need for designing adaptable houses. For example, young couples which buy a house, want a possibility for future expansion for the new-born children. Childless couples who work at home need separate offices. Unrelated buyers prefer a two-suite arrangement with two bathrooms. When children "leave the nest" or an elderly family member is hosted, another arrangement is needed. A higher divorce rate brings new single parent households or remarrying scenarios, etc. [FRIEDMAN, 2002].

In "*The Adaptable House – Designing Homes for Change*", A. Friedman gives an example of life-cycle changes, illustrated in Figure 3.4. In this example, the scenario start with a young couple and evolves throughout the birth of children, the departure of the children, the divorce of one of the children and the return of this child, the remarrying and second departure of this child and the death of one partner.

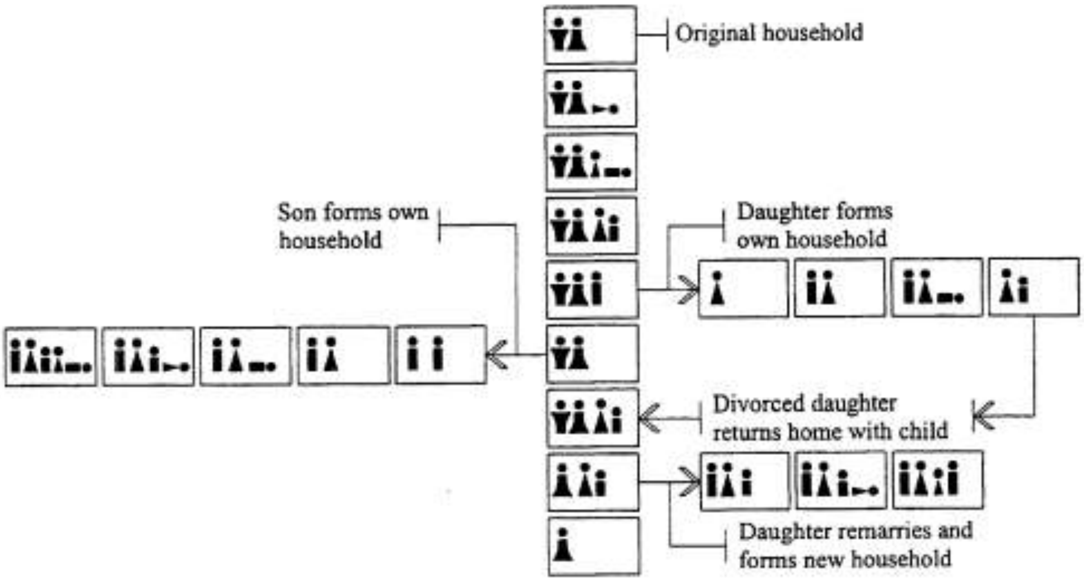
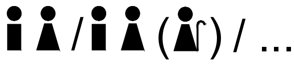
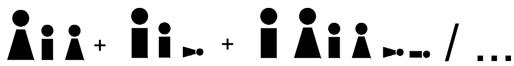
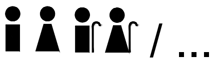


Figure 3.4: Household scenario, example [FRIEDMAN, 2002, p 6]

3.3.2 Scenarios

Based on the demographical statistics of [SURKYN & WILLAERT, 2008], the household-types specified in [BOULANGER et al, 2009] and the scenario examples of [FRIEDMAN, 2002], examples of standard scenarios will be developed in this paragraph.

The households are redefined in Table 3.4. Since the married and unmarried couples have the same needs of space, no distinction will be made.

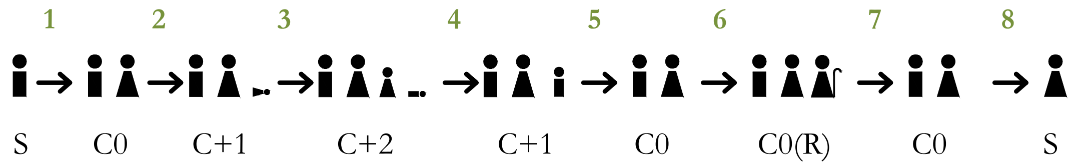
1.	S	*Singles*	
2.	C0(R)	*Couples without children (+ eventually other residents)*	
3.	C+(R)	*Couples with children (+ eventually other residents)*	
4.	1P(R)	*1 parent households (+ eventually other residents)*	
5.	COLL	*Collective households*	
6.	O	*Others households*	

* S=single; C=couple; 0=without children; +=with children; 1P = one parent, COLL = collective, O= others, (R)=eventual other residents

Table 3.4: Households

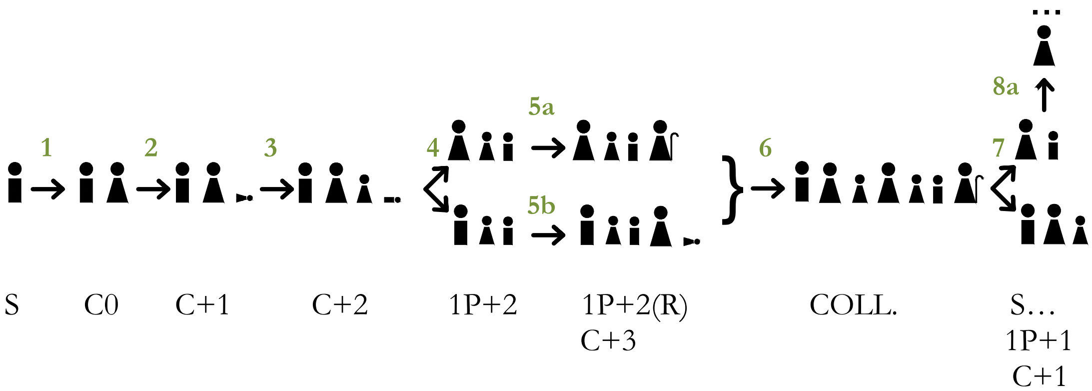
Two possible scenarios are listed below. An infinite number of scenarios are possible. However, to use them in case studies, only two have been selected: one classical and one more complex case.

Classical Scenario



1 = marriage or cohabitation
2 = first newborn child
3 = second newborn child
4 = first child leaves the nest
5 = second child leaves the nest
6 = extra resident (grandmother)
7 = decease of resident
8 = decease of husband

Complex Scenario



1 = marriage or cohabitation
2 = first newborn child
3 = second newborn child
4 = divorce
5a = elderly resident
5b = remarriage
6 = collective house for 2 families
7 = decease elderly resident and separation families
8a = first child moves out

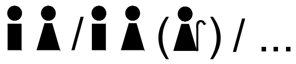
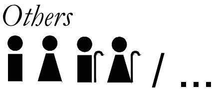
Figure 3.5: Scenarios[11]

Adaptability will support the changes in household compositions.

3.3.3 Timespans

It is interesting to connect needs and time duration to each step in a scenario. The residential needs such as number of bedrooms, bathrooms of different households are summarised in Table 3.5. Based on the statistical data in [STATISTICS BELGIUM], [BOULANGER et al, 2009] and [SURKYN & WILLAERT, 2008], various approximate timespans are given to the household types.

[11] All Figures without reference are personal drawings by the author.

Years	Abbr.	*Household type*	Rooms needed
2 – 4	S	*Singles* 	1 bedroom 1 kitchen 1 bathroom 1 toilet 1 living room (+ 1 parking)
1 – 3	C0(R)	*Couples without children* *(+ eventually other residents)* 	1 bedroom for two 1 kitchen 1 bathroom 1 toilet 1 living room (+ 1 office and/or parking + 1 bedroom for resident)
10 – 20	C+(R)	*Couples with children* *(+ eventually other residents)* 	1 bedroom for two 1 bedroom per child 1 kitchen 1 bathroom (2 if more than 2 children) 1 toilet (2 if more than 2 children) 1 living room (+ 1 office and/or parking + 1 bedroom for resident)
5 – 8	1P(R)	*1 parent households* *(+ eventually other residents)* 	2 bedrooms or more (1 room for parent + 1 room per child) 1 kitchen 1 bathroom 1 toilet 1 living room (+ 1 office and/or parking + 1 bedroom for resident)
5 – 7	COLL	*Collective households* 	1 bedroom per couple / person 1 kitchen 1 bathroom per household 1 toilet per household 1 living room per one or two households (+ office space and/or parking)
	O	*Others* 	

S=single;
C=couple; 0=without children; +=with children;
1P = one parent,
O= others,
COLL = collective,
(R)=eventual other residents

Table 3.5: Timespans and residential needs of household types

It should be noted that in the consideration above, no difference was made between renting and buying. The area, occupancy factor or rental price could be added in further research.

3.4 Social housing

The possible scenarios are numerous. In the case study analysed in the Design Studio, social dwellings are renovated. The renovation design of the apartment block will enable a mixture of different household types.

The scenarios of social housing blocks are from a different kind than classical 'family home' scenarios. The scenarios are therefore a step further in complexity, due to the complete change of family structure and the unpredictable nature of the future changes.
In Table 3.6, the residential needs are reformulated following the social housing standards [SURKYN & WILLAERT, 2008, p 49]. Timespans are dependent on the socio-economical status of the households and are therefore not connected to the household type.

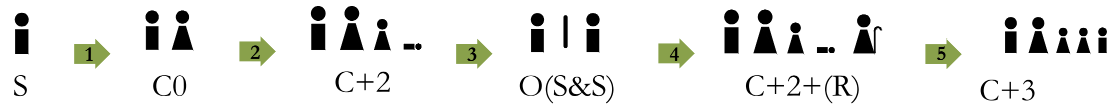
Abbr.	***Household type***	**Social housing standards**
S	*Singles* /	• 1 bedroom + 1 bathroom with toilet • 1 kitchen
C0(R)	*Couples without children* *(+ eventually other residents)* / () / ...	• 1 bedroom for two + 1 bathroom + 1 toilet • 1 living room + 1 kitchen • (1 bedroom for resident)
C+(R)	*Couples with children* *(+ eventually other residents)* / / ...	• 1 bedroom for two • 1 bedroom for 2 children <9yrs or 2 same sex children 9-12yrs or for 1 child >12yrs • 1 bathroom + 1 toilet • 1 living room + 1 kitchen • (1 bedroom for resident)
1P(R)	*1 parent households* *(+ eventually other residents)* / /...	• 1 bedroom for parent (smaller than bedroom for two) • 1 bedroom for 2 children <9yrs or 2 same sex children 9-12yrs or for 1 child >12yrs • 1 bathroom + 1 toilet • 1 living room + 1 kitchen • (1 bedroom for resident)
COLL	*Collective households* + + / ...	• 1 bedroom per couple / single person, parent • 1 bedroom for 2 same family children <9yrs or 2 same family and same sex children 9-12yrs or for 1 child >12yrs • 1 bathroom per household • 1 toilet per household • 1 kitchen per 6 persons • 1 living room per 6 persons
O	*Others* / ...	

Table 3.6: Social Housing Standards

3.5 *Example scenarios for stress tests in case study*

Next to the scenarios defined in Figure 3.5, an extra scenario with boundary conditions of social housing will be tested on the case study of the Brigittinnen in the Marollen neighbourhood. In this scenario, illustrated in Figure 3.6, rotation from one household to another is implemented. It stays an example, since the different possibilities are numerous.

Social Housing Scenario



S single 1 C0 childless couple 2 C+2 couple, 2 children 3 O (S&S) 2 single p. 4 C+2+(R) couple, 2 children, 1 elderly resident 5 C+3 couple, 3 children

Figure 3.6: Scenario Social Housing - Rotation from one household to another

This example will be elaborated in chapter 4, when the scenarios will be tested on the apartments of the case study in the Marollen.

4. Case Study "Brigittinnen"

"The renovation of residential buildings is not merely a technical task; design is also an integral and extremely important factor." – Georg Giebeler [GIEBELER, 2010, p19]

The first chapter explained the four-dimensional design strategies and approaches. The second and third chapter analysed the building typologies and life scenarios in a metropolitan context. This chapter is devoted to test the feasibility of the ideas from chapter one by combining the different levels of four-dimensional design on a case study, which represent one of the most common urban typologies, enabling transitions from one scenario to another.

In this chapter, the four-dimensional architecture is applied to a case study of the Brigittinnen apartments in the Marollen neighbourhood in Brussels, Belgium. The relations between the existing advances in four-dimensional design as discussed in the first chapter, are reconnected through building level, component level and material level. The added value of the design in this chapter is the consideration and analysis at several scales. The in-depth design of the practical case study, applied on an existing typology deals with the challenge of positively changing of the architectural heritage as well as ensuring our future environmental and social needs.

The discussed case is the renovation of a social housing apartment block in the Marollen. In this neighbourhood in Brussels various projects of social housing were developed throughout the years. Next to housing, several functions are present in the area: hospitals, schools, religious buildings, offices and recreation centres. The Brigittinnen apartment block was built in 1968 by architects Charles Van Nueten and Gaston Brunfaut in a modernistic style. The social housing complex is in charge of the Foyer of Brussels ("*Brusselse Haard*").

The Brigittinnen apartments type is 'apartments – blocks high density' and was build in the post-war period (1946-1970). In Brussels, this typology is the most common and most in need for a renovation. The building has no thermal insulation and has humidity and safety problems. Consequently, the Foyer of Brussels is asking for a deeper renovation. A façade renovation is already considered in the coming years. In this dissertation, the renovation is extended to an in-depth design enabling social mixing, adaptability and collective housing.

A dynamic re-design of the multi-storey apartment block of 1968 is necessary for the following reasons. First, the thermal and acoustic performances of such typical post-war apartments need an urgent upgrade. Furthermore, the architecture is outdated, with monotone, small and uncomfortable apartment layouts. Moreover, the flexibility of this social housing block is very low. Finally, the ignorance or prejudices about these kinds of cases often leads to demolition instead of implementing urgent renovation measures. Indeed, the load-bearing structure can be re-used instead of demolished, in order to limit demolition waste.

The building will be analysed based on a (theoretical) disassembly: which materials are used, how are they combined to components, which material is for short run and which is for long term? Each element will have a minimal and maximal lifetime.

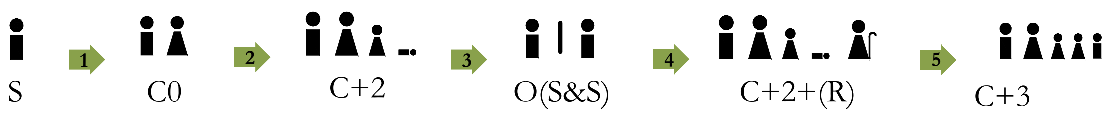
In the previous chapter, a usage scenario was developed for the case study. How can the dwellings be adapted according to the evolving living processes? The design studio will prove its efficiency through selected scenarios illustrating the evolving living process. The distilled boundary conditions of the research will be applied on the site.

The (re-)design is *not a final goal*, it is a dynamic concept, a step-by-step redesign enabling gradual changes in this renovation as well as in the future. Consequently, the aim of this chapter is to apply the relative advantages of dynamic building solutions to the case study of the Brigittinnen apartments, as this post-war apartment block is a representative existing urban building type. The social housing enables the implementation of deeper and more frequent renovations adapted to frequent changing needs.

4.1 Scenarios

The living patterns in social housing are different than in other residential buildings. Indeed, the attribution is based on certain criteria and waiting lists exist to get a social dwelling attributed.
For the purpose of this design studio, different household compositions are defined. Quick adaptations from one household type to another are required in the design.
The complete elaboration of four apartments will follow in the next sections. The scenarios that are the starting point of the apartment designs are illustrated in Table 4.1.

Social Housing Scenario



S single ➔1 C0 childless couple ➔2 C+2 couple, 2 children ➔3 O (S&S) 2 single p. ➔4 C+2+(R) couple, 2 children, 1 elderly resident ➔5 C+3 couple, 3 children

Table 4.1: Life scenarios

The scenarios are different than in a classical housing living pattern. In the case of social housing, the scenario does not simply consist of family expansion or evolution. The apartments need to be adaptable for different kinds of households, for example a single, a childless couple, a couple with two children, two single unrelated people, a couple with two children and an elderly resident and a couple with three children. These examples will all be supported by the design elaborations in this chapter.

Since the social housing renovations and adaptations to new scenarios are not related to one unique family, a regulation system is needed for the timing and impact of the renovation. The proposed system repeats a new listing of the actual needs every five years. At that moment, a renovation of two vertical strips in the building is carried out. Horizontal and flexible extension or contraction (see paragraph 4.3.1.) is made possible on these two bays, so that a solution for the changed needs can be brought every five years.

4.2 *Existing building analysis*

4.2.1 Historical context

The Brigittinnen complex is an example of the approach to cope with the hygiene problems in the Marollen neighbourhood in the sixties. In 1953, the inhabitants of the slums on the site were expropriated to build three towers of social housing. However, due to financial problems, the actual building was only one block, built 15 years later. After two declined projects, the Foyer of Brussels finally accepted the offer of Charles Van Nueten and Gaston Brunfaut for 153 households. However, due to adaptations in the road plan of Brussels, the two initial blocks were placed in L-form, to gain space. Construction of the eleven floors building started in a hurry in 1968, to take advantage of the budget for that year.

Figure 4.1: View from the topfloor on the South Tower and Brussels City

4.2.2 Urban context & master-plan

Open – Closed area

The neighbourhood consists mainly of closed building blocks. However, the zone directly around the Brigittinnen apartments is open. Figure 4.2 presents an air photo of the site (a) and a view on the building (b). We can observe railways are crossing the site, with a station located near the apartments.

(a) **(b)**

Figure 4.2: Air photo of the site, source: Google Earth (a); View on the Brigittinnen building from the Justice Court of Brussels (b)

Public – Private Area

A lot of public or semi-public spaces are present, but not always in a qualitative way. The zone around the railways is public, but crossed with streets and left without adequate urban furniture, except from the skate park above the railway tunnel. The open spaces are mainly used for recreation: a few benches to meet up at 'Recyclart'[12] (see Figure 4.3.b), a basketball field next to the Brigittinnen apartments (see Figure 4.3.c), the skate park at the highest point of the site. However, the spaces enclosed by the L-shape of the Brigittinnen building are completely abandoned (see Figure 4.3.a), as is the site on the other side of the railway.

(a) (b) (c)

Figure 4.3: Surroundings of the apartment block, space enclosed by L-shape (a), benches at Recyclart (b), Basketball field (c), source: Design Studio Master 1 VUB-ULB 2011-2012

Green spaces & Pedestrian circulation

The green spaces can be divided in two groups: trees along the streets, and parks. The parks are very small and don't show their potential. More qualitative green spaces could be developed. The pedestrian circulation is illustrated in Figure 4.4.

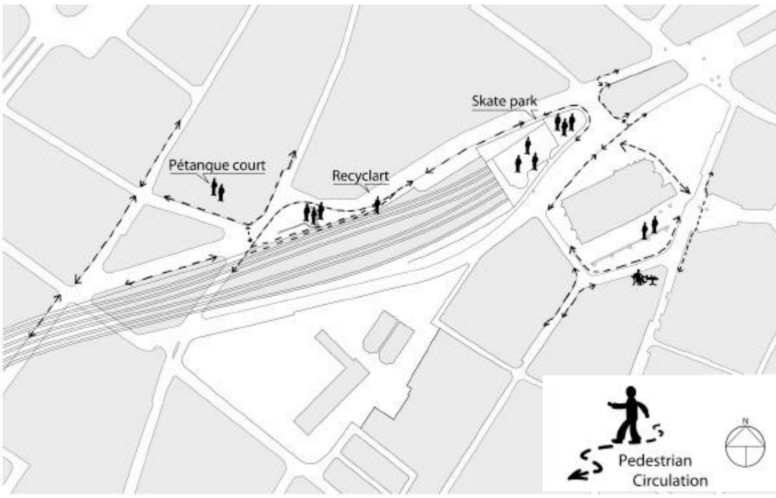


Figure 4.4: Pedestrian circulation, source: Design Studio Master 1 VUB-ULB 2011-2012

Master-plan

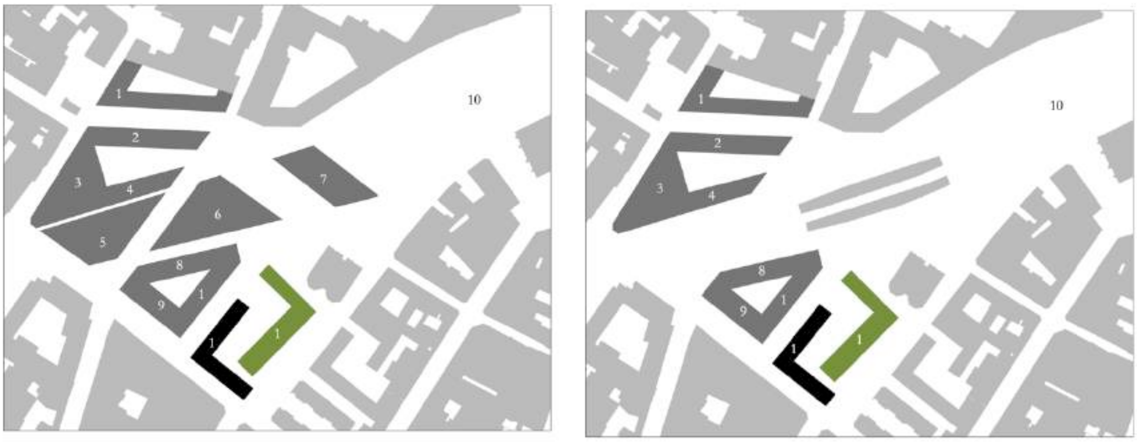
A proposal for a master-plan is given in Figure 4.5, based on the design studio of Master 1, 2011-2012. The master-plan follows the existing axes and creates view lines and new circulation patterns for pedestrians. The abandoned spaces make place for new functions, to bring life to the site: next to extra housing and hostels, a theatre, film theatre, art gallery,

---

[12] Recyclart is an organization in Brussels, with the following mission: transforming the rupture caused by the urban North-South junction in a living connection, ensure a strong link between the surrounding neighbourhoods.

workshops and a bar will enhance the artistic character of the neighbourhood. Also, the actual basketball court will be covered in a sport hall, to repeat the sportive character of the skatepark. The spaces left open will be green spaces, designed to purify rainwater and create a qualitative public space.

As the research of this dissertation concentrates on the building, component and material level interactions, a further elaboration of the master-plan is out of scope.



1. Residential; 2. Hostel; 3. Theatre; 4. Film theatre; 5. Art Galery; 6. Bar/Club; 7. Train Station; 8 Workshops; 9. Sport hall; 10. Skatepark

Figure 4.5: Masterplan, based on Design Studio Master 1 VUB-ULB 2011-2012

4.2.3 Qualities and disadvantages of the existing building block

When looking at the transformational capacity of a renovation of the Brigittinnen building block, several advantages and disadvantages occur, mainly typical for this post-war residential typology.

For a clear understanding in the rest of the text, the two wings of the L-shaped building will be named 'wing A' and 'wing B', as illustrated in Figure 4.6.

Figure 4.6: Wings of L-shaped apartment block of the Brigittinnen[13]

The column-beam structure permits a large freedom in the interior wall partitioning. The circulation hallways in both wings of the 'L-shape' offer potential. The stairs of wing B are emblematic in the street view. These external stairs also offer a great view on the city.

The disadvantages are the following (see Figure 4.7). The technical services are rather scattered. The technical ducts are small and their positioning is not consequent. The

[13] All Figures without reference are personal drawings by the author. All photographs without reference are photographed by the author.

sanitary zones are also not arranged in a systematic way. The internal walls are brick walls and therefore difficult to change. Various scattered circulations placed as an obstacle rather than an added value also mark the permanent character of the building.

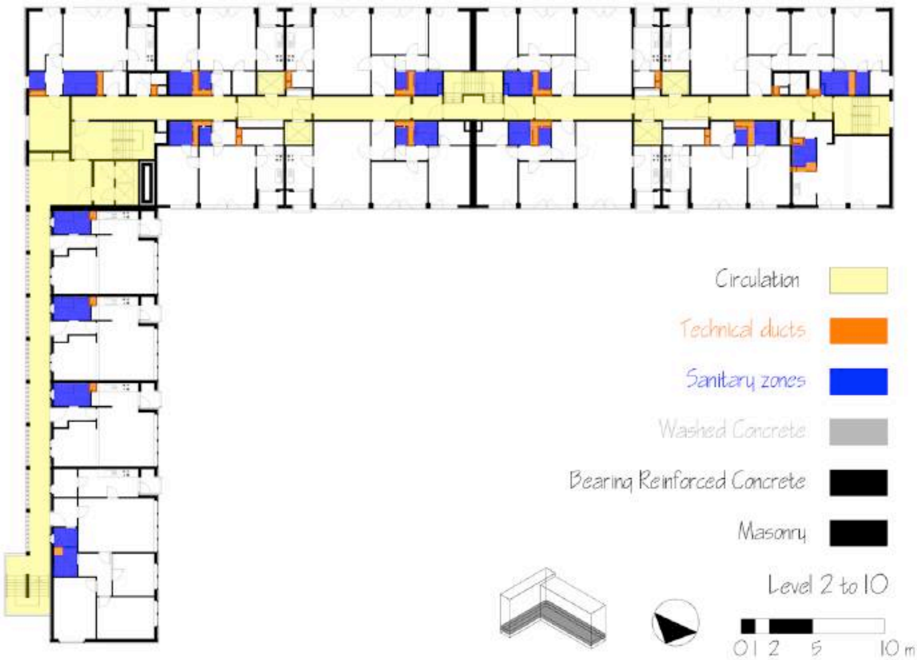


Figure 4.7: Existing building, typical floor plan with circulation, technical services and materials

The circulation in both wings is illustrated in Figure 4.8. The circulation hallway in wing A has no natural lighting and is partitioned by a lot of fire safety doors due to the scattered vertical circulation. This gives an unsafe experience while walking to the apartments. The circulation hallway in wing B however, is on the exterior side and offers a great view on the city, the Brigittinnen chapels and the South Tower in Brussels.

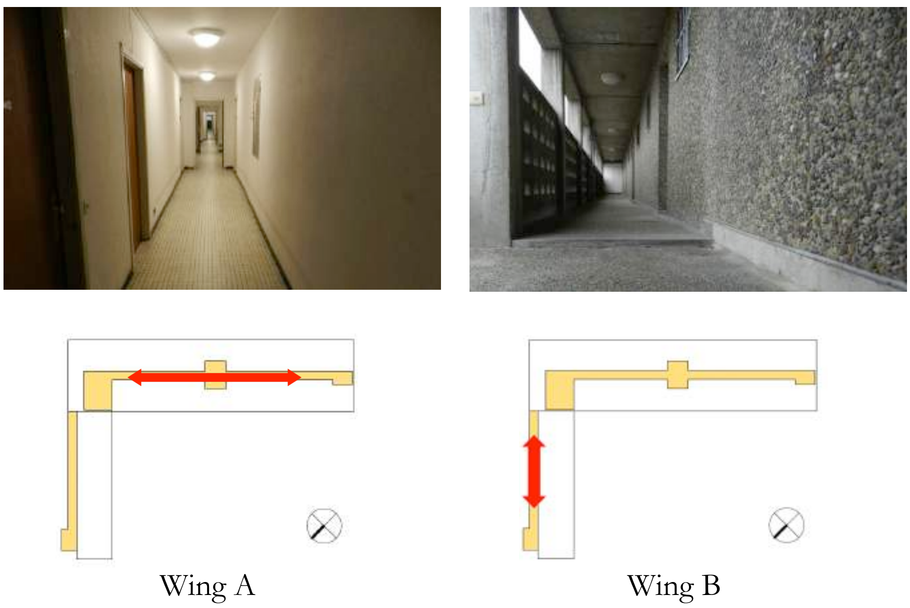


Figure 4.8: Horizontal circulation

4.2.4 Materials and structure

The column-beam structure (see Figure 4.9) is made from reinforced concrete. Since no thermal insulation is present, the structure is visible on the outside. The concrete is covered with white/grey paint. The façade panels between the structural gridlines are composed of PVC window frames and washed concrete showing the gravel texture, giving the building the white and grey aspect.

(a) Structure **(b) Concrete column** **(c) Washed concrete** **(d) PVC frames**

Figure 4.9: Actual materials in existing building

4.2.5 Typical existing apartment

The apartments in the existing configuration are small and used by more people than the foreseen households. The typical size of an apartment in wing B (Figure 4.10.a) is comparable to a one-student house (one room, one bathroom, one kitchen with small living), yet a family with two children are occupying the space. The children's mattresses are put in the living room, so that no space is left for a dining table (Figure 4.10.b). The walls on the last floor have humidity problems (Figure 4.10.c) and the inhabitants are complaining about the cold temperatures in the winter due to the lack of insulation and the bad quality of window frames. The kitchen is small and the little space available on the balconies is used as garbage storage (Figure 4.10.d).

(a) Empty apartment **(b) Children sleeping place in the living room** **(c) Humidity problems** **(d) Kitchen with terrace**

Figure 4.10: Apartment interiors in actual situation of the Brigittinnen complex

4.2.6 Generative grid based on existing measures

Since this design case is a renovation of an existing building, the original structure and architectural rhythm must be analysed for further changes on all levels. The building was stripped to the load-bearing structure and research was done on the existing used measures of the original design. The findings showed three measures always returned: 130, 170 and 45 cm. In every combination, these measures formed a grid that generates all the measures in the original design. This grid is illustrated in Figure 4.11. An internal grid of 30 by 30 cm has been developed inside the existing grid for further changes, in accordance to the methodology proposed by SAR (see Chapter 1).

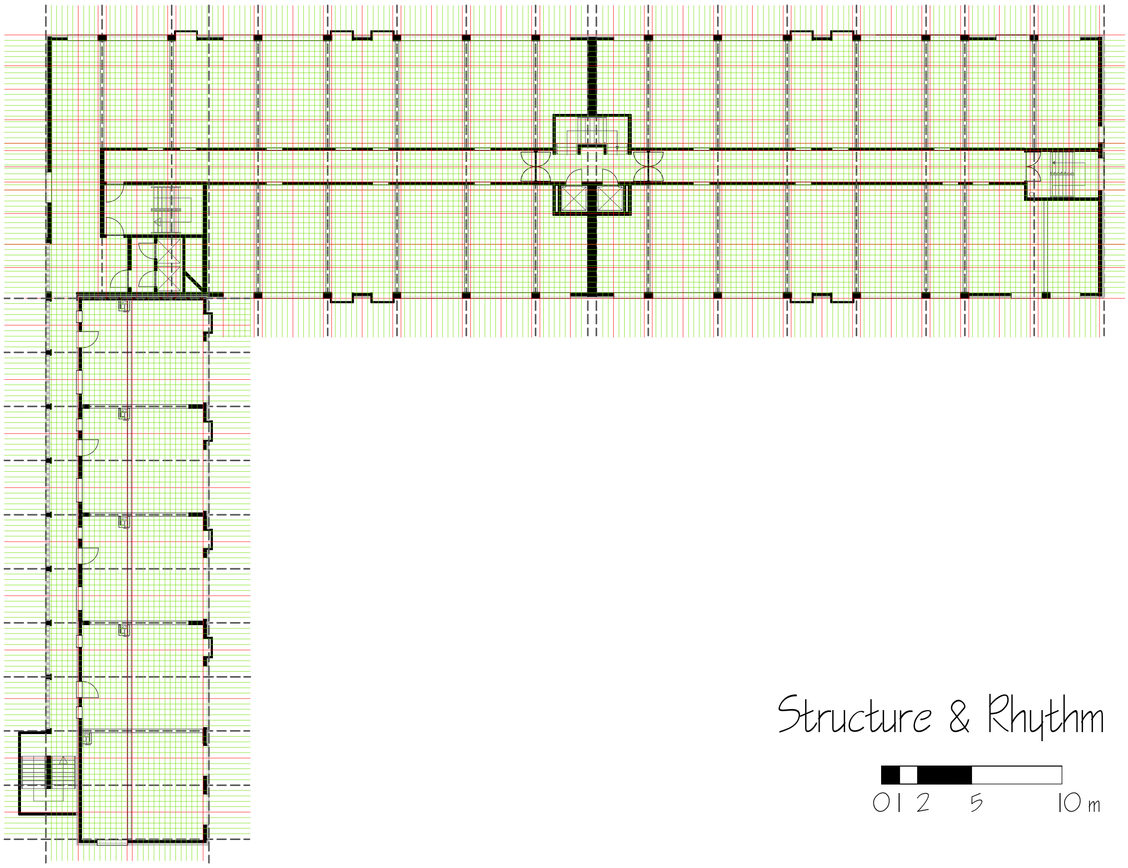


Figure 4.11: The load-bearing structure is indicated by the black dotted lines, the internal measure grid is indicated by the red (130-170-45 cm) and green (30 cm) lines

4.3 Concept of the building renovation

In this section, the building level is analysed for a flexible residential renovation. Starting from the common circulation to the individual apartments, the building concept enhances the flexible qualities of the apartment block and enables step-by-step redesign possibilities for the present and future use of the residential building.

4.3.1 From L-shape to L-concept: using the flexibility of "Unités d'Habitation" in a demountable way

The plan of the building is shaped in an "L". The L-shape will be used in the section of the building as well. Indeed, the "Unité d'habitation"-principle of Le Corbusier is applied in this building. For three levels, two duplexes (in L-section) are placed around a central corridor. In this way, only one hallway is needed for three storeys. This will not only permit to gain surfaces (6 levels of hallway surfaces are given back to the individual living spaces in the apartments), but will also permit an enhanced spatial quality: each apartment will now have at least *two different views* and rooms on *two or more levels* in the duplexes and triplexes. Also these trans-level openings inside the apartments lets the *light in deeper*.
For the communal parts of the building, this will permit a concentration of vertical and horizontal circulation. This concentration of circulation spaces makes it possible to provide *natural light* in the hallways, thanks to *less partitioning* for fire safety measures (since the vertical circulation is not cutting the horizontal hallways in several parts anymore).

This concept is illustrated for wing A in Figure 4.12 and for wing B in Figure 4.13. From left to right, the section and 3D axonometric views illustrate the following added qualities of this concept:

- The L-shape offers at least two different views per apartment.
- The concept enables vertical flexibility: an extension of the housing units in the vertical direction is possible. For example, two duplexes are replaceable with a triplex and a studio. Also, the space on two or three levels brings sunlight deeper into the rooms.
- The both sides of the section receive an additional frame structure to create terraces and a green façade.
- The green façade can be seen as a framework for extension of the individual apartments, following the need for extra outer space of each household.
- This will give the inhabitants 'real' terraces (instead of balconies for garbage), which are big enough for spatial quality, which will be increased by the vegetation of the railings.

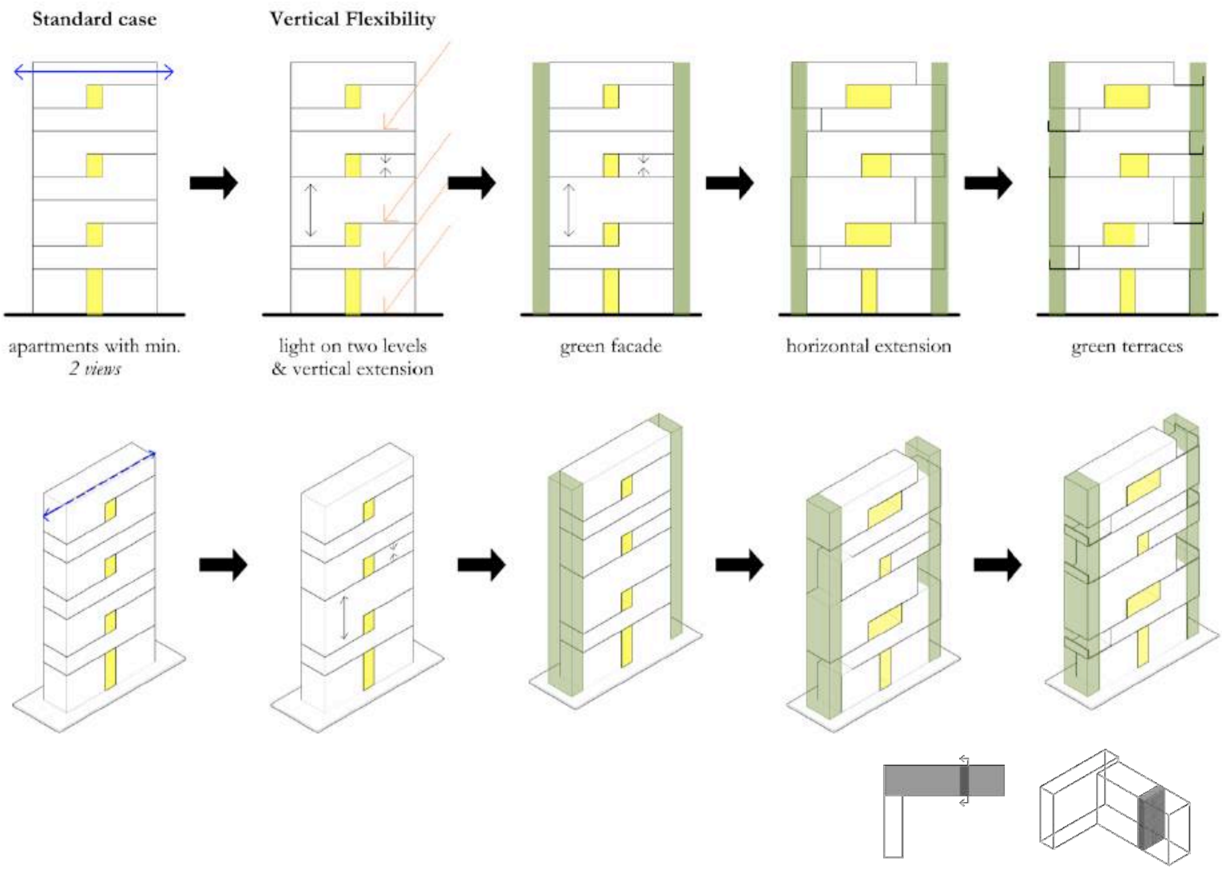


Figure 4.12: Concept illustrations applied on wing A of the Brigittinnen apartments

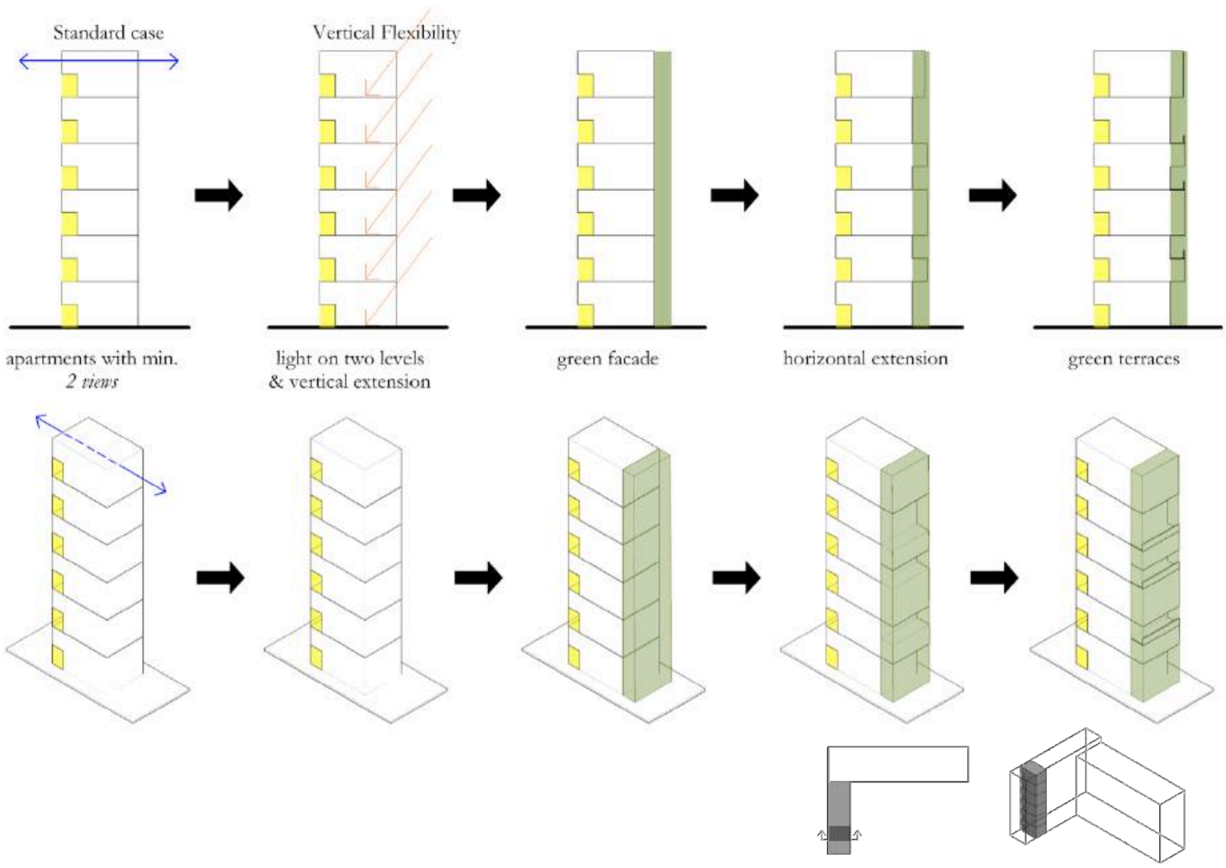


Figure 4.13: Concept illustrations applied on wing B of the Brigittinnen apartments

The vertical flexibility enabled by this concept is explained in Figure 4.14. Left, an axonometric view, a façade strip of one horizontal bay, a transversal section and an exploded plan view of the standard case is given: two L shapes around one horizontal circulation generating two duplexes are taking three levels of space. On the right, the vertical flexibility is shown with the creation of a triplex instead of a duplex. This will result in a combination of duplex and studio in the levels above.

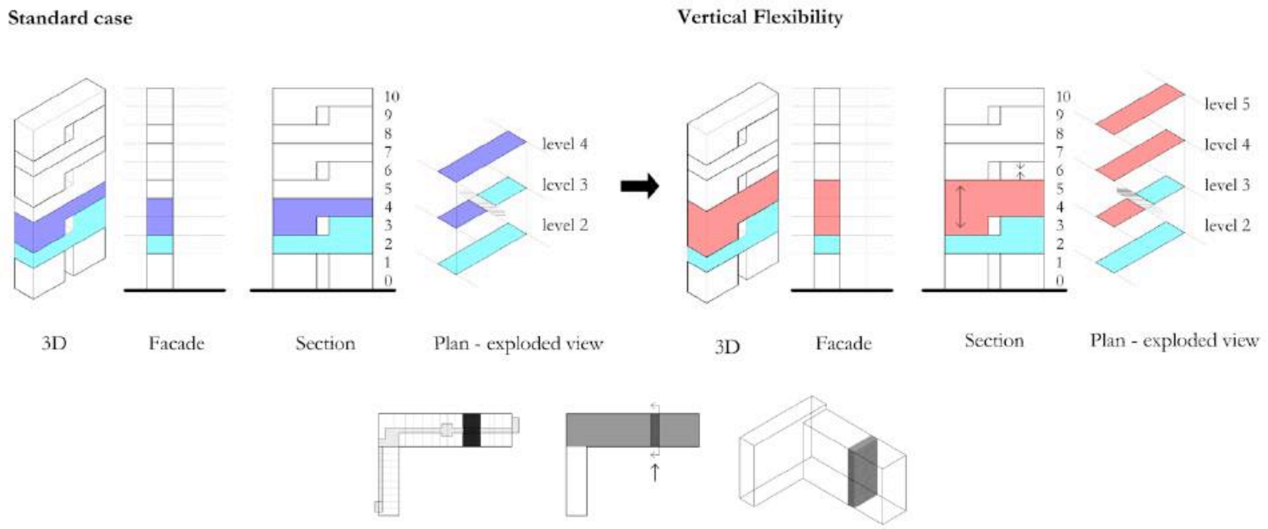


Figure 4.14: Vertical flexibility

In Figure 4.15, the horizontal flexibility is illustrated. Indeed, the standard case can also be extended to the next bay, on the whole depth of the building or on a part. The cyan coloured apartment is extended on the whole depth, whereas the blue coloured apartment is an example of partial horizontal extension. This will result in a smaller duplex and a studio in the neighbouring bay.

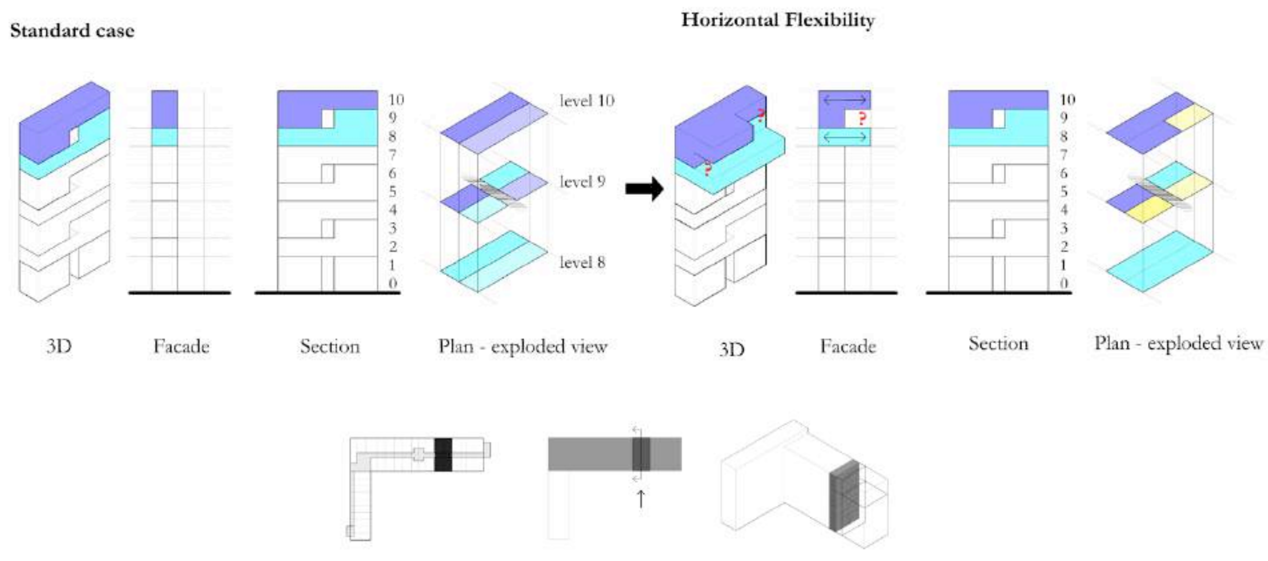


Figure 4.15: Horizontal flexibility

4.3.2 Layers of change vs. permanent building parts

In the first chapter (paragraph 1.1.4.), the building layers of Leupen were defined as followed: Structure, Skin, Scenery, Services and Access. Any of these layers can function as the 'frame' or permanent part of the building and the other layers are the 'generic space', i.e. the changing layers.

In the proposed concept of the Brigittinnen case study, the frame on the long run is the structure. It is the remaining building part of the past (existing) building. For mid-term, the newly designed access with concentrated circulation forms the second permanent part, around which the other layers can change according to their different lifespans. The services are also designed for a longer lifespan, since the conducts are next to the circulation, enabling the rest of the apartment freedom around this sanitary 'core'. The arrangement of the services next to the conducts is however allowed to change. The generic space is consequently composed of mainly the scenery and the skin. The building layers of Leupen are applied on the case of the Brigittinnen in Figure 4.16.

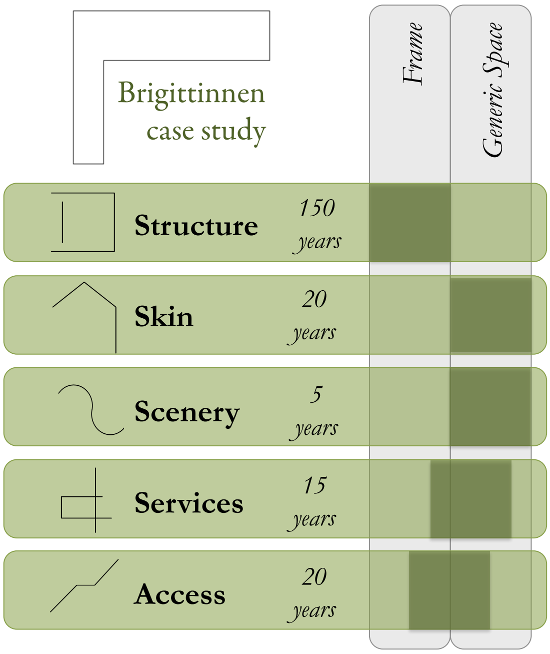


Figure 4.16: Layers of Leupen applied on the case study Brigittinnen

The demountable character of the used components and the choice of recyclable or biodegradable materials as well as the connections between these materials and components will support this flexibility on the building level.

4.4 Elaboration: plans, sections, façades – building, component, material interactions on apartment level

In this paragraph the plans, sections and façades of the renovated building are explained. The flexibility is incorporated in the redesign of the Brigittinnen apartments in different levels: the interior design, the access, the building arrangements, the façade development, the division into modular components, the material choice and the connection between the components.

- First, the adaptation in the circulation will be illustrated on a typical floor plan, on one of the levels with a corridor.
- Next, the standard case, i.e. the combination of two interconnected L-sections on one bay of the most common measure in the existing grid rhythm on three levels, will be elaborated.
- Thereafter, the possibility of different extensions or contractions of the standard case will be tested with new scenarios and extended plans and sections.
- Finally, the result on the global façade will illustrate the impact of the new flexible design on the neighbourhood.

4.4.1 Concentration of the circulation

The vertical circulation is concentrated in central areas, making the hallways less partitioned and the access clearer. The horizontal circulation is reduced to one hallway for three levels in wing A and one hallway for two levels in wing B. This is illustrated in Figure 4.17.

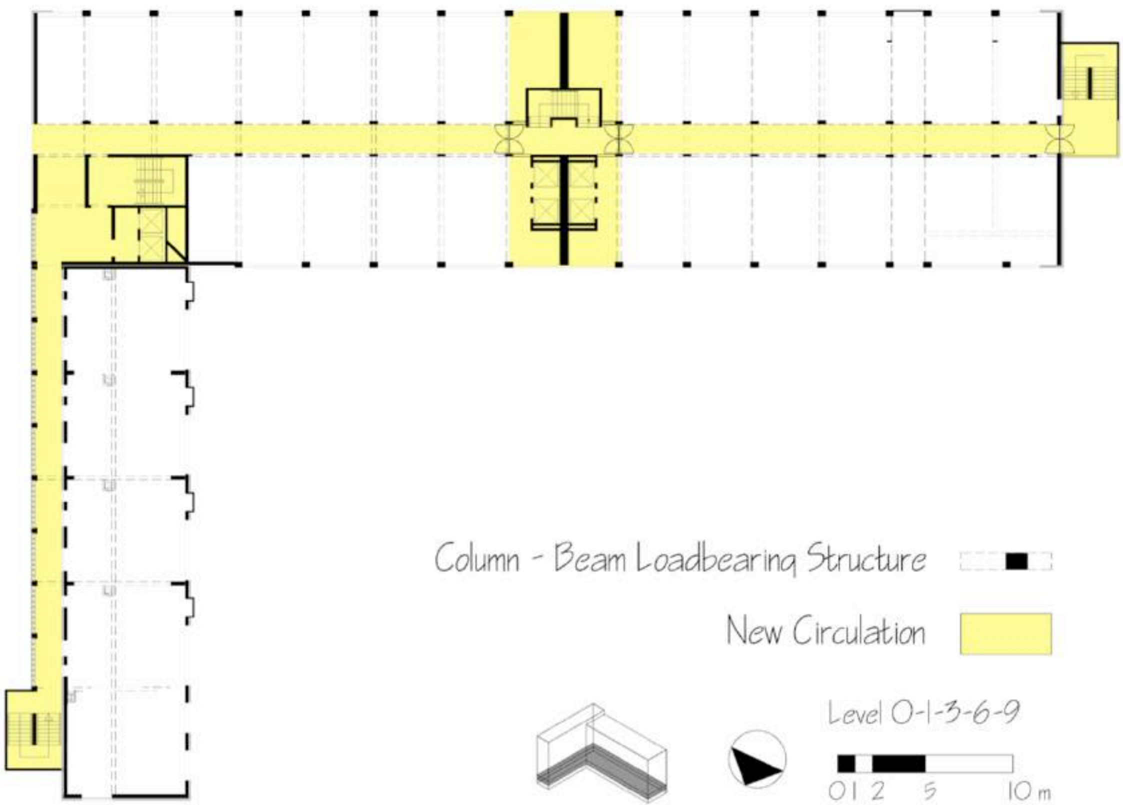


Figure 4.17: New circulation, concentration of vertical circulation to enable natural light in the hallways

4.4.2 Standard case apartments, scenario 1

The standard case consists of two duplex apartments, interconnected as two L-shaped sections around the corridor. These apartments are used for couples, singles or two unrelated singles living together, with simple adaptations in the bedrooms. The wall components are pre-assembled wooden panels, containing flexible electrical tubes with pulleys (explained in Chapter 5), so that the interior partitioning becomes a fast process. The interior core is used for wet areas or technical services, since the technical ducts are placed next to the corridor for easier access. Also these are the zones that need less natural light. On the duplex side, the living space and kitchen/eating space are divided on the mezzanine and under, depending on the available space for proximity between the kitchen and the dining room. The area with only one level serves as a bedroom, with a winter garden. The views on both sides of the apartment are left open during the day. Extra terraces are possible on the framework for the double green façade. Every division is processed on the generative grid, with basic wall components combined by basic connection systems (explained in Chapter 5). The materials where chosen so that dismantling is possible. The standard case consequently is composed of reusable components made of recyclable or biodegradable materials. The plans, sections and 3D section of the standard case follow. The 3D image (Figure 4.18) gives an idea of the perception of the transformable panels in the interior design.

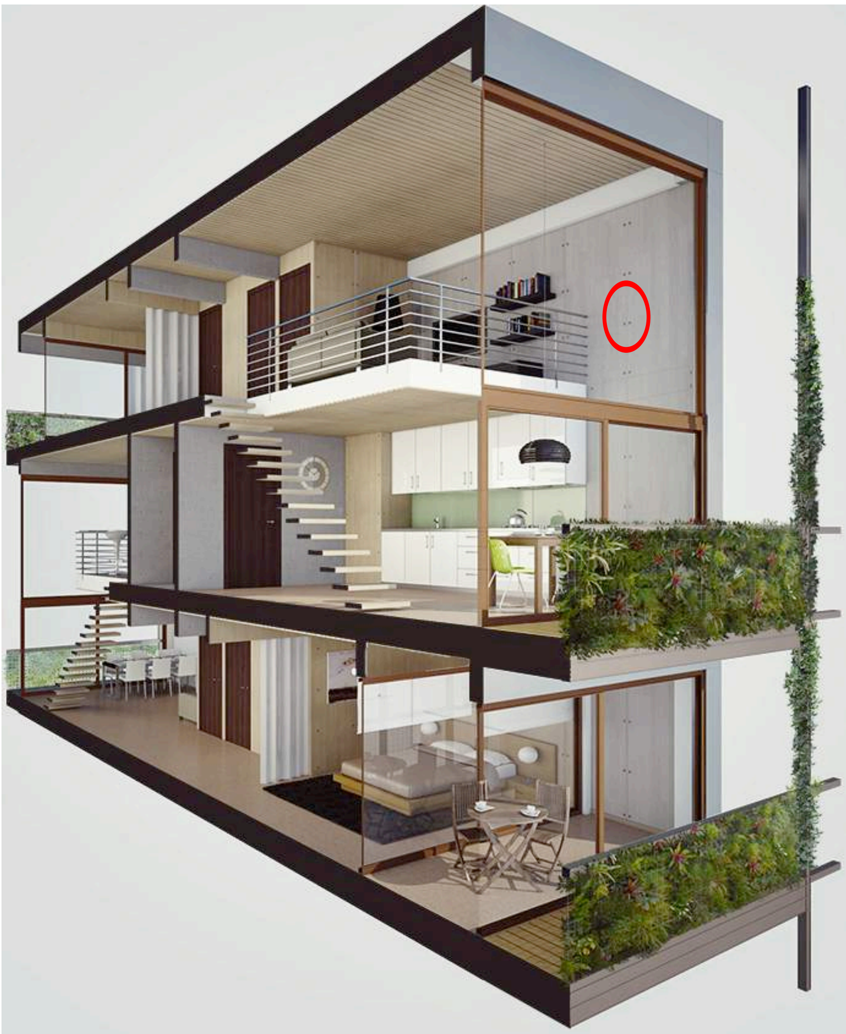
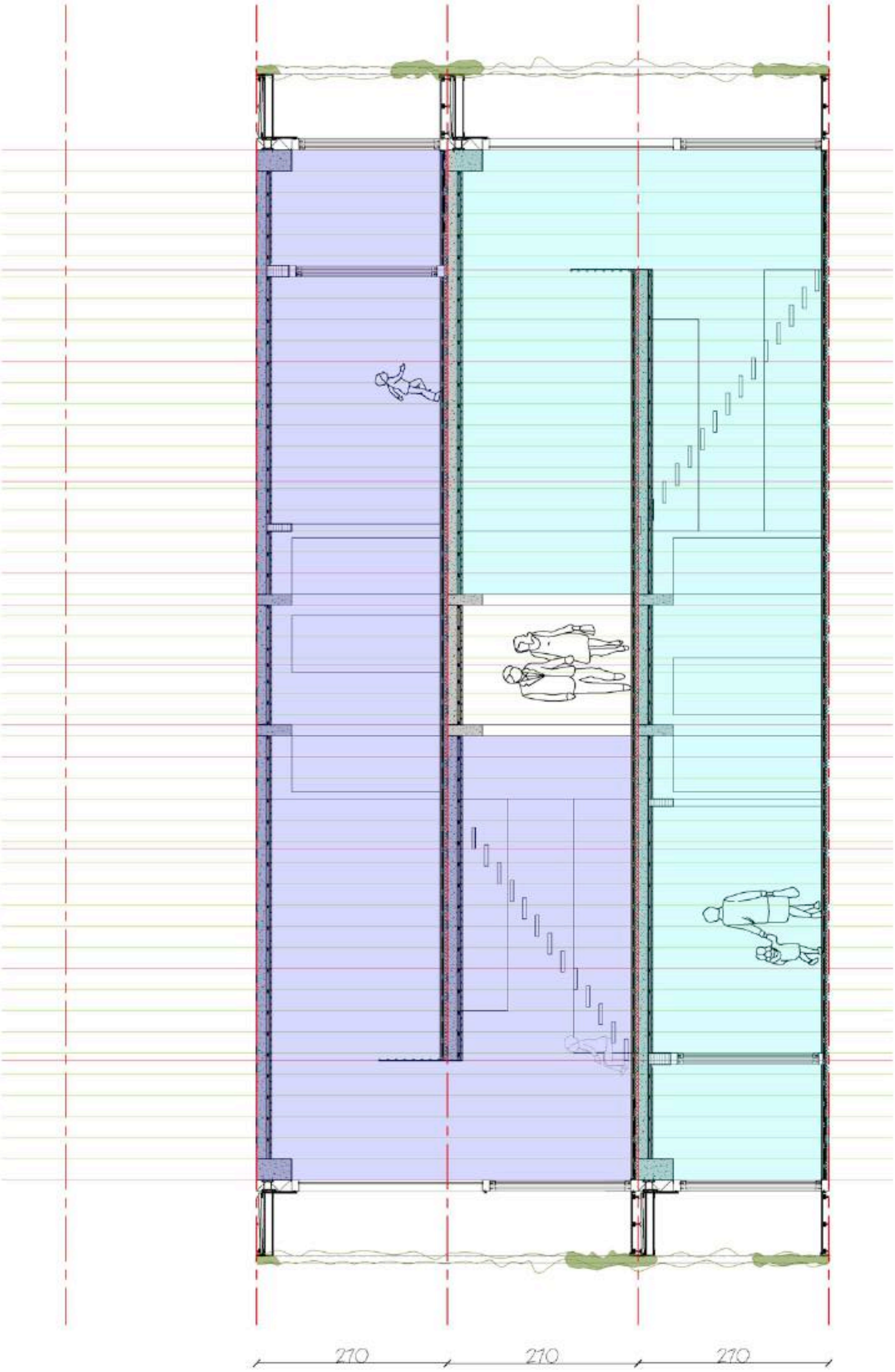
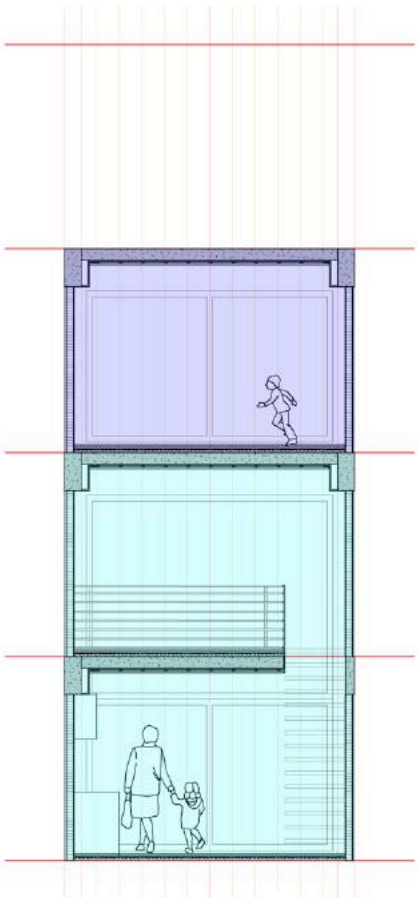


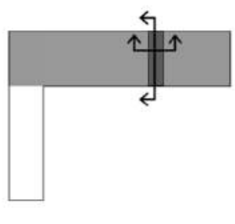
Figure 4.18: 3D section of the standard case

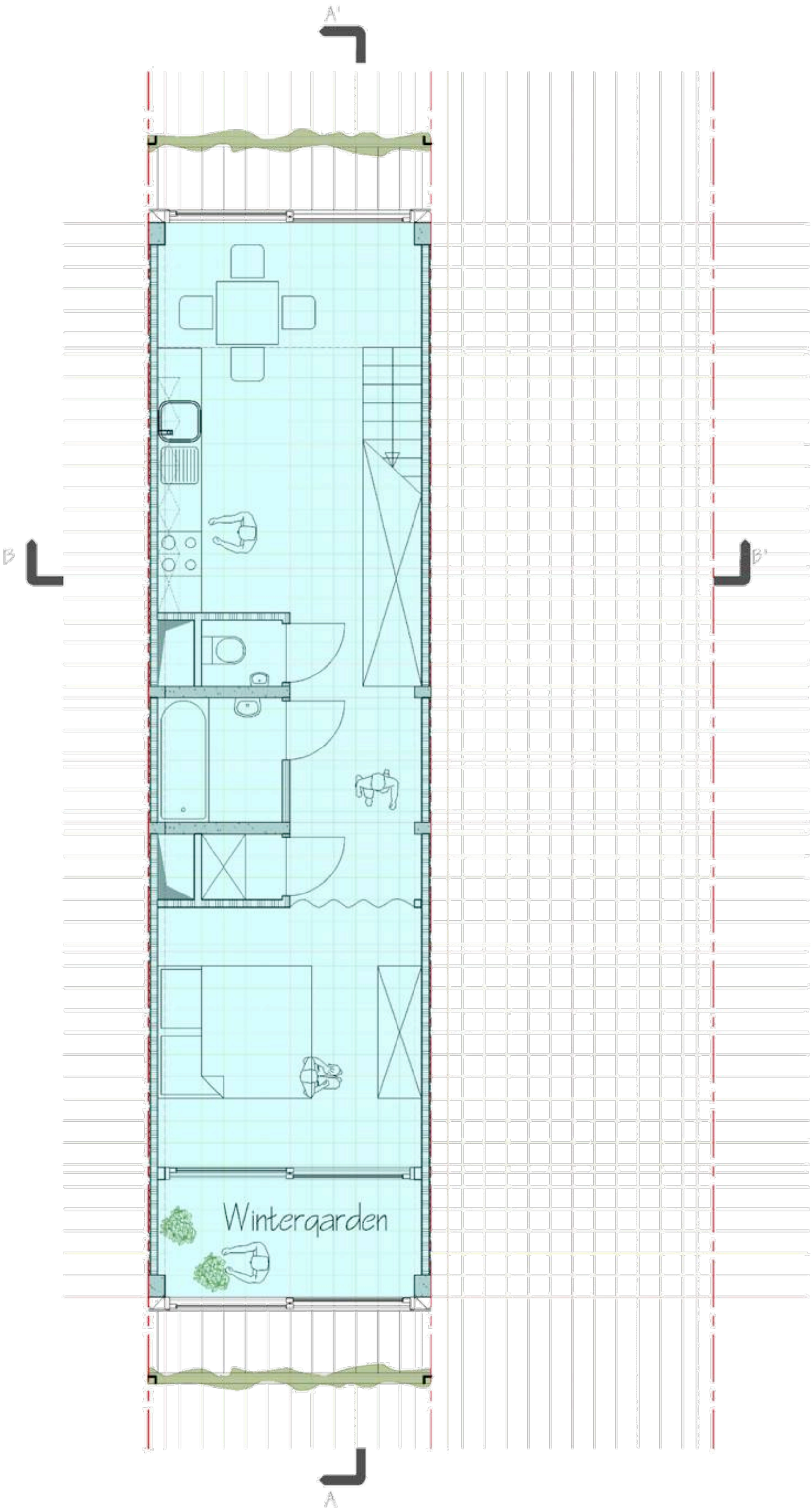


section AA'



section BB'

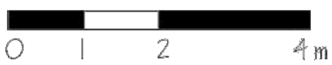


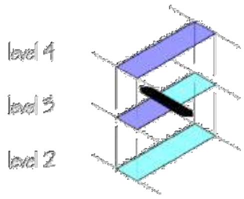


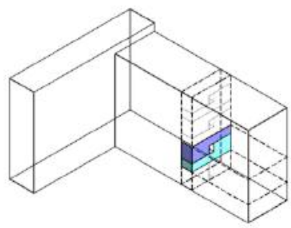
level 2

level 3

level 4

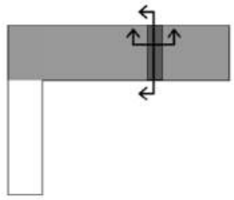




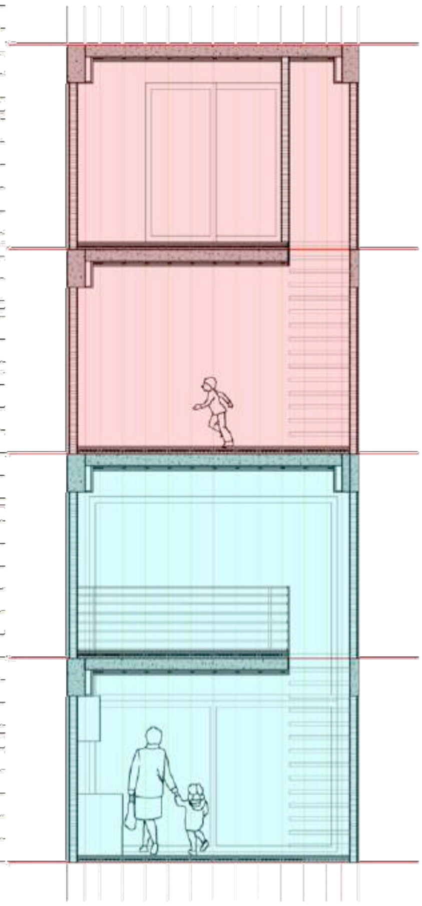


4.4.3 Vertical extension, scenario 2

The plans and sections describe the vertical extension. The lower apartment remains the same as in the standard case, but the upper apartment is extended to house a family with two or more children. The generating grid is still determining the exact division possibilities and the same components are used in a different configuration. The two first levels are used for day functions and office space and the third level for night functions. The technical services stay at the centre of the apartment, next to the technical ducts.



section AA'



section BB'


0 1 2 4 m
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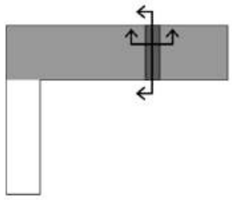
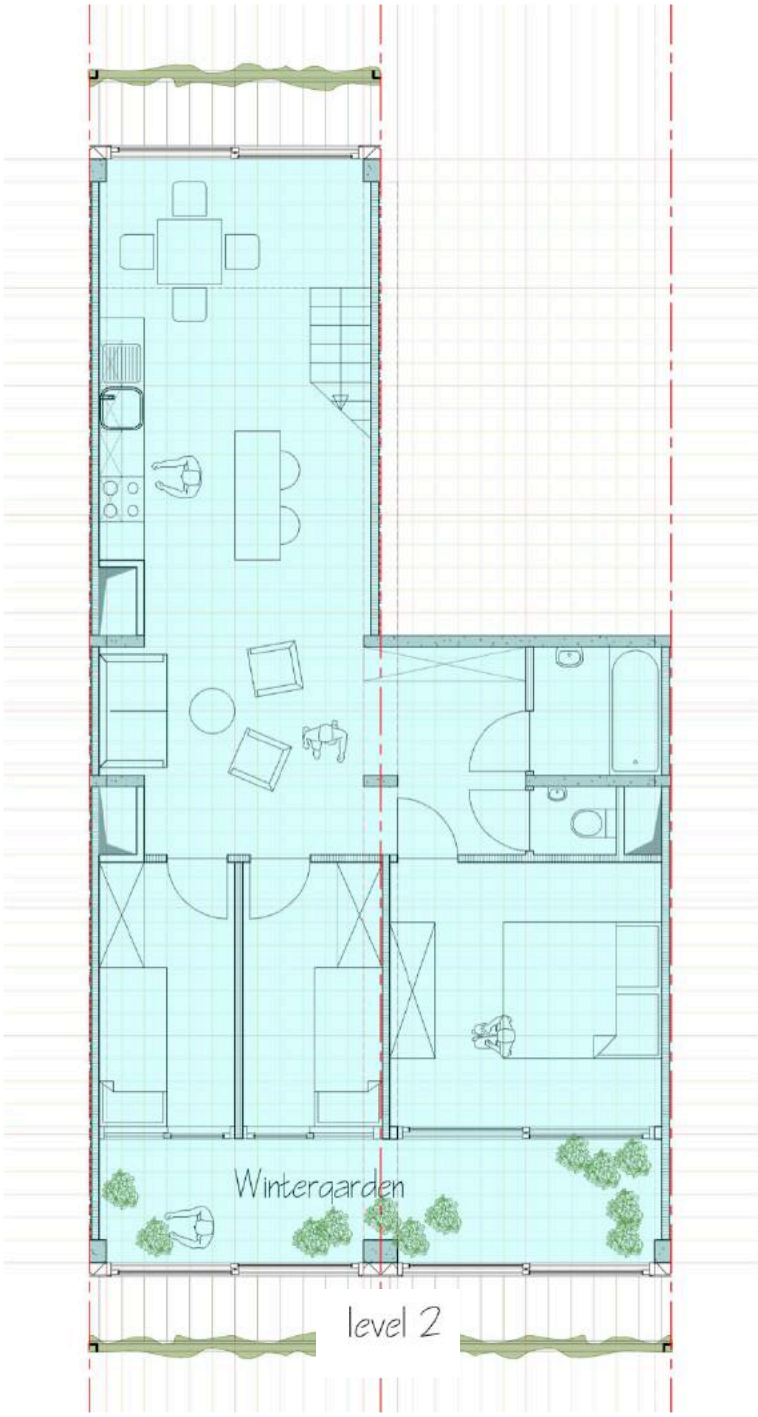
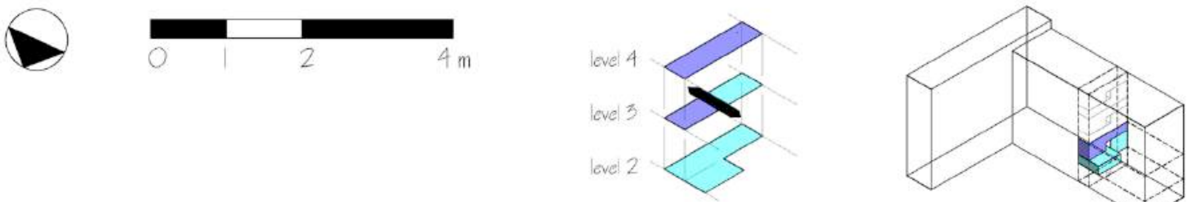
45
130
170
130
170
645
170
645
1460
22.5
170
170
22
385
level 3
level 4
level 5

4.4.4 Horizontal extension, scenario 3

A horizontal extension is also possible on a part of the neighbouring strip, starting from the standard case. Additional bedrooms are then possible with a few changes in the internal wall configurations. The part of the strip that is not used for the extension, becomes a studio duplex for a single person.







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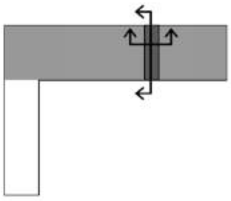
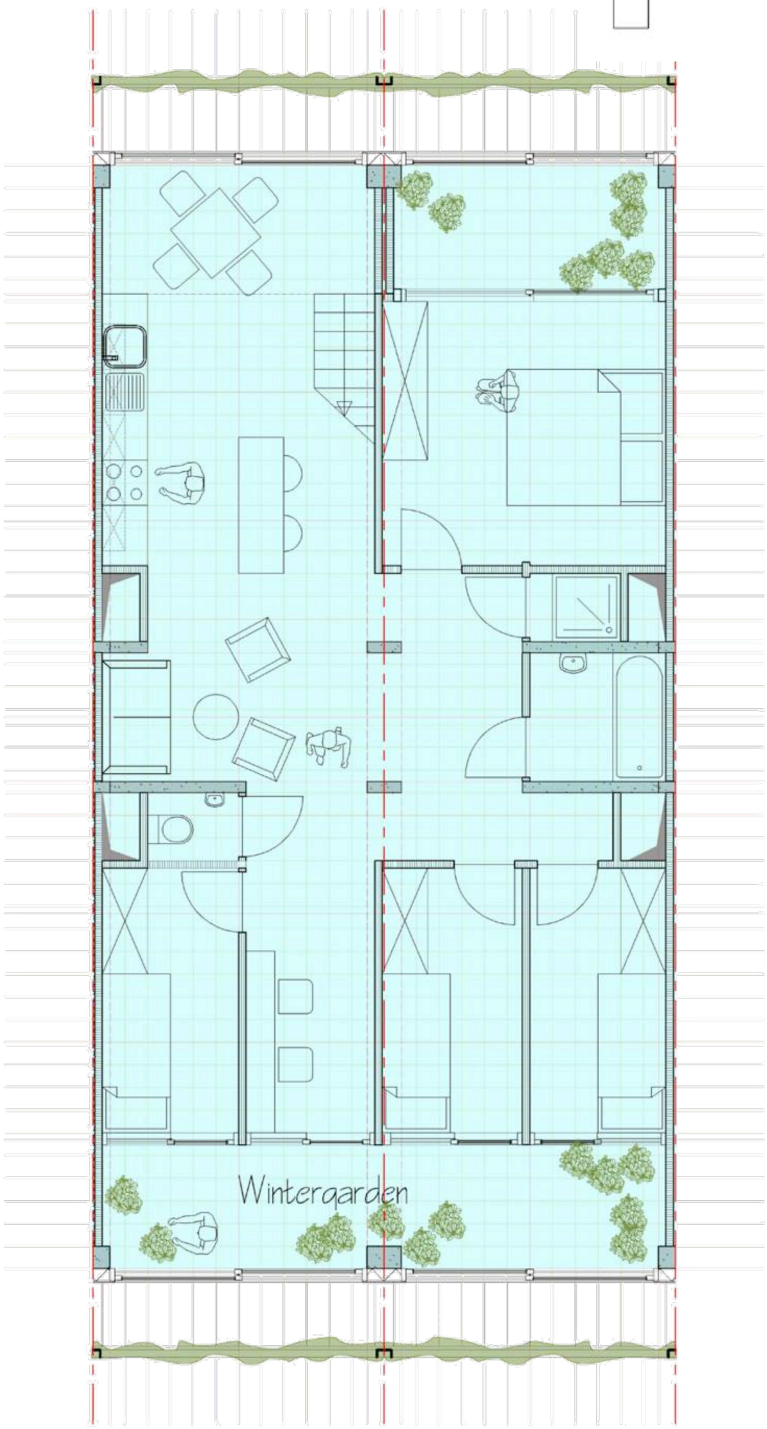
170
170
22.5
385
level 3
level 4

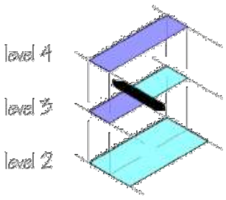
4.4.5 Horizontal extension, scenario 4

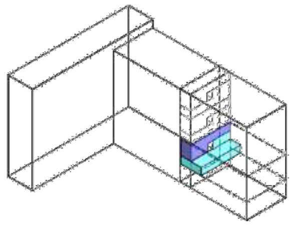


For larger families, a complete extension on the neighbouring strip is also possible. Four bedrooms are then possible in different configurations, for example parents, children and an elderly resident. The wall components are re-configured in a new way.

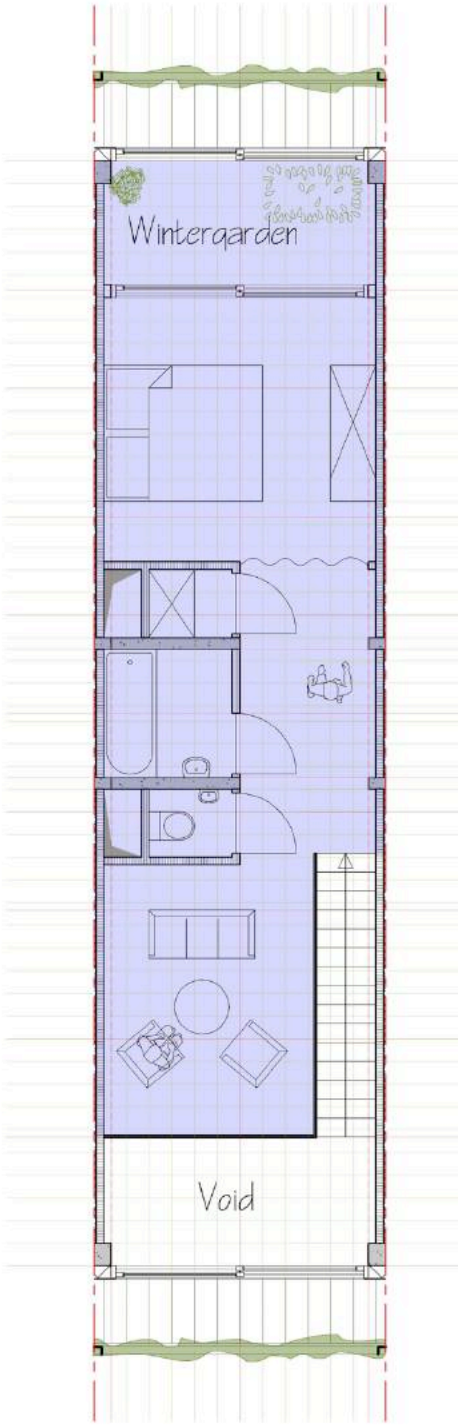


level 2





level 3



level 4

4.4.6 The façades: trademark, exterior spaces & enhancing indoor climate

The selection of material for the façade (see Figure 4.19) is influenced by the desire to let the façade function as an example. Two spheres were defined by the Cradle to Cradle principles: the biosphere and technosphere. The façade covering is therefore composed of aluminium panels, which are mounted easily and recycled to the same quality level using less energy than used to make the initial panels (see paragraph 4.5). The aluminium panels represent the recyclable technological materials. Next, the double façade, existing of a framework for green railings for the exterior terraces, will be covered by vegetation, which will represent the biodegradable materials, together with the untreated wooden window frames.

Figure 4.19: New "double" west façade: combination of technosphere (first façade) and biosphere (second façade)

4.5 Material choice

This section explains the reasons behind the material choices in the design case of the "Brigittinnen". The selection was based on listings with scoring indicating if the material can easily be recycled or composted.

Daniël Tulp listed standard construction materials and alternative materials from the NIBE[14] environment classification and the GPR building with a score to evaluate the possibilities for applying the Cradle to Cradle concept [TULP, 2009]. Mieke Vandenbroucke studied the feasibility of the Cradle to Cradle approach on building materials in [VANDENBROUCKE, 2011]. The listings of the materials from both researches are given in the appendix 1 and 2.

[14] Nederlands Instituut voor Bouwbiologie en Ecologie, English: Dutch Institute for construction biology and ecoloy

From their research, several materials are 'valid' choices within the Cradle to Cradle principles, and can be applied to the case study of the "Brigittinnen apartments".
Since the **structure** doesn't change, the material stays reinforced concrete.
For the new **internal walls**, the following choices are possible:

- *wood*, if it is not manufactured and no glue is used (unless it is biodegradable);
- *limestone*, since lime can completely be recycled thanks to the decomposing to the original constituents (N.B.: limestone can be used with mud mortar and finished with lime plaster.) [TULP, 2009, p32];
- *aluminium*, as it can be recycled to the same material with the same properties, and needs a limited amount of energy for recycling (7% of the initial energy for the primary aluminium) thanks to the low melting temperature [TULP, 2009, p26].

For the **façade cladding**, we can opt for:

- a *vegetal (green) façade*, resulting from the building concept and master-plan;
- *wood*, if no coating or treatment is added (special attention should go to the connections with windows for example, to avoid traces formed by rain water flows);
- *zinc*, as it can be completely recycled for the same (non-constructive) purposes [TULP, 2009, p27].

For the **flat roof**, a *vegetal (green) roof* is selected based on the master-plan concept.
For the **water barrier**, the available options are the following:

- *polystyrene*, which can be recycled, although no market is available for this [TULP, 2009, p28];
- *zinc*.

For **insulation**, we can use on of the following:

- *expanded cork*, which is biodegradable and is resistant for biological deterioration;
- *flax*, which is biodegradable on the condition that organic binding agents are used;
- *biofib*, a natural material.

The **interior finishing** can be made of one of the following:

- *wood*, without glue;
- *cork*;
- *lime plaster*.

The **floor cladding** can consist of:

- *wood*;
- *linoleum*, a natural product;
- *expanded* cork;
- *matts from vegetable fibres*.

The final material choices are described and illustrated in the design bundle.

4.6 Discussion

The interactions between the building level, component level and material level discussed in chapter 1 are applied on the case study of the "Brigittinnen". The *frame* is the existing load-bearing structure, where the *generic space* is shaped by the interior layout of the apartments. A *generative grid* of 30 x 30 cm is created within the existing building measures (with rhythm of recurrent measures as 170 cm, 130 cm and 45cm). The design of the components is based on the *HVDA* and the materials are selected in accordance with the *Cradle to Cradle* principles. The chosen materials influence the design of components, through the integration of connections.

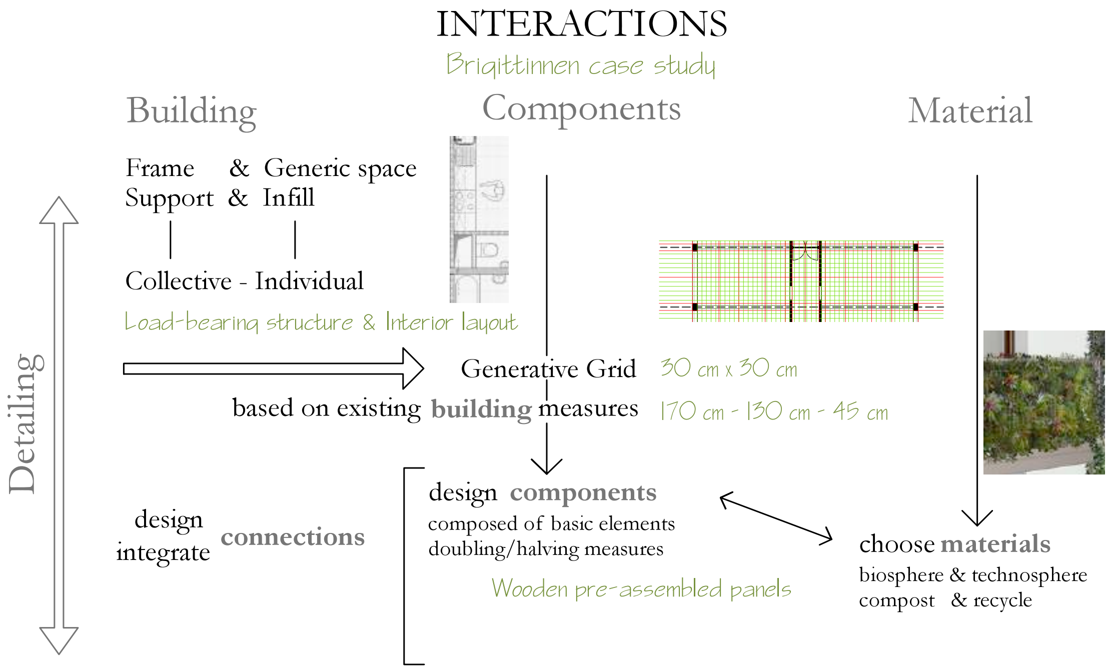


Figure 4.20: Application of 4D design strategies on the case study of "Brigittinnen"

This case study proves it is possible to implement the different approaches discussed in chapter 1 in a practical design case without losing any of the more conventional architectural qualities in the design. Indeed, the interactions of the four-dimensional principles and tools on building, component and material level not only result in a demountable building, but also introduce several other qualities. First, the choice of working with extendable L-sections gives a *spatial* value with possibilities for spaces on two or even three levels. Second, the *circulation* has been concentrated so that there is more room for the apartments and the access benefits from natural light and less partitioning. Third, the apartments now have *two different views* and have *incoming sunlight on both sides* of the building.

Even though the building has improved when considering architectural layout and potential, the feasibility of the demountable nature of the proposal is yet to be revealed. In the next chapter, the demountable character of the refurbished building will be demonstrated focusing on the connections between building parts and components and discussing them more in detail.

5. Sub-layering of building parts in apartments: material connections.

"Design of building connections is the last aspect of design for disassembly. Interfaces define degree of freedom between components, through design of product edge, and specification of connection type." – Durmisevic [DURMISEVIC, 2006, p182]

In the first chapter, the literature on four-dimensional approaches and strategies was illustrated. The four-dimensional design on the three levels was discussed in the context of design for versatility/adaptability (building level), design for deconstruction (component level) and design for dismantling (material level). The fourth chapter illustrated the design decisions in the case study of the "Brigittinnen" on different levels.

In this chapter, the *technical aspects of the connections* between the levels are detailed in order to define the building parts of residential buildings: the façade, the roof, the partitioning wall, the internal wall and the separating floor.
The **first** section gives a theoretical study on relationships between components, on assembly sequences and on ways of connecting in literature. In the **following** sections, the building parts are discussed separately, more particularly the façade, the roof, the partitioning wall, the internal wall and the separating floor. For every building part, a definition will introduce their sub-layering in apartments. The building parts will then be divided in different categories for the renovation of residential buildings. Aside from this, the connection of materials to components will be detailed in examples and applied to the case study of the Brigittinnen complex. The building technology behind these connections will be illustrated with drawings of technical details.

This will lead to characteristics of level interactions needed for a dynamic redesign of connections. Numerous connection possibilities exist for different building parts. The ways the chosen materials are connected depend on the materials themselves, the desired transformability, but also the building physics, the required tolerances and the desired aesthetic.

5.1 Theory on connections

Before considering each building part separately, it is important to understand the relations between components, the sequence of assembly and the different ways of connecting, since these are key factors of a strategy of change.

5.1.1 Component relations

In [AUSTIN et al, 2011], literature on the dependency between components is summarized. These relationships between components listed in Table 5.1 are crucial to the understanding of adaptability in architectural products.

Pimmler & Eppinger (1994)	Spatial	Energy	Information	Material	
	Adjacency	*Transfer*	*Data or signal exchange*	*Exchange*	
Rush (1986)	Remote	Touching	Connected	Meshed	Unified
	No touching	*Contact, no permanent connection*	*Permanent*	*Interpenetrate*	*One physical form*
Slaughter (2001)	Spatial	Functional	Physical		
	Independent but in the same room	*Enhance, complement, degrade*	*Connection, intersection, adjacency*		
Helmer (2007)	Spatial	Energy	Signal	Material	Structural
	Adjacency	*Transfer*	*Data exchange*	*Exchange*	*Load exchange*

Table 5.1: Component relationships, based on [AUSTIN, 2011, p4]

The recurrent relations between components are the following: spatial (adjacent), physical (connected, etc.), energetic (transferred), functional (complemented) and informational (data exchanged).

5.1.2 Assembly sequences

Since the mountable character and the possibility to disassemble are one of the important aspects in four-dimensional design, this paragraph discusses assembly sequences. The adaptability is indeed dependent on the sequences of the combination of different elements to components.

Five assembly sequences are defined by Durmisevic [2006], illustrated in Table 5.2: *parallel* sequence, *interlock* sequence, *closed circle* sequence, *gravity* (or attraction) sequence and *sequential* sequence. The parallel sequence leads to the fastest building processes, whereas the sequential sequence leads to dependencies and complicated substitution. Parallel sequences are therefore preferred for adaptable connections [DURMISEVIC, 2006].

In Table 5.2, the different sequences are illustrated.

Parallel	Interlock	Closed circle	Gravity	Sequential

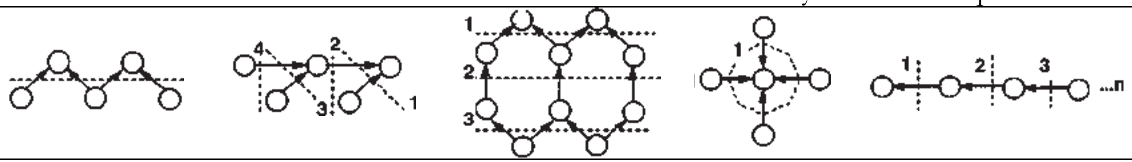


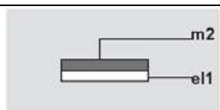
Table 5.2: Assembly sequence types, based on: [DURMISEVIC, 2006, p181]

The parallel sequences lead to an assembly where all components are independent. If the disassembly of only one part of the sub-components is required, not the whole component but only a part must be disassembled. In this chapter, parallel sequencing is used for the detailing of the case study in chapter 4.

5.1.3 Connection types

The connection types (see Table 5.3) determine the assembly sequences. From fixed to flexible connections, Durmisevic [2006] defines the following types of connections, divided in direct and indirect connection types:

- *Direct chemical connections*: fixed adhesive permanent connection
- *Direct connections between two pre-made components*: the elements are dependent
- *Indirect connection with third chemical material:* permanent connection with a third material enables the combination of two elements
- *Direct connections with additional fixing devices*: the connection is made by a extra accessory and can be dismantled when an element should be removed
- *Indirect connection via dependent third component*: a third element connects the two elements, but the dependency stays the same
- *Indirect connection via independent third component*: all elements can be reused and recycled, although the elements are still dependent from one another.
- *Indirect connection with additional fixing device: no dependency is existing between the different elements*

<table>
<tr><td>Direct</td><td>chemical connections</td><td>
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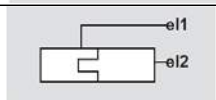
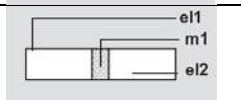
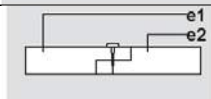
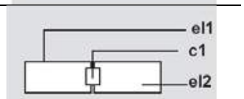
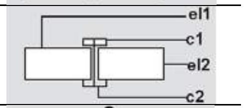
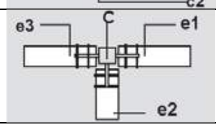
<tr><td>Direct</td><td>connections between two pre-made components</td><td>
</td></tr>
<tr><td>Indirect</td><td>connection with third chemical material</td><td>
</td></tr>
<tr><td>Direct</td><td>connections with additional fixing devices</td><td>
</td></tr>
<tr><td>Indirect</td><td>connection via dependent third component:</td><td>
</td></tr>
<tr><td>Indirect</td><td>connection via independent third component</td><td>
</td></tr>
<tr><td>Indirect</td><td>connection with additional fixing device</td><td>
</td></tr>
</table>

Table 5.3: connection types, based on: [DURMISEVIC, 2006, p183]

Debacker [2009] worked on the comparative analysis of typical connections in the built environment, shown in Table 5.4. He divides the connections in three categories instead of two: infilled, direct and indirect. *Infilled* connections make the components permanently attached to each other, for example in adhesive or welded bonds. *Direct* connections enable disassembly, but difficultly due to overlapping or interlocking components, for example with nails. *Indirect* connections are the most preferable way, since the components stay independent from other ones, for example in screw or bolt fixing. The dry connections must however also satisfy conditions of building physics and tolerances.

	Type	Construction speed	Strength	Reuse	Disassembly
Mortar	*Infilled*	-	- to +	-- to -	+/-
Adhesive	*Infilled*	+/-	- to ++	--	--
Welding	*Infilled*	+/-	++	-	--
Resin	*Infilled*	+/-	++	-	--
Nail	*Direct*	+/-	+/-	+/-	+/-
Riveted	*Direct*	+	+	+/-	-
Bolt	*Indirect*	+	+	++	++
Screw	*Indirect*	+	+/-	+	+
Friction	*Indirect*	+	-	++	++

(--) none; (-) limited; (+/-) average; (+) substantial; (++) extensive

Table 5.4: comparative analysis of typical connections in the built environment [DEBACKER, 2009]

In the following paragraphs, the four-dimensional connections will be illustrated for different building parts.

5.2 Material connections in the structure

Since the structure in most renovation cases of residential post-war buildings will be reused as a static support structure, this paragraph will only illustrate one example of structural material connections. The case study of the Brigittinnen complex keeps its original concrete column-beam structure. Therefore, no new connection scenarios are elaborated.

An example of lightweight structure connections is the yacht house designed by R. Horden (see Figure 5.1). In this flexible house, the architect found inspiration in the details of yacht rigging for the connection in order to create an extendable house. The connections are 'dry', so that the structure can easily be disassembled or extended by unscrewing and reconnecting the components of the nodes [DURMISEVIC, 2006, p147], [HCLA, 2012].

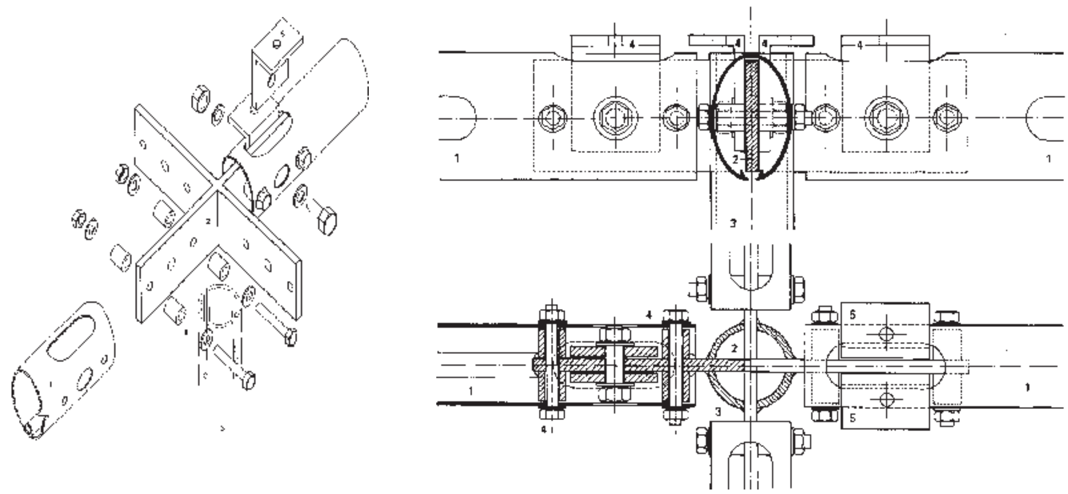
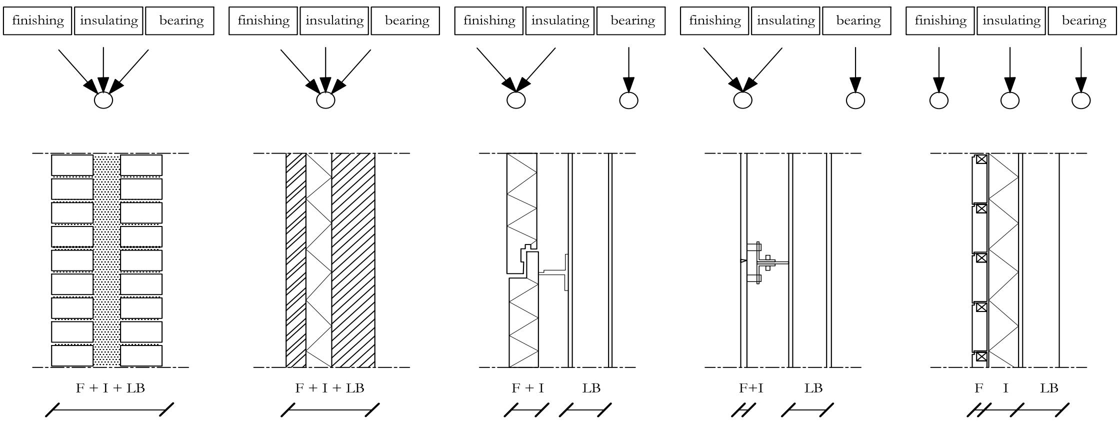


Figure 5.1: Connection detail of the yacht house by R. Horden, source: [DURMISEVIC, 2006, p147]

5.3 *Sub-layering and connections in the façade for apartments*

5.3.1 Façade sub-layering

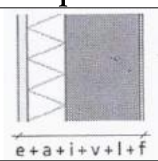
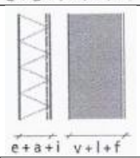
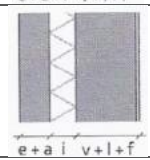
The façade can be decomposed in layers, connected together in different compositions. Durmisevic [2006] separated three standard elements composing the façade: the loadbearing structure, the insulation and the finishing. The various configurations (illustrated in Figure 5.2) imply either the combination of the three elements, the combination of both finishing and insulation separated from the loadbearing structure or the complete separation of the three elements [DURMISEVIC, 2006]. In Design for Reuse, the last case is prefered.

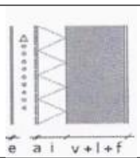
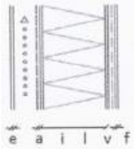


F = Façade; LB = Loadbearing structure; I = Insulation

Figure 5.2: configurations of the façade layers [DURMISEVIC, 2006, p164]

Paduart [2012] categorized more detailed sub-layering scenarios of façade systems (see Table 5.5). The façade is decomposed into 'sublayers' by their function: external weather proofing (e), air tightness (a), insulation (i), vapour barrier (v), load-bearing function (l) and internal finishing (f). The different compositions of the sub-layering scenarios are ranging from fixed to dynamic. The completely fixed composition uses adhesive connection techniques, whereas the most dynamic system separates all the functional sub-layers. Table 5.5 illustrates the range of possible façade compositions [PADUART, 2012].

	Sub-layers	Composition		*Example*
Fixed	e a i v l f		One leaf – no ventilation cavity	*ETICS*
	e a i v l f		Two leaves – no ventilation cavity (outer leaf clustering exterior functions)	*Warm panel systems*
	e a i v l f		Two leaves – no ventilation cavity	*Cavity walls*

Dynamic	e a i [v l f]		Two leaves – ventilation cavity	*Rain screen façade systems*
	e a i v l f		Two leaves – ventilation cavity	*Rain screen systems combined with wooden/steel load-bearing structure*

e = external weatherproofing, a = air tightness, i = insulation, v = vapour barrier, l = load-bearing function and f = internal finishing

Table 5.5: Sub-layering scenarios of façade systems, based on [PADUART, 2012, p87]

The practical application of a dynamic façade system on the case study of the "Brigittinnen" will be discussed in paragraph 5.3.5.

5.3.2 Renovation of residential building façades

In post-war residential buildings, certain types of façade systems exist. An important aspect for the renovation of the façade is the presence and location of insulation. For the external walls, a division is made based on the load-bearing capacity of the façade and the position of the thermal barrier (Table 5.6) [PADUART, 2012].

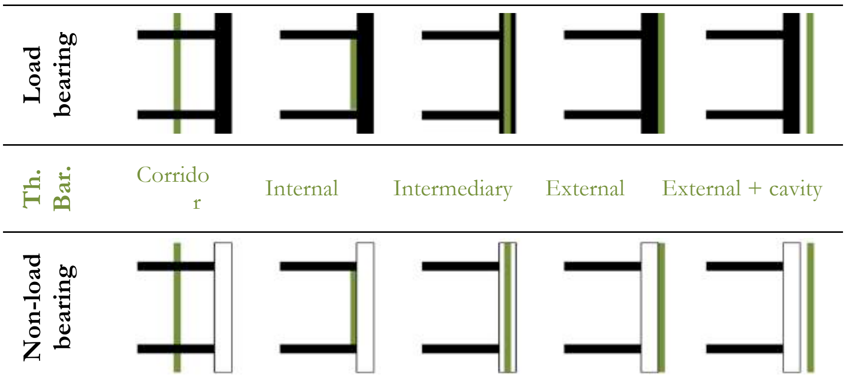
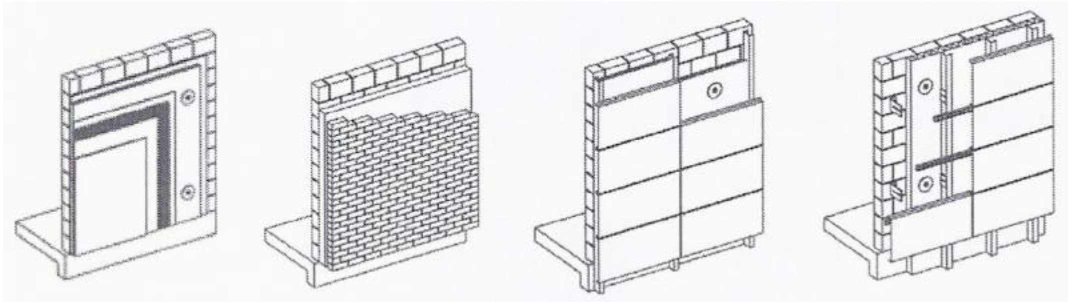


Table 5.6: Categories of façade compositions in multi-storey housing, based on [PADUART, 2012, p82]

5.3.3 Façade categories of post-war residential buildings

In this paragraph, the post-war residential building façades are divided in categories. For renovation practice, four used façade systems can be used (see Figure 5.3) [PADUART, 2012].

- *Category 1*: External Thermal Insulation Composite Systems (ETICS), i.e. a layer of insulation added externally, covered with rendering
- *Category 2*: Traditional masonry cavity wall with insulation
- *Category 3*: Sandwich (modular, non-ventilated) panels with incorporated mineral wool insulation fixed to the building via a framework
- *Category 4*: Supporting grid with mountable modular rain (ventilated) screens. A subdivision is defined between wooden rebating on wooden frameworks (4a) and other coverings on aluminium frameworks (4b).



ETICS | *Masonry wall* | *Warm panel façade* | *Ventilated façade*

Figure 5.3: Façade systems, source: [PADUART, 2012, p84]

The façade system that will be designed for the case study of the Brigittinnen will be close to Category 3 and 4.

5.3.4 Material connections in the façade

Before looking at the façade connections, it is important to differentiate the levels of dependence that can exist. For the façade system and its components, different levels of dependence can be considered. The independent façade system consists of façade panels that are suspended directly on the structure. Within the façade system, independent components can exist. Finally, independent elements can be connected to form the components of the façade systems as illustrated by Figure 5.4 [DURMISEVIC, 2006].

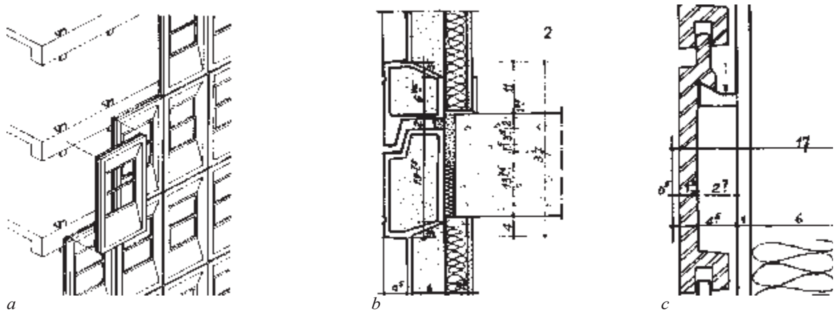
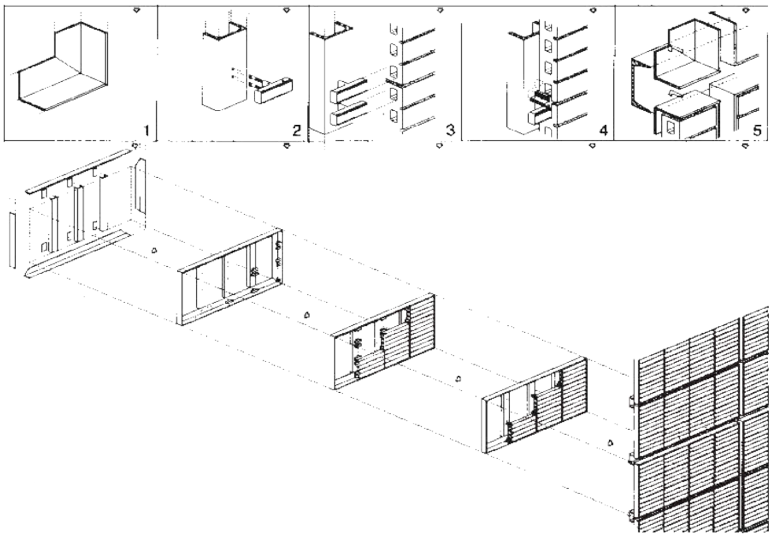


Figure 5.4: levels of dependence (a) independent façade system, (b) independent component within façade system, (c) independent element within façade component, source: [DURMISEVIC, 2006, p150]

The connection possibilities for façade systems depend on the architect's choice of materials for the external representation of the building, on the existing structure type and on the detailing choices. In the Brigittinnen case study, the third level of independency will be reached (Figure 5.4.c) in order to enable a high level of flexibility.

For example, Durmisevic [2006] discusses the façade system designed by Renzo Piano for the IRCAM building extension, based on brick elements (see Figure 5.5). An aluminium frame structures the panel. The brick elements are suspended on cast aluminium mounting pieces, fixed on the aluminium frame. A neoprene spacer provides the space between the brick element panels. The whole panel (aluminium frame with brick elements) is attached to the steel U-profile of the façade structure by means of stainless steel hooks [DURMISEVIC, 2006].



1. Aluminium frame for the panel
2. Cast aluminium mounting piece
3. Suspension system brick elements
4. Neoprene spacer
5. Attachment of panels against the steel U-profile by means of stainless steel hooks

Figure 5.5: Façade system designed by Renzo Piano for the IRCAM building extension, source: [DURMISEVIC, 2006, p154]

5.3.5 Connections in the façade of the Brigittinnen apartments case study

In this paragraph, the material connections for the façade of the apartments in the Brigittinnen case study will be illustrated. A separation of different sub-layers was discussed above: the rain screen, the air tightning, the insulating layer, the vapour barrier and the load-bearing structure can be easily disconnected from one another. These layers together form a ventilated façade.

Drawings of the technical detailing illustrate the connections of exterior finishing and insulation to the existing column-beam load-bearing structure.

The 3D view is shown in Figure 5.6. A section on scale 1/10 is shown in Figure 5.7. No adhesive connections are used, only dry connections. The external terraces are on an aluminium framework, with a green double façade. A plan detail on scale 1/10 is illustrated in Figure 5.8.

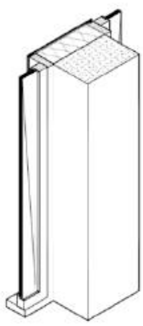


Figure 5.6: 3D detail of the façade connection on the load-bearing structure: external insulation[15]

[15] All figures without reference are personal drawings of the author.

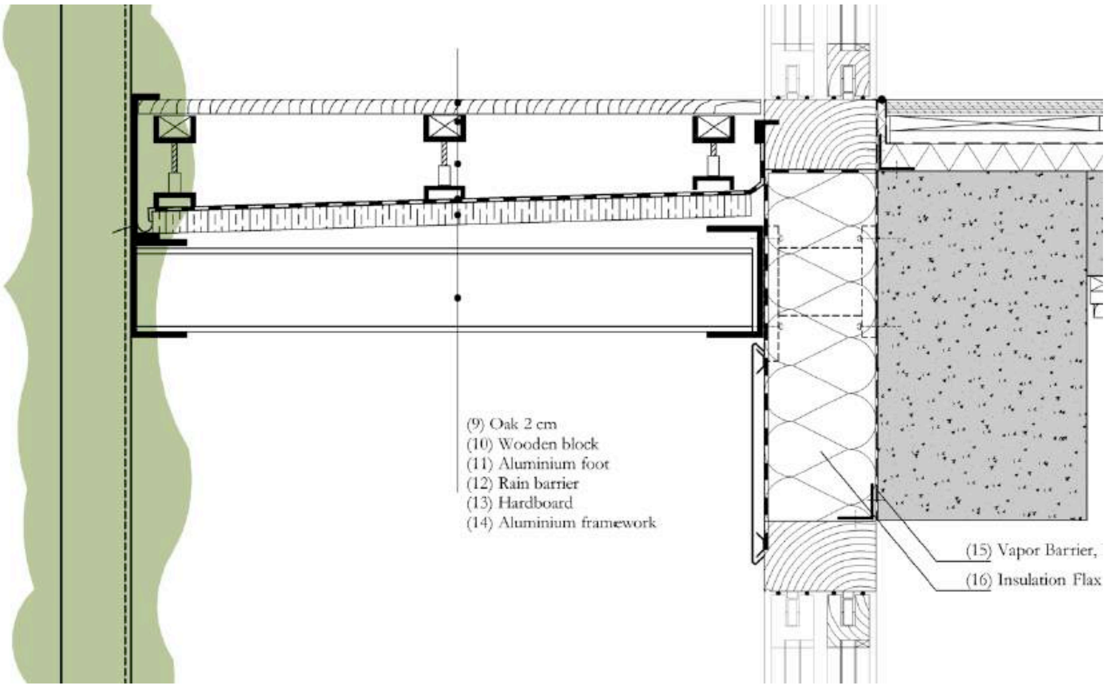


Figure 5.7: Section detail of the façade connection with the load-bearing structure in the Brigittinnen apartments

The façade is composed of a combination of biodegradable and technical (recyclable) materials, as an example of how to use different kind of materials in a 'Design for Reuse' approach. The green façade on the aluminium framework accentuates this duality. The terraces are supported by an aluminium structure, but the covering is made of wood. The windows are made of wood, but the covering of the façade consists of aluminium clips. The flax insulation is completely natural. The concrete beams and columns are a reuse of the existing structure.

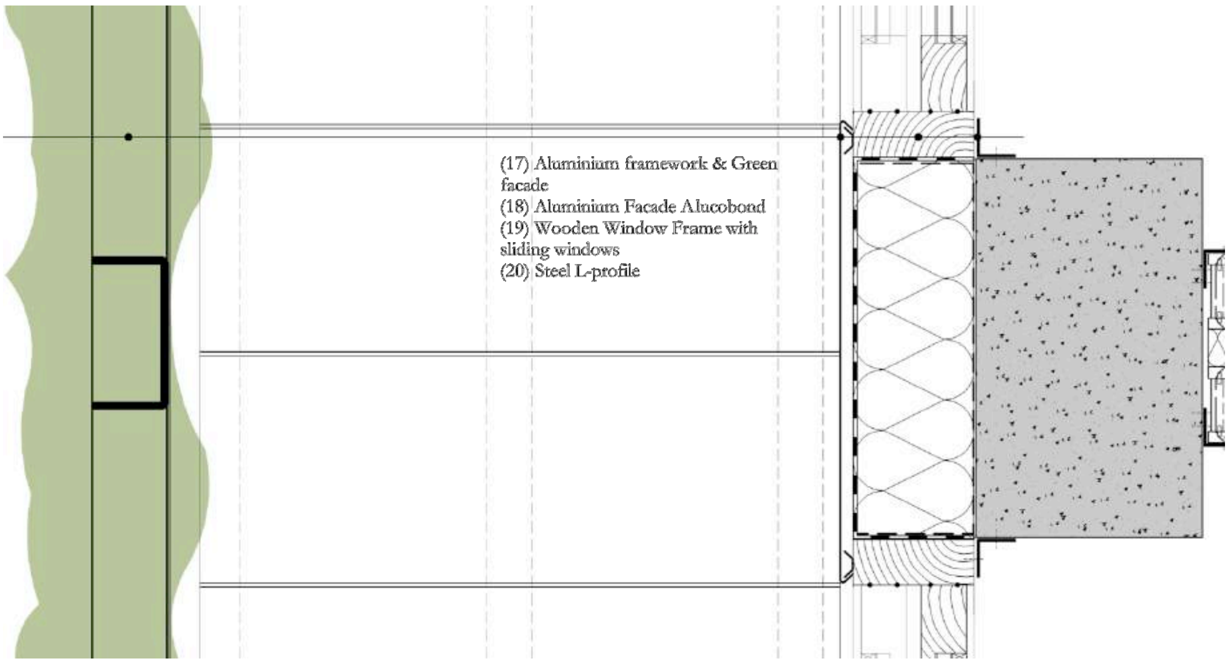


Figure 5.8: Plan detail of the façade in the Brigittinnen apartments

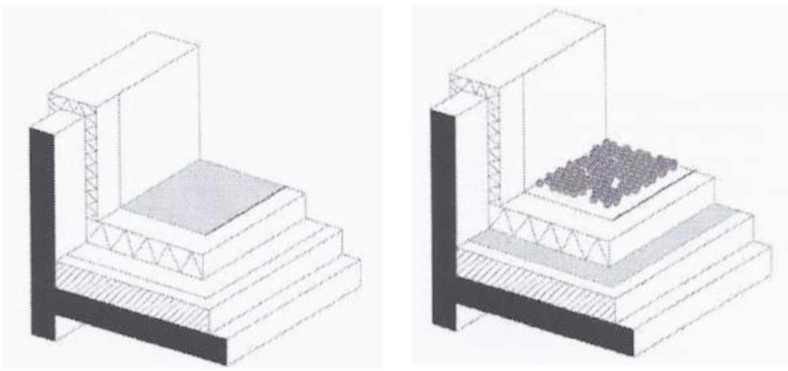
5.4 Sub-layering and connections in the flat roof for apartments

5.4.1 Roof sub-layering

The functional sub-layering of flat roofs is similar to façades. An external weatherproofing (e) against water (water barrier) and sun (ballast) is needed as well as air tightness (a). The insulation layer (i) and vapour barrier (v) are present as well. The roof structure (s) is often finished at the inside (f).
The separation of these sub-layers enables a dynamic approach to the renovation of these residential building types with flat roofs.

5.4.2 Renovation of residential building roof: roof categories

Two categories are defined for the thermal upgrade of roofs (see Figure 5.9). In the *first category*, thermal insulation is laid over the existing roof membrane, covered by a new waterproof layering. In the *second category*, thermal insulation is laid loose on the existing membrane and no new waterproof layer is added, but a movable sheeting and ballast [PADUART, 2012].



Category 1 *Category 2*

Figure 5.9: Thermal upgrade roof categories, source: [PADUART, 2012, p103]

5.4.3 Material connections in the roof structure

An example of a transformable roof structure is illustrated in Figure 5.10. The design starts from the functional decompositions of the components. The relation between different parts is open. Therefore, the roof structure is easily transformable, independently of the façade.

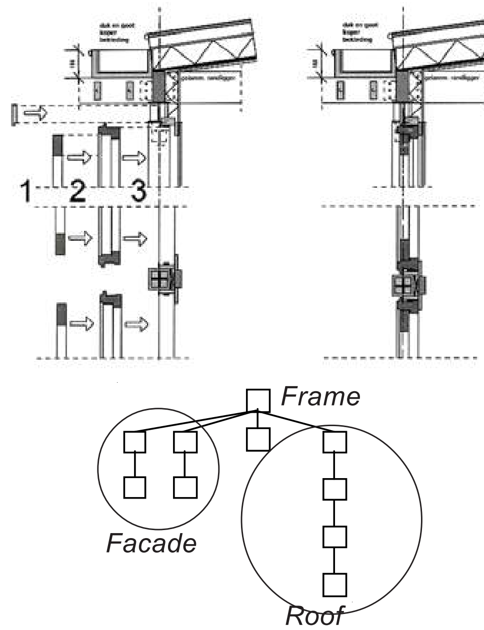


Figure 5.10: Example of wooden roof structure: deconnexion façade – roof, source: [DURMISEVIC, 2006, p278]

5.4.4 Roof connections of the Brigittinnen apartments case study

In the case study of the Brigittinnen apartments, the flat roof will be renovated to form a green roof (see Figure 5.11), which will be the common garden for the inhabitants. The connections with the existing concrete roof is composed of the layers of an extensive green roof: a new roof deck for the insulation and waterproofing to renovate the existing damaged covering, a layer for protection and storage of water, a drainage layer, a root permeable filter, a substrate for extensive growing vegetation.

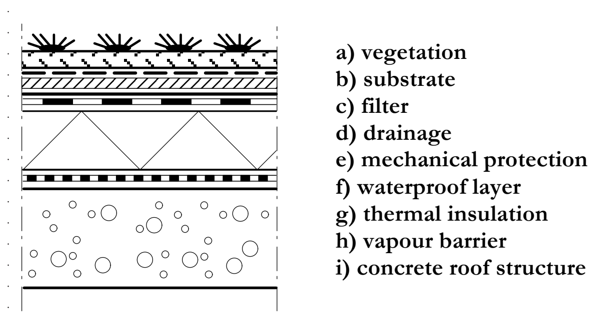


Figure 5.11: Extensive green roof layers, source: [WTCB GROENDAKEN, 2006, p7]

5.5 Sub-layering and connections of the partitioning wall

The walls can be divided in two groups: partitioning walls and internal walls. The partitioning walls separate two living units, whereas the internal walls divide the spaces within the same dwelling unit.

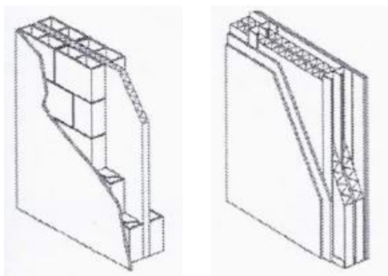
5.5.1 Partitioning wall sub-layering

In general, the acoustic, thermal and fire safety requirements are therefore more important for partitioning walls. This results in a slightly different sub-layering. A partitioning wall consists of two leaves, separated by insulation in the classical case or a combination of a double (for better acoustic performance) framework with insulation in dry connected walls. The walls are finished on both sides. The sub-layering is composed as follows: finishing (f), double-layered wall composition with insulation (d+i), finishing (f).

5.5.2 Renovation of partitioning walls between dwellings: partitioning wall categories

The different definitions of partition wall categories in the renovation of dwellings are defined, according to [PADUART, 2012], as follows (see Figure 5.12):

- *Category 1*: two brick wall leaves separated by a soft insulation layer, finished with gypsum plaster and paint
- *Category 2*: dry walls – double layered metal stud composition



Category 1 *Category 2*

Figure 5.12: Partition wall categories, source: [PADUART, 2012, p97]

For the Brigittinnen complex, a new design of partitioning walls will be proposed. The flexible principle in the case study lies the closest to category 2.

5.5.3 Material connections in the partitioning walls

Paduart [2012] developed different connection details, applicable to partitioning and internal walls. The starting point is the assembling of pre-assembled panels with steel, wooden or aluminium connection elements. The examples shown below use steel L-profiles, increasing the flexibility and feasibility. The illustrations are developed for internal walls, but the principles are also applicable to partitioning walls, with an extra layer of insulation. The examples will be discussed in this paragraph for both internal and partitioning walls. The non-structural composing elements are an insulation layer of glass wool (50 mm), preassembled boarding of OSB (15 mm) and additional boarding of MDF (15 mm) and connections with bolts and screws.

The first example (see Figure 5.13) consists of the basic linear connections between two preassembled panels finished on site. The steel profiles of the preassembled panels are compressed by rubbers and then by vertical elements to hold the two panels together. An additional boarding is added with clipped vertical strips, which are the only visible connection elements of the finishing.

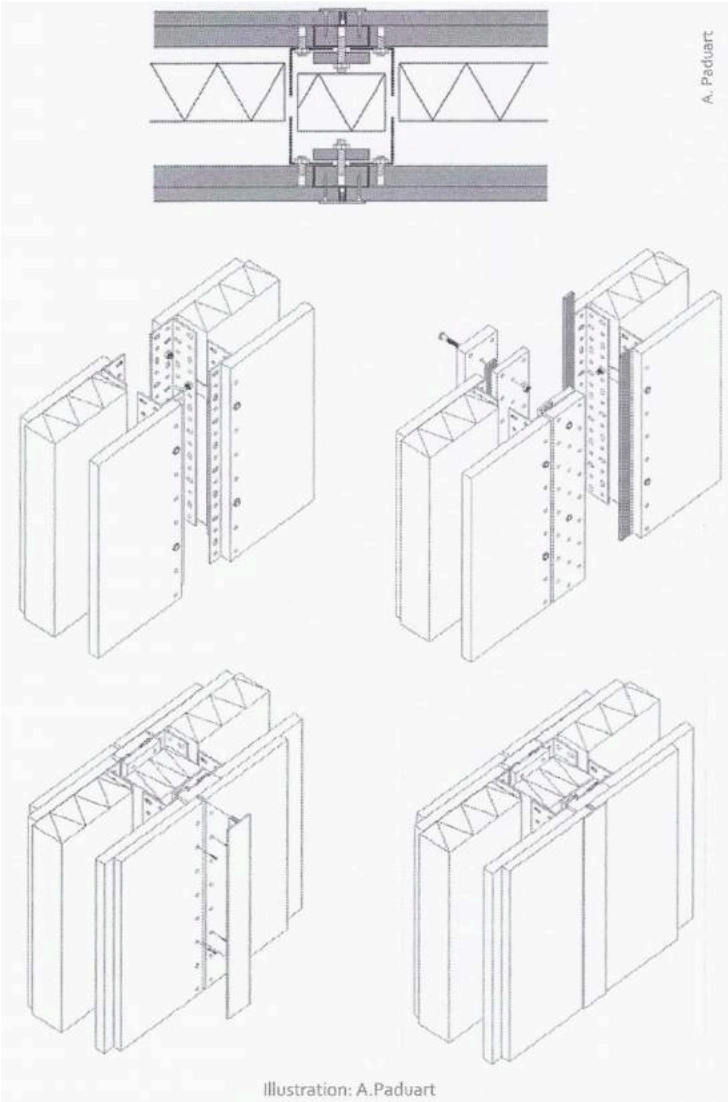


Figure 5.13: Assembly of preassembled panels finished on site, source: [PADUART, 2012, p166]

Other situations are also illustrated. For example, the linear connection with an existing column is shown in plan in Figure 5.14. This can be used for partitioning walls when the existing column-beam structure remains the same.

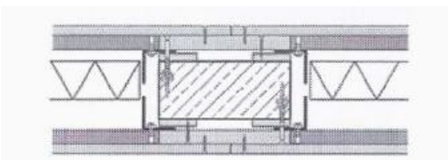


Figure 5.14: Linear connection with existing column, horizontal section, source: [PADUART, 2012, p172]

Another example is the connection with an existing ceiling, illustrated in Figure 5.15. The connection combines the preassembled panel with a wooden ceiling finishing. The panels are connected to the ceiling with steel L-profiles.

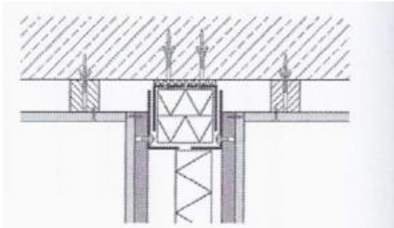


Figure 5.15: Connection with the ceiling, vertical section, source: [PADUART, 2012, p172]

The last example is the connection with an existing floor beam, as shown in Figure 5.16. The principles stay the same as the connection with the ceiling illustrated above, but additional horizontal elements are needed.

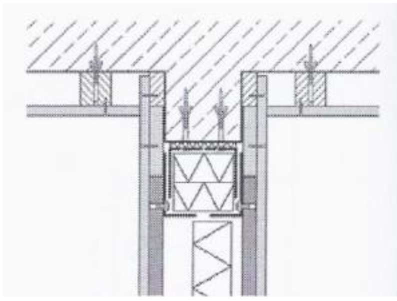


Figure 5.16: Connection with an existing floor beam, source: [PADUART, 2012, p172]

5.5.4 Connections in the partitioning walls of the Brigittinnen apartments case study

For the case of the Brigittinnen apartments, the preassembled panels are designed based on the Holz100 principles. The walls are preassembled wooden panels with dry connections, illustrated in Figure 5.17. The preassembled wall is composed of two finishing oak boards on both exterior sides, separated by OSB plates in T-shape. The T-lamellas are shaped in order to enable a parallel assembly sequences. The pins that connect the wooden panels to each other are also made of wood. The system of Holz100 is used: in dry circumstances (prefab inside), the pins are placed in the foreseen holes in the lamellas; in real circumstances (in situ), the water absorbed by the pins induces their swelling, which forms the connection. For disassembly, the preassembled panels are simply dried in the factory again.
The assembly on site is possible thanks to steel L- and U-profiles. Wooden or aluminium frames would have been possible as well, but the steel connection elements had the advantage to form hole tubes that could be used for electrical conducting.

A horizontal section of the assembly of the partitioning walls is given in Figure 5.17. The linear connection between the panels consists of steel L-profiles, where the connection with the existing column is composed of a wooden frame and steel L-profiles.

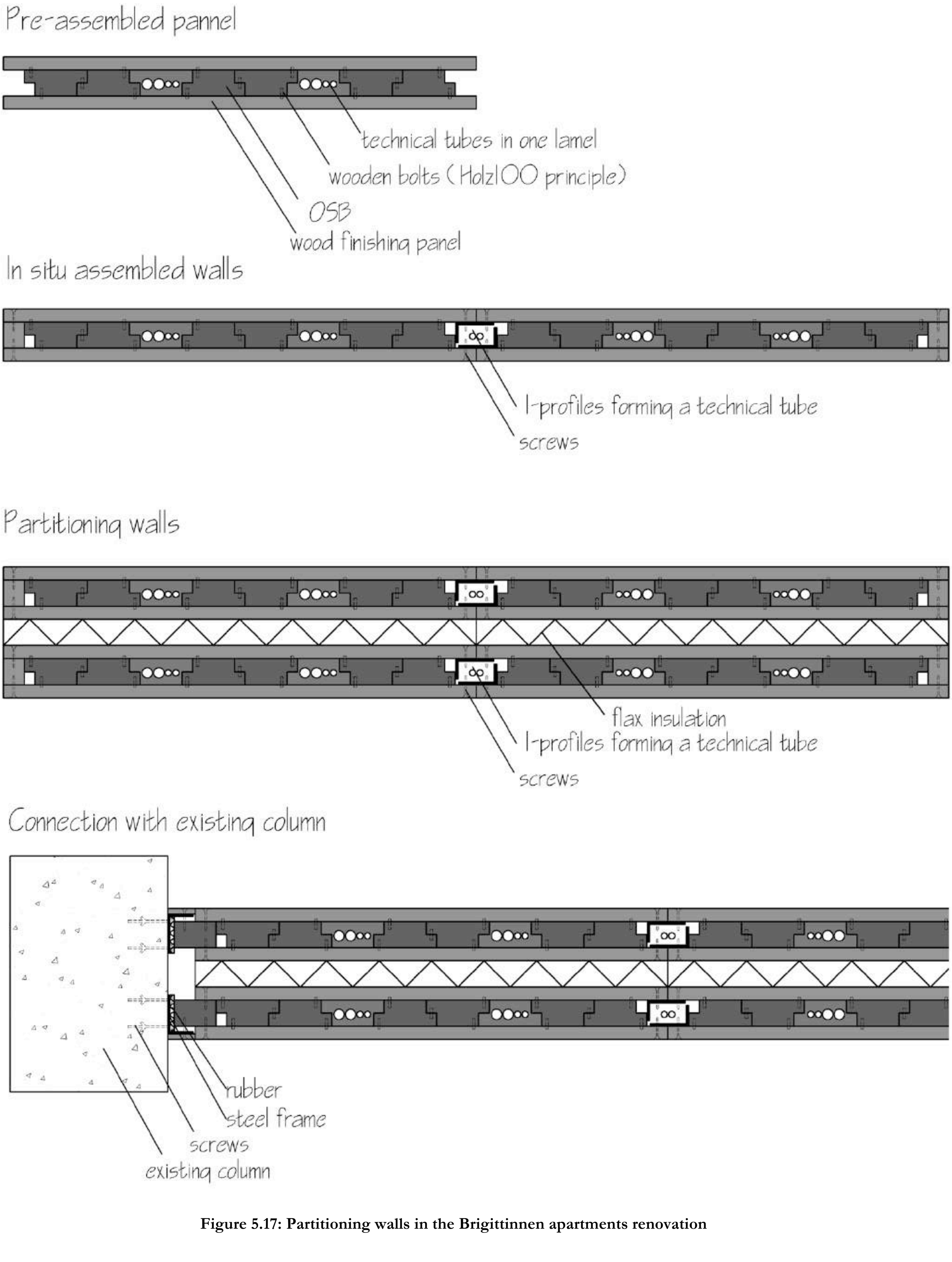


Figure 5.17: Partitioning walls in the Brigittinnen apartments renovation

A 3D exploded view in Figure 5.18 explains the assembly sequences of the partitioning walls.

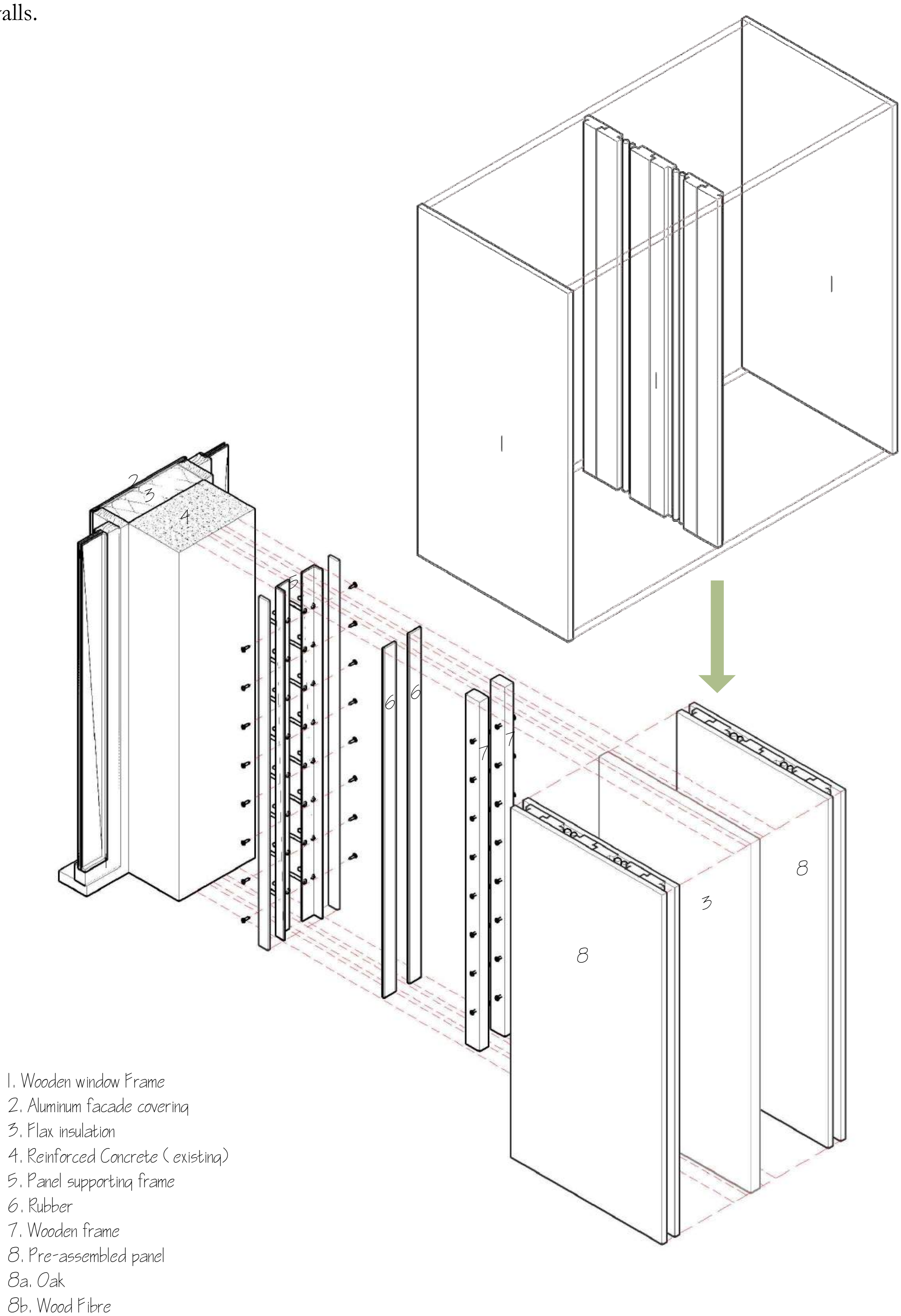


Figure 5.18: Partitioning walls in the Brigittinnen apartments renovation

The connection to the ceiling and the floor is illustrated in Figure 5.19.

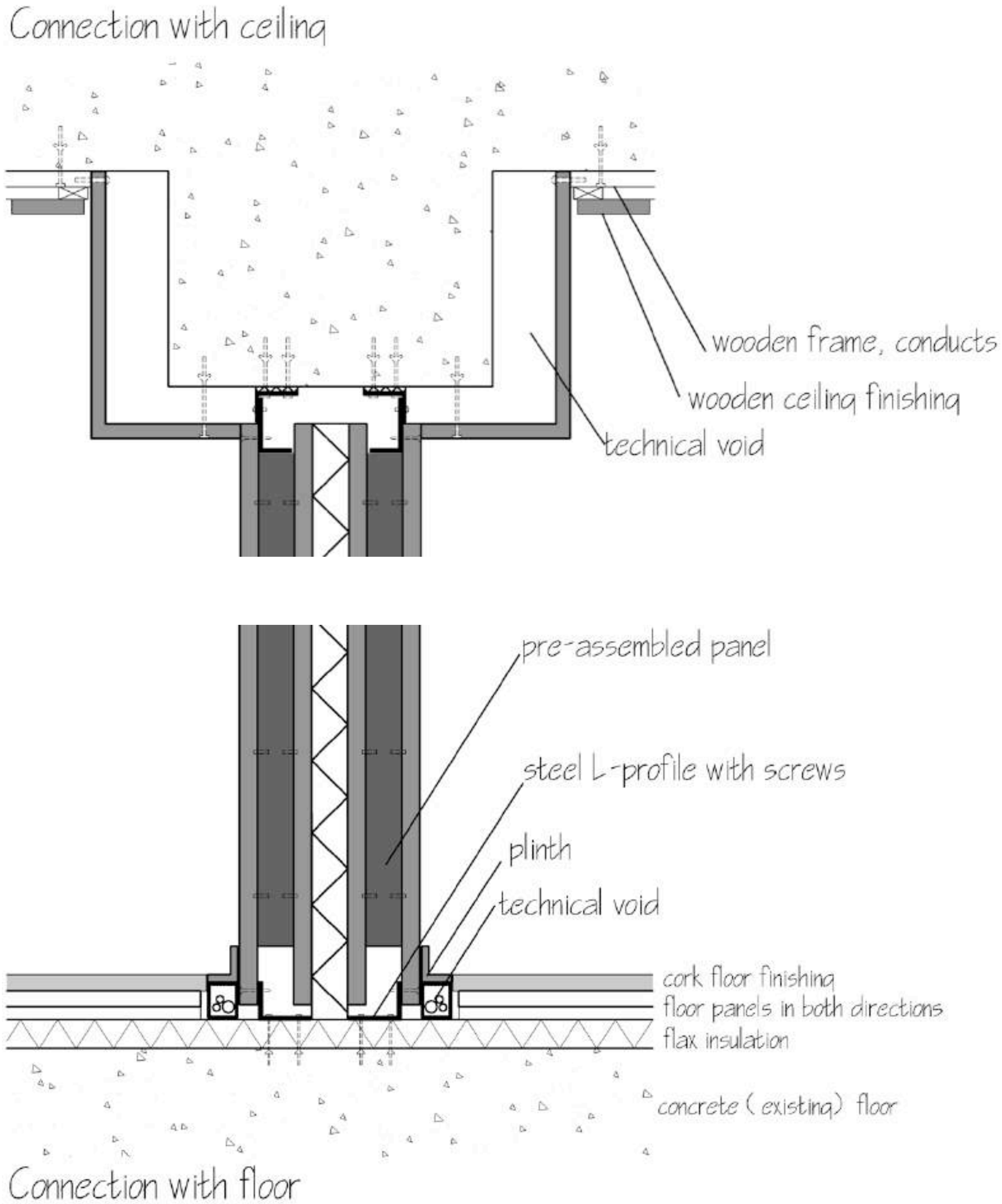


Figure 5.19: Connection of the partitioning walls with the floor and ceiling in the Brigittinnen apartments

The connection with the floor and ceiling is explained further in paragraph 5.8 on the integration of the technical layer.

5.6 Sub-layering and connections in the internal walls

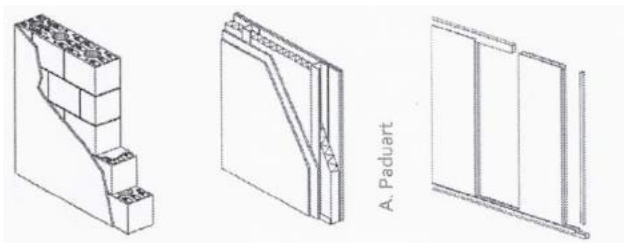
5.6.1 Internal wall sub-layering

This paragraph discusses the sub-layering of internal walls in general. The internal walls separate the different rooms within a dwelling unit. The acoustic, thermal and fire safety requirements for internal walls are consequently less important than for partitioning walls. The internal walls are therefore single-layered, perhaps with added finishing. The sub-layering is simple: finishing (f), single layer (s), finishing (f).

5.6.2 Renovation of internal walls within a dwelling unit: internal wall categories

The different definitions of existing internal wall categories are defined, according to [PADUART, 2012], as followed (see Figure 5.20):

- *Category 1*: single-layered brickwork wall
- *Category 2*: dry walls – metal studs or wooden battens
- *Category 3*: flexible system partitions in metal modular partitions with mineral wool as internal filler; excluded from residential projects because of the poor acoustical, thermal and fire safety performance



Category 1 *Category 2* *Category 3*

Figure 5.20: Internal wall categories

5.6.3 Material connections in the internal walls

The material connections discussed in the previous paragraph on partitioning walls can also be applied to internal walls, with fewer restrictions on insulation and fire safety. An additional connection exampled is illustrated in Figure 5.21, where the assembly on site is in different directions.

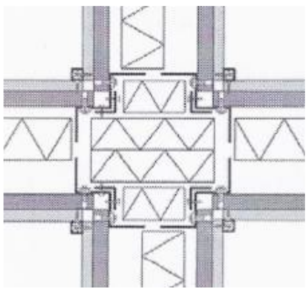


Figure 5.21: Connection of the preassembled panels finished on site in different directions, horizontal section, source: [PADUART, 2012, p172]

A last example of transformable wall connections is the adaptations against an existing wall (see Figure 5.22).

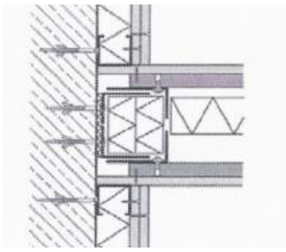


Figure 5.22: Connection with existing wall, horizontal section, source: [PADUART, 2012, p172]

5.6.4 Connections in the internal walls of the Brigittinnen case study

For the internal walls, the same preassembled panels as those developed in this dissertation for the partitioning walls are chosen, to obtain a unity during construction and in the interior.

The 3D view (see Figure 5.23) of the internal wall connections illustrates the use of the holes formed by the connecting L-profiles for electrical wiring. The green colour indicates the possible ways in which the electrical network can function: either in the pre-assembled panels through the foreseen tubes with pulling cables or through the tubes formed by the connecting L-profiles. A plinth is clipped on the technical void between the floor finishing and the wall. Every 30 cm, this plinth can be removed for accessibility to the technical void.

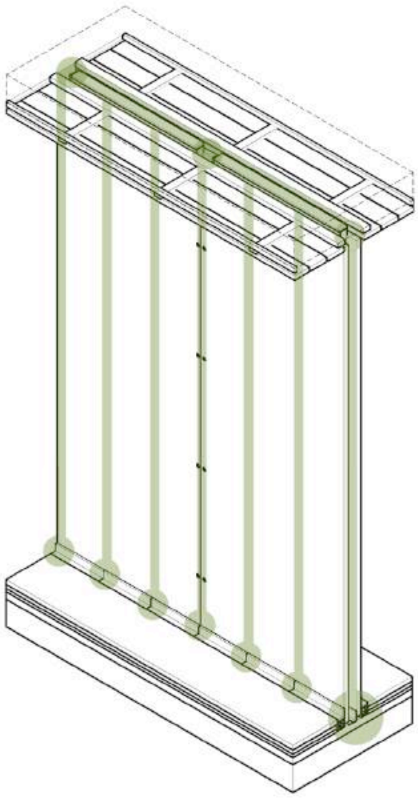


Figure 5.23: 3D view of internal wall connections

The connections (screws) between the panels are visible in the interior design of the apartments. This is a design choice where all connecting elements are left visible, to accentuate the transformable character of the spaces.
The plan and section details of the different connections are given in Figures 5.24 and 5.25.

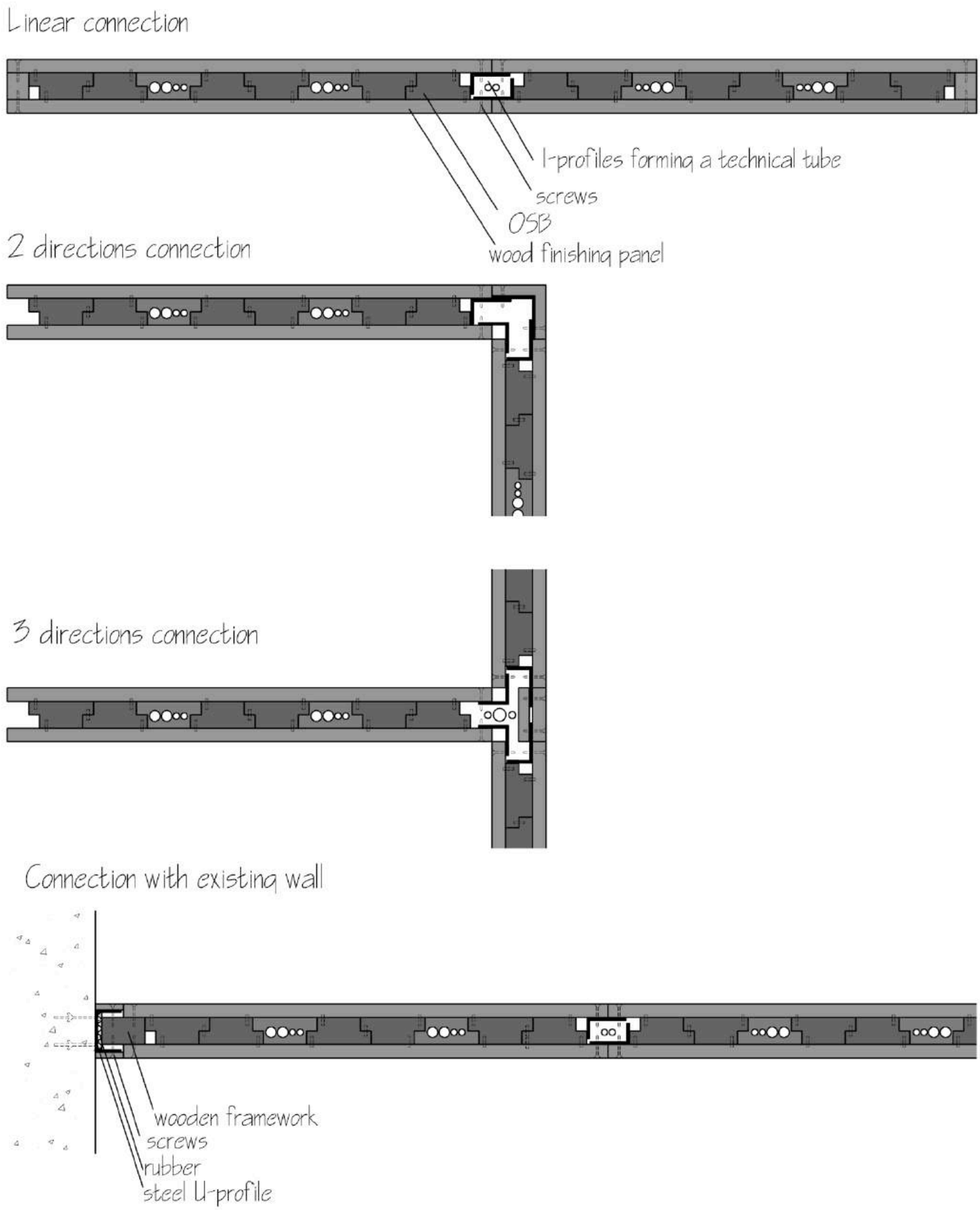


Figure 5.24: Internal walls: linear and more directions connection

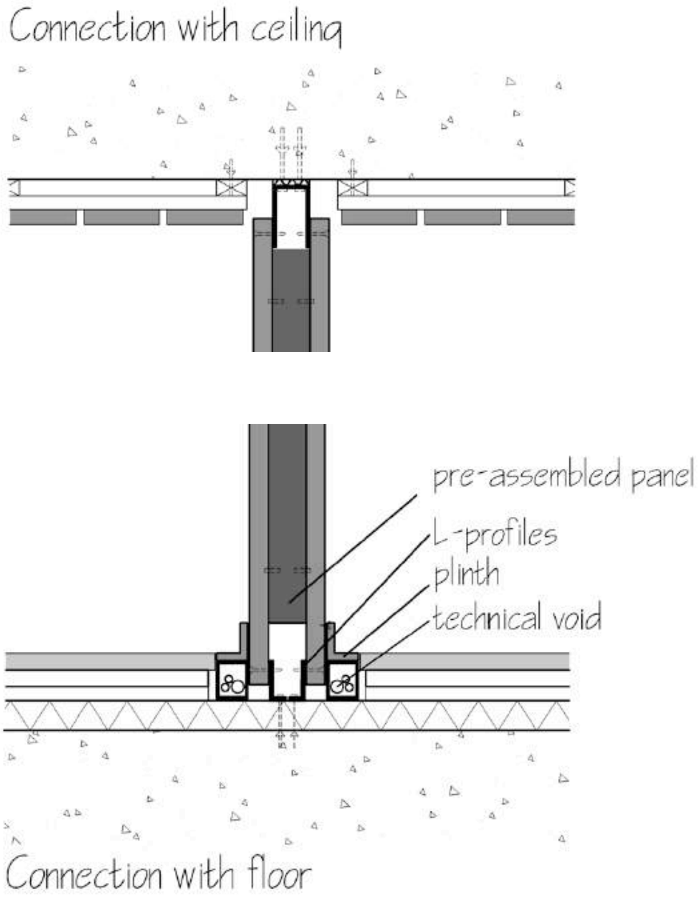
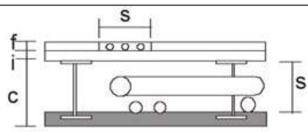
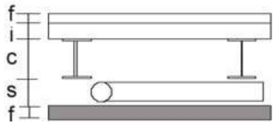


Figure 5.25: Connection with floor and ceiling of the internal walls

5.7 *Sub-layering and connections in the separating floors*

5.7.1 Separating floor sub-layering

This paragraph illustrates the sub-layering of separating floors in general. For separating floors, the composition can also be divided in sub-layers. The different combinations lead to a ranging of floors from fixed to demountable (see Table 5.7). The recurrent sub-layers are the finishing (f) of the ceiling and floor, the servicing (s) which can be totally or partially integrated in the other sub-layers, the construction itself (c) and the acoustic insulation (i) [DURMISEVIC, 2006, p166].

	Sub-layers	Composition	
Fixed	[c s f]		Total integration
	[c s] i [f s]		Planned interpenetration
	c [i s] f		Unplanned interpenetration
Dynamic	f s c i f		Total separation

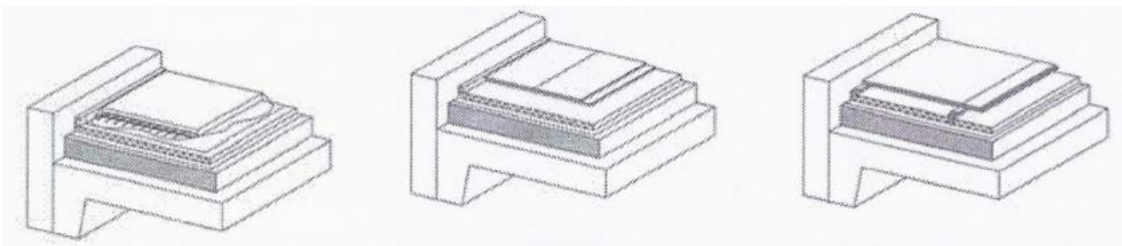
c = construction, f = finishing, s = servicing, i = insulation

Table 5.7: Function autonomy levels of sub-layers in separating floors, based on: [DURMISEVIC, 2006, p166]

5.7.2 Renovation of separating floor categories in urban dwellings: separating floor categories

The different definitions of separating floor categories are defined, according to [PADUART, 2012], as followed (see Figure 5.26):

- *Category 1*: floating screed floor construction with integrated technical installations
- *Category 2*: dry floating floor – gypsum or wooden decking panels are continuously supported and not fixed to the floor base
- *Category 3*: self-supporting dry floating floor – timber battens or joists support at regular intervals



Category 1 *Category 2* *Category 3*

Figure 5.26: Separating floor categories [PADUART, 2012, p 100]

5.7.3 Material connections in the separating floors

The IFD program created demountable floor systems. Two examples are illustrated in Figures 5.27 and Figure 5.28 [DEBACKER, 2009].

The first example mainly uses a steel structure. The floor is composed of a gypsum board (1), a corrugated steel deck (2), an acoustical strip (3), a steel cassette (4), a service shaft (5), a thermal insulation (6) and an integrated steel beam (7) [DEBACKER, 2009].

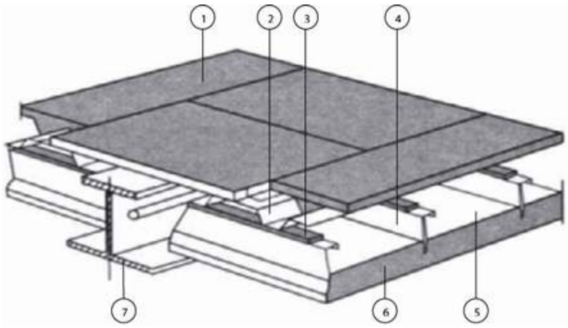


Figure 5.27: IDES floor system, source: [DEBACKER, 2009, p35], adapted from [PADUART, 2006]

The second example uses a combination of wooden and steel frameworks on a concrete slab. The composition is as followed: a fibreboard on top (1), a timber framework (2), service ducts (3) integrated in steel beams (4) on top of a concrete slab (5).

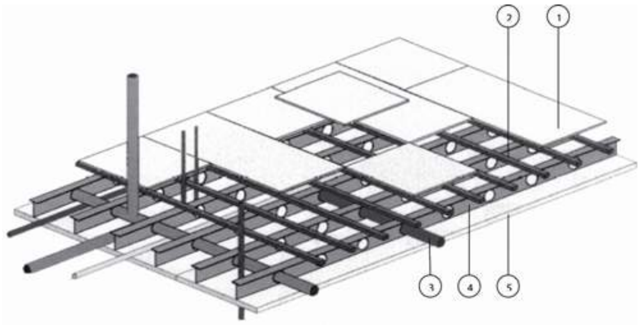


Figure 5.28: INFRA+ floor system, source: [DEBACKER, 2009, p35], adapted from [PADUART, 2006]

5.7.4 Connections in the separating floors for the Brigittinnen case study

In the case study of the Brigittinnen the core of the separating floors (15 cm concrete) remains the same. The finishing's on both sides are renovated to allow flexible conducting, with particular attention to a minimum of height, due to the limited storey height of this typical post-war residential building.

The next solution for the separating floors is proposed (Figure 5.29). The existing concrete layer is covered by natural acoustic insulation made of flax, covered by a vapour barrier and a network of wooden panels to create a massive layer above the acoustic insulation. The finishing is composed of cork panels. The ceiling itself is made of a wooden framework as well, in two direction so that the electrical wires can pass. The ceiling finishing is composed of wooden slats, separated to enable the expansion and contraction of the natural wood.

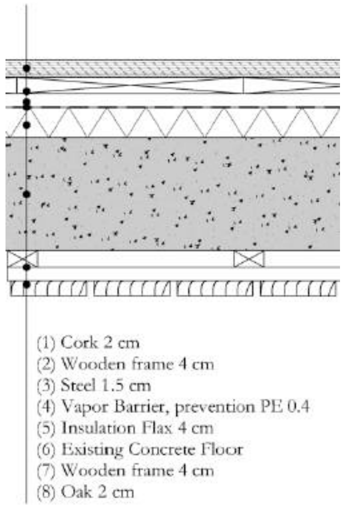


Figure 5.29: Separating floors in the Brigittinnen apartments

5.8 Integration of the technical layer in the connections

This section discusses the integration of the technical layer in the Brigittinnen case study. The integration of the technical layer is made possible thanks to different interventions that also increase acoustic comfort and help to deal with floor and ceiling unevennesses.

The connection of different preassembled panels is made of steel L-profiles and a wooden vertical spacer element, so that a technical void is created between the panels. This void (see Figure 5.30 left) can for example be used for the electrical wiring to the outlets. Furthermore, the preassembled panels include wiring tubes with pulling cables (see Figure 5.30 right), so that electrical outlets, lights and switches can be placed every 30 cm.

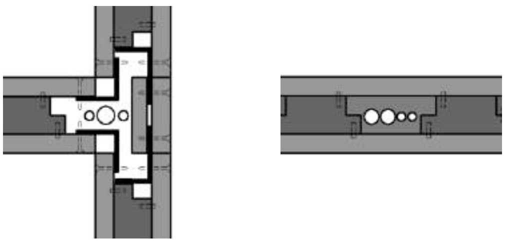


Figure 5.30: Integration of wiring in the walls, in connection zones (left) or in preassembled tubes with pulling cables (right)

The transition from horizontal networks to vertical networks is made clear in the drawing of Figure 5.31, where the green colour on the 3D view indicate these transitions.

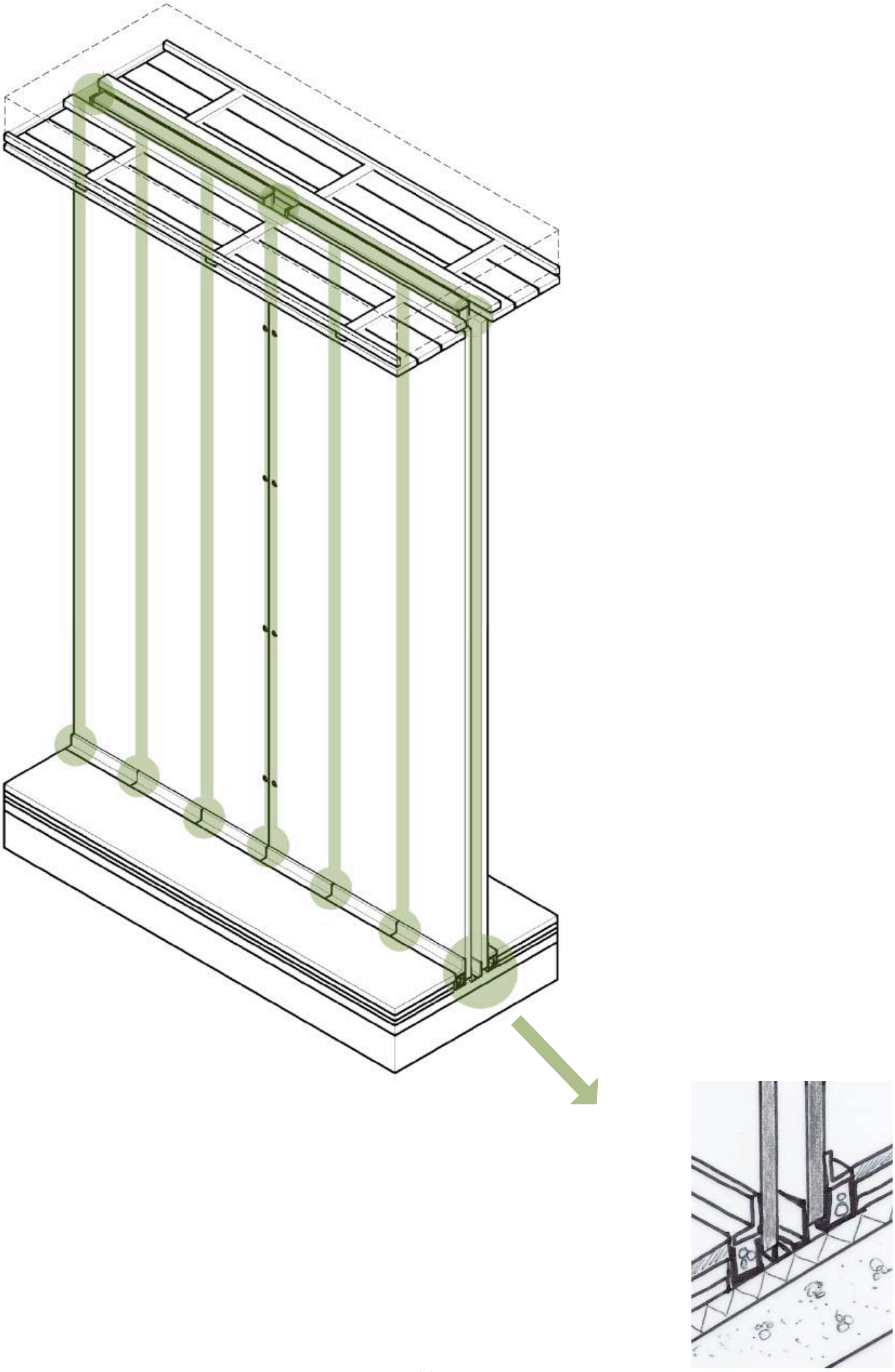


Figure 5.31: Technical layer

The biggest spaces are needed for ventilation and water conducts. Therefore, an extension of the existing concrete beams is foreseen with wooden panels that create a technical void against the ceiling and the partitioning walls, as shown in Figure 5.32.

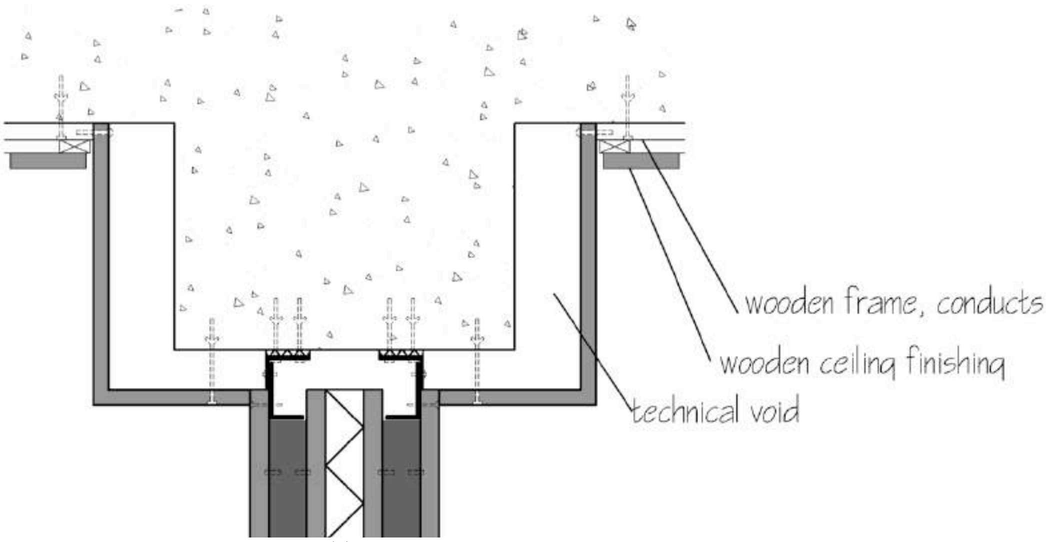


Figure 5.32: Technical layer against the ceiling, vertical section

For electrical wiring, the ceiling structure is made of a wooden framework in two directions, connected to the technical void of the connections between the pre-assembled panels (see Figure 5.33).

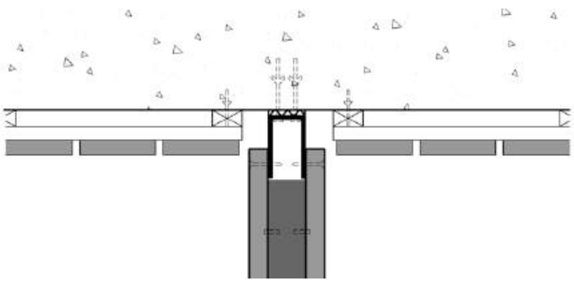


Figure 5.33: Ceiling structure and connection with an internal wall

5.9 Discussion

This chapter discussed the theory behind the connections. Connection detailing is the key factor of adaptable architecture, as it defines whether the building or its parts can be disassembled. The relations between components, the assembly sequences and connections were defined and applied to the Brigittinnen case study.

The connections between materials and components were discussed for each of the different building parts such as the façade, the roof, the separating floor, the partitioning and the internal wall. Aside from disassembly criteria, fire resistance, acoustic comfort, thermal performance and sufficient tolerance were taken into account. For the Brigittinnen apartments, solutions were designed for the various building parts, taking the criteria mentioned above into consideration.

During the elaboration of the connection details, different aspects appeared to be crucial. First, the assembly sequences define the shape and material choices. For example, in the partitioning walls, U-profiles cannot be used, since the fixations on the side of the flax insulation can only be screwed for one of both panels of the double wall.
The next observation was that the transformable character of the connections is only one of the many criteria to take into account when detailing. Sometimes a compromise is needed to satisfy all comfort and normative regulations.
Moreover, the connections define not only demountable components, but also the flexibility of conducts for water, electricity, etc.
Finally, the most important attitude when designing connection details is to ‘keep it simple’: when a complicated detail is difficult to execute on site, often a simpler but better alternative is possible.

6. Synopsis & conclusions

The final chapter of this dissertation contains a synopsis, conclusions and a base for further research. The *synopsis* summarizes the aims of this dissertation and the approach followed to come to a synthesis about four-dimensional design tools and the application in a design case study. The *conclusions* describe the benefits and innovative aspects, but also downsides of the research topic and results. Finally, *possible future research* on the subject is listed.

6.1 Synopsis

The aim of this dissertation on Life Cycle Design was to implement interactions between the building, component and material level in the re-design of residential high-rise buildings through sustainable material management. The four-dimensional design strategies were therefore applied to the renovation of a typical social housing apartment block of 1968, the "Brigittinnen" complex, in the Marollen neighbourhood in the centre of Brussels.

Table 6.1 summarizes the approach used in this dissertation. The steps towards the holistic dynamic re-design of residential high-rise buildings are as follows:

1. Chapter 1 describes a literature study and synthesis of existing four-dimensional strategies. The strategies are divided in design approaches, each in turn consisting of design tools and principles. The innovative aspects of the synthesis are the description of many overlaps between the various approaches, which results in a simplified total approach on the building level, component level as well as the material level.
2. The typological study of the existing metropolitan building stock in Chapter 2 revealed that the omnipresent post-war apartment blocks in Brussels need urgent renovation, making these buildings the most suitable cases for a case study.
3. The definition of existing households and corresponding timespans in Chapter 3 led to the development of living scenarios.
4. In Chapter 4, these scenarios were then used in a case study of a typical post-war apartment block, "The Brigittinnen", in order to test the four-dimensional strategies. A generating grid was used as the starting point for building flexibility, component assembly and material choices in this case study. Particular attention was given to the connections and detailing in Chapter 5.

These steps led to a proof-of-concept of the four-dimensional design strategies by implementing their principles and tools in the design case. The resulting design is not an end state, but an intermediate, adaptable solution.

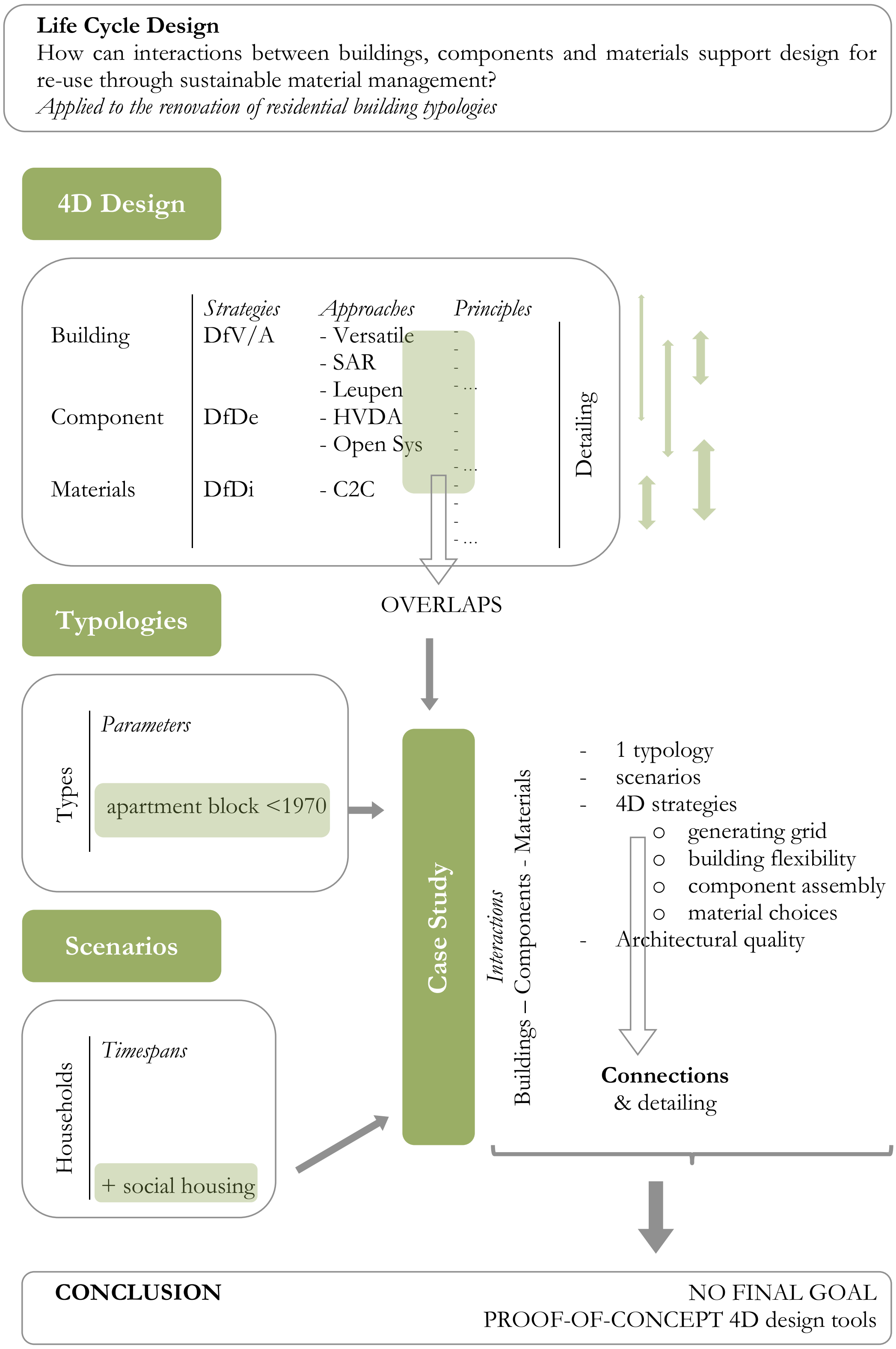


Table 6.1: Synopsis of the approach in this dissertation

Synthesis of four-dimensional design tools

One of the recurrent ***overlapping*** design *tools* is a (multi-) modular coordination system, which enables compatibility of components. This characteristic is necessary to allow potential reuse of components and adaptability of buildings. Physically, this should preferably be done by means of reversible connections and joints between the materials and components. *Detailing* is therefore the key element of re-use, whether the focus is on the building, the components or the materials.
The *goal* of the different design approaches is always improving a building (part) without imposing a final state, by introducing an intermediate, changeable building state. Therefore, connections and joints are particularly important.

Application of four-dimensional design case study: proof-of-concept

The case study of the "Brigittinnen" demonstrated the feasability of the strategies by successfully applying them to an actual construction. The impact of this design research led to a proof-of-concept of the life cycle re-design through interactions between the building, component and material level.

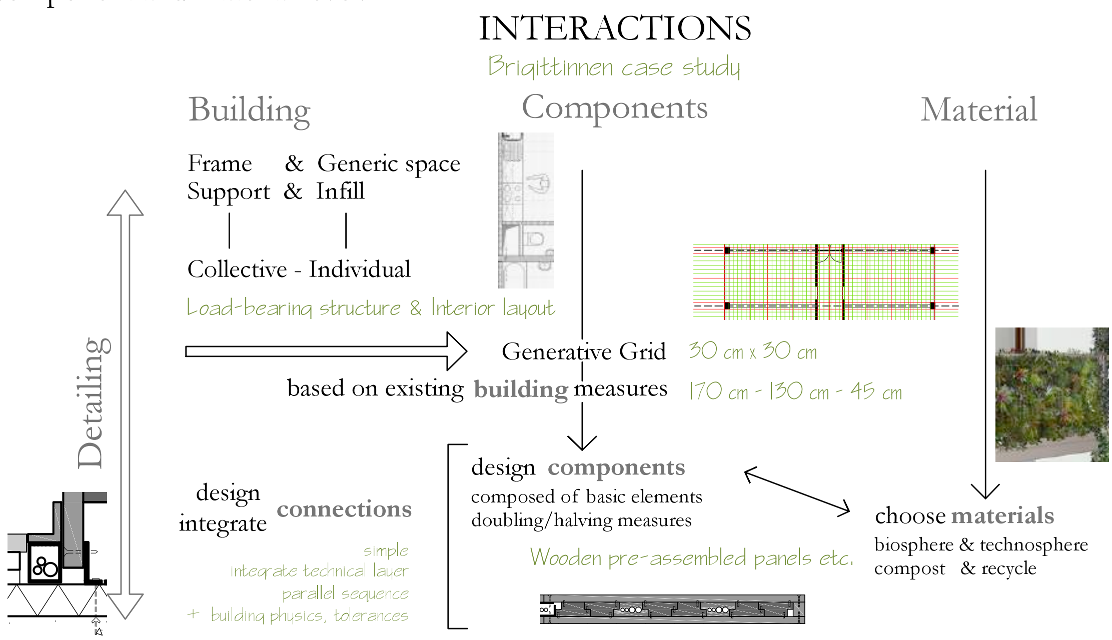


Figure 6.1: Interactions between the building, component and material level, applied on the "Brigitnnen" case study

Figure 6.1 illustrates the application of the total 4D design approach developed in Chapter 1 on the case study of the "Brigittinnen" apartments. 4D design principles, tools and goals from the building, component and material level are integrated. The "frame and generic space"-concept is the departure point of the renovation: the existing load-bearing structure remains the same, with an adaptable new interior layout. A generating grid is developed, based on the specific measurements of the building, in order to design multi-modular components. Connections between components are influenced by the material selection, which is based on Cradle to Cradle principles. Detailing of reversible connections is a crucial factor for a 4D design attitude in this case study. The design of connections must be simple, leading to an easily demountable construction with attention to the assembly sequences and dimensioning tolerances, integrating the technical layer as well as satisfy conventional building physics regulations.

6.2 Conclusions

Important conclusions considering Life Cycle Design result from this dissertation. Introducing sustainable material management into the re-use of end-of-life buildings allows responding to evolving environmental, economical and social needs. Constant changes in living patterns increase the need for faster responses and adaptable architecture. The application of a total (building–component–material) approach in four-dimensional design on a typical case study demonstrates the possible re-use of end-of-life buildings. This adaptable re-use responds to the problem of limited landfill space, reduces considerably demolition waste and corresponds to the increasing environmental awareness.

The innovative aspect resulting from the literature study is the development of a synthesis of four-dimensional design tools and principles, based on a comparative analysis. The overlapping ideas led to an easier unified four-dimensional design approach integrating the interactions between the building level, the component level and the material level. This holistic approach is applied to the renovation of existing buildings and can be implemented by following a set of principles, guidelines and tools. The most important result of this approach is the overall consideration of four-dimensional design on three levels.
The balance between permanent and changeable aspects of the renovated building stock is found by using the "frame and generic space" concept. The buildings' frame (the permanent part) symbolises a communal supporting structure, whereas the generic space enables an individual infill of the frame. The existing building measurements are then analysed to generate a modular grid to enable compatibility with building independent components. The modular measurements and component design are linked to the selection process that determines which biodegradable or recyclable materials can be used. The design and detailing of connections integrates the compatibility between components in a total approach. Hence, the added value of this total approach to transformable architecture is that it integrates different strategies over the range of existing scales in adaptable building.

Equally important to the theoretical development and detailing of a unified four-dimensional design approach, was the feasibility test of the newly developed unified approach in a case study design. A typological study showed the post-war apartment blocks are the most common dwelling type in need for a renovation. This led to the choice of a representative design case: the "Brigittinnen" complex, a social apartment block in the centre of Brussels. The innovative approach used in the case study of this dissertation can help with finding a four-dimensional alternative to the demolition of these buildings. The advantage of applying the theoretical findings on this case is to refine the unified design approach. However, other typologies should be analysed as well in order to develop a more general approach.

Another intermediate result of this dissertation, aside from the typological study, was the development of existing and likely future living pattern scenarios. The configuration of the current Belgian households and their evolution was studied, as well as social housing demands, in order to develop different living pattern scenarios that can be used in design cases. The developed scenarios used in the practical case of the "Brigittinnen" could also help in further research for other building types.

The scenarios applied on the case study resulted in a design project integrating the interactions between the building, the component and the material levels. The diverse aspects of the unified design approach resulting from the literature synthesis were tested in practice through the "Brigittinnen" case study. The design of a flexible building with adaptable components and re-usable materials led to adjustments, nuances and more detailed guidelines in the developed unified four-dimensional design approach. The detailing of the adaptable connections enabled new insights on the practical side of 4D design.

The proof-of-concept of four-dimensional design aspects on different levels leads to a starting point for a complete strategy of adaptable architecture. The synthesis of the interactions between the building level, the component level and the material level as well as the application in the case study demonstrated the feasibility of transformable architecture.

6.3 Further research

Based on the approach developed in this dissertation, the following paths are open for exploration:

- *Other typologies and case studies* should be analysed. This dissertation only analysed one representative typology. In metropolitan areas, as well as in others, the building stock includes many other building types. This will further test the validity of my implementation of the interactions in this dissertation and its applicability on other typologies.

- The presented research could be *extended to the district level.* This dissertation focused on the interactions between three levels: materials, components and buildings. However, life cycle design is also applicable to the district level. Further research could integrate this fourth level.

- *Establishment of a second-hand market for components and materials and collaboration with product manufacturers* would greatly increase the potential of the developed concept. A market where second-hand building components or materials are available and can be exchanged from one project to another would support the implementation of Life Cycle Design in the society.
  For the compatibility of components from one project to another, modular coordinating rules, based on a fractal generating dimensioning system, should be defined in accordance with the product manufacturers. Moreover, joints that can act as adapters between multi-modular and non-standard components should be developed.

- *A political and financial framework* is needed. In order to stimulate re-use of buildings and components or the recycling of materials, solutions need to be proposed to deal with existing financial and legislative constraints, so that short term support measures reinforce long-term life cycle design benefits. Solutions might be subsidies or eco-taxes, penalty taxes for waste, an integrated product policy, etc. Aside from political and economical measures, social measures that stimulate the growth of a re-use culture could also influence the demand for adaptable solutions.

- *Assessing* four-dimensional buildings can eventually permit ranking and scoring them. Existing assessment methodologies today pay attention to certain levels. However, the interactions are not implemented adequately. The follow-up of this dissertation could include an assessment of the case study. Scoring the different life cycle principles could scale the feasibility of adaptable design.

6.4 Final thought

By developing a proof-of-concept of interactions between different four-dimensional strategies through a case study, this dissertation contributes to the concept of a circular-flow economy, where resources are managed in a sustainable way, so that re-designing architecture is supported by interactions between the building, its components and its materials.

"Change is the only constant" – Georg Giebeler
[GIEBELER, 2010, p 16]

References

Archives

[BRUSSELS archive a] Brussels, Archive of the City Brussels, *Section Administrative Archive,* Brigittinnenstraat, Huidevettersstraat 65, 1968.

[BRUSSELS archive b] Brussels, Archive of the City Brussels, ASB ARCH 85, *Section Administrative Archive,* Le Foyer Bruxellois – rue des Brigittines. Projet de construction du complexe des Brigittines – 1959. Avant-projet d'extension du complexe des Brigittines – 1968-1974. Plans et une photographie, Huidevettersstraat 65, 1974.

[BRUSSELSE HAARD] Brussels, Archive of the Brusselse Haard, *Plans and Sections Brigittinnen,* Papenvest 134/35, 1968-2007.

Books and articles

[ALBERTS & VAN DEN DOBBELSTEEN, 2001] ALBERTS K., VAN DEN DOBBELSTEEN A., *Milieueffecten van bouwmaterialen. Duurzaam omgaan met grondstoffen,* Technische Universiteit Delft, Delft, The Netherlands, 2001, 14-15, from: http://www.wegwijzerduurzaambouwen.be/pdf/174.pdf, (last consulted on January 29, 2012).

[ALLACKER et al, 2008] ALLACKER K., DE TROYER F., JANSSEN A., PUTZEYS K., *Sustainability, Financial and Quality Evaluation of Dwelling Types.*, *Note on selection of representative dwelling types – December 2008*, SuFiQuaD, Wetenschap voor een duurzame ontwikkeling, Programmatorische Federale Overheidsdienst Wetenschapsbeleid, Brussels, 2008, 41p.

[ALLACKER, 2010] ALLACKER K., *Sustainable Building – The Development of an evaluation method*, PhD thesis, Faculty of Engineering Katholieke Universiteit Leuven, Leuven, 2010, 464p.

[ALLACKER et al, 2011] ALLACKER K., DE TROYER F., DEBACKER W., DELEM L., GEERKEN T., JANSSEN A., PUTZEYS K., SPIRINCKX C., TRIGAUX D., VAN DESSEL J., *Sustainability, Financial and Quality Evaluation of Dwelling Types.*, *SuFiQuaD Summary, SSD Project SD/TA/12*, Science for Sustainable Development, Katholieke Universiteit Leuven Departement ASRO – VITO - BBRI, Brussels, 2012, 6p.

[ALLACKER et al, 2012] ALLACKER K., DE TROYER F., DEBACKER W., DELEM L., GEERKEN T., JANSSEN A., PUTZEYS K.,

SPIRINCKX C., TRIGAUX D., VAN DESSEL J., *Sustainability, Financial and Quality Evaluation of Dwelling Types.*, *SuFiQuaD Final Report, SSD Project SD/TA/12*, Science for Sustainable Development, Katholieke Universiteit Leuven Departement ASRO – VITO - BBRI, Brussels, 2011, 104p.

[AUSTIN et al, 2009] AUSTIN S., BROWN D., SCHMIDT III R., *Designing adaptable buildings*, in: proceedings of the 11th international Design Structure Matrix Conference, Greenville, South Carolina, USA, 12-13 October 2009, 4p.

[AUSTIN et al, 2011] AUSTIN S., EGUCHI T., GIBB A., SCHMIDT III R., *What is the meaning of adaptability in the building industry?*, in: proceedings of the CIB 16th International Conference on Open and Sustainable Building, Bilbao, Spain, 17-19 May 2010, 10p.

[BLUM & GHRULER, 2009] BLUM A., GRUHLER K., "Typologies of the built environment – an approach for inventory, benchmarking and monitoring towards sustainability", in: SASBE, *3rd International conference on smart and sustainable built environments,* in-house publishing, Rotterdam, Netherlands, 2009, p 6-7.

[BOSMA et al, 2000] BOSMA K., VAN HOOGSTRATEN D., VOS M., *Housing for the millions: John Habraken and the SAR (1960-2000)*, NAi, Rotterdam, Netherlands

[BOULANGER et al, 2009] BOULANGER P.-M., DEBOOSERE P., LAMBERT A., LESTHAEGE R., LOHLE-TART L., SURKYN J., WILLAERT D., *Huishoudens en gezinnen in België*, ATLAS: Valorisatie van de resultaten van de Sociaal-Economische Enquête 2001, Monografie 4: Huishoudens en gezinnen, FOD Economie, K.M.O., Middenstand en Energie, Algemene Directie Statistiek en Economische Informatie, Brussels, Belgium, 2009, 186p.

[BRAND, 1995] BRAND S., *How Buildings Learn: What Happens After They're Built?,* Penguine Ed., UK, 1995, 243p.

[BRAUNGART & MCDONOUGH, 2002] BRAUNGART M., MCDONOUGH W., *Cradle to Cradle: Remaking the Way We Make Things,* North Point Press, New York, USA, 2002, 197p.

[BRAUNGART & MCDONOUGH, charter] BRAUNGART M., MCDONOUGH W., *Cradle to Cradle Building Charter*, USA, 1p.

[UNCSD, 2007] United Nations Commission on Sustainable Development, *Framing Sustainable Development - The Brundtland Report – 20 Years On*, April 2007, 2p.

[DEBACKER et al, 2007] DEBACKER W., DE WILDE W. P., ELSEN S., HENDRICKX H, PADUART A, *Four-dimensional design: from strategies to cases – generation of fractal grammar for reusing building elements*, International Journal of Ecodynamics, 2, n° 4, 2007, p 258 – 277.

[DEBACKER et al, 2007b] DEBACKER W., DE WILDE W. P., HENDRICKX H, HENROTAY C., PADUART A, *Lowering the embodied energy of constructions through reuse of building elements*, in Proc. Of the 5th Int. Conf. on Design and Manufacture for Sustainable Development, Loughborough, UK, paper 32 on CD, 2007, 10p.

[DEBACKER, 2009] DEBACKER W., *Structural design and environmental load assessment of multi-use construction kits for temporary applications based on 4Dimensional Design,* PhD thesis, Vrije Universiteit Brussel, 2009, 370p.

[DE CONINCK & VERBEEK, 2006] DE CONINCK R., VERBEEK G., *Technisch-economische analyse van de rendabiliteit van energiebesparende investeringen. Eindrapport*, Brussels Instituut voor Milieubeheer, Bijzonder bestek nr. Energie/E04-154, Brussels, 2006, 131p.

[DE HAES et al, 2002] DE HAES UDO HA. FINNVEDEN G., GOEDKOOP M., HAUSCHILD M., HERTWICH E.G., HOFSTETTER P., JOLLIET O. KLOPFFER W., KREWITT W., LINDEIJER E., MULLER-WENK R., OLSEN S.I., PENNINGTON D.W., POTTING J., STEEN B., *Life-cycle impact assessment: striving towards best practice*, Society of Environmental Toxicology and Chemistry (SETAC), Pensacola FL, USA, 2002, 272p.

[DE MYTTENAERE, 2006] DE MYTTENAERE, K., *Vers une Architecture Soutenable.* PhD thesis, Louvain-La-Neuve: Architecture et Climat, 2006.

[DE TROYER, 2002] DE TROYER F., *Bouwen met prefab beton: een "ontwerpgids" en "ontwerpvrijheid", een uitdaging*, FEBELCEM, Brussels, Belgium, 2002, 10p, available at: www2.asro.kuleuven.be/asro/english/home/fdt/, last consulted on February 2012.

[DE TROYER, 2002b] DE TROYER F., *Raster: hulp of hinder?*, from: bouwen met prefab beton – Ontwerpgids, FEBELCEM, Brussels, Belgium, 2002, 12p, available at: www2.asro.kuleuven.be/asro/english/home/fdt/, last consulted on February 2012.

[DE TROYER & KENIS, 2003] DE TROYER F., KENIS R., *Industrieel, flexible en demontabel bouwen. Toekomstgericht ontwerpen*, FEBE, WTCB, Katholieke Universiteit Leuven, editor: Van Dessel J., Leuven, Belgium, 2003, 76p, available at: www.IFDbouwen.be, last consulted in March 2012.

[DURMISEVIC, 2006] DURMISEVIC E., *Transformable Building Structures*, PhD thesis, Technical University of Delft, Delft, The Netherlands, 2006, 306p.

[DE ZEEUW et al, 1997] DE ZEEUW P., GRAFE Ch., KÖRNIG N., LAMPE M., LEUPEN B., *Design and analysis*, 010 Publishers, Rotterdam, the Netherlands, 1997, 224p.

[FRIEDMAN, 2002] FRIEDMAN, A., *The Adaptable House – Designing Homes for Change*, McGraw-Hill, New York, USA, 2002, 272p.

[GALLE, 2011] GALLE W., Time-Based Design, Over de aanpasbaarheid en het ontwerpen van gebouwen, Master Dissertation, Vrije Universiteit Gent, Ghent, Belgium, 2011, 108p.

[GIEBELIER, 2010] GIEBELIER G., *Renovating residential buildings: Change is the only constant*, from: Daylight & architecture magazine by VELUX, issue 14, Horsholm, Denmark, autumn 2010, p16-31.

[GWPE, 1984] VAN CAENEGEM R.C., GROENMAN Sj., LAUWERIER H.A., LISSENS R.F., MENGELBERG M.M.C., *Grote Winklerprins Encyclopedie,* Elsevier, Amsterdam/Brussel, 1984, 25 delen, achtste druk.

[HABRAKEN, 1961] HABRAKEN N.J., *De Dragers en de Mensen: Het einde van de massa Woningbouw,* Scheltema & Holkema N.V., Amsterdam, The Netherlands, 1961, 130p.

[HEIJNE et al, 2005] HEIJNE R., LEUPEN B., VAN ZWOL J. (eds.), *Time-based Architecture*, 010 Publishers, Rotterdam, 2005, 249p.

[HENDRICKX & VANWALLEGHEM, 2002] HENDRICKX H., VANWALLEGHEM H., *Solutions derived from natural processes harmonising nature and material culture*, Department of Architecture, Vrije Universiteit Brussel, Brussels, Belgium, 2002, 11p.

[HENROTAY, 2008] HENROTAY C., *A contribution to an integrated and more sustainable design approach for the material support of shelter after disaster*, PhD thesis, Vrije Universiteit Brussel, 2008, 513p.

[KENDALL & TEICHER, 1999] KENDALL S., TEICHER J., *Residential Open Building*, Spon Press, UK, 1999, 314p.

[KRONENBURG, 2007] KRONENBURG R., *Flexible – architecture that responds to change,* Laurence King Publishing Ltd, London, UK, 2007, 240p.

[LEE, 1971] LEE M. E., *The Habraken Support System: some implications with respect to the American context*, Massachusetts Institute of Technology, Boston, USA, 1971, 71p.

[LE ROY & STOUTHUYSEN, 2009] LE ROY D., STOUTHUYSEN P., *Cradle to Cradle: Theoretical framework*, European Union, European Regional Development Funt, Interreg IVC (innovation and environment, regions of Europe sharing solutions), printed by Gruppo Stampa GB, Cologno Mnzse (MI), Italy, 2009, 28p.

[LEUPEN, 2006] LEUPEN B., *Frame and generic space. A study into the changeable dwelling proceeding from the permanent*, 010 Publishers, Rotterdam, the Netherlands, 2006, 254p.

[PADUART, 2006] PADUART A., *Ontwerp voor aanpasbare transithuisvesting: bouwfysische en bouwtechnische detaillering - Ontwerp van een trefcentrum verbonden met transithuisvesting,* Dissertation, Vrije Universiteit Brussel, Brussels, Belgium, 2006, 195p.

[PADUART, 2012] PADUART A., *Re-design for change, A 4Dimensional renovation approach towards a dynamic and sustainable building stock,* PhD thesis, Vrije Universiteit Brussel, Brussels, Belgium, 2012, 402p.

[PUTZEYS & VAN DESSEL, 2004] PUTZEYS K., VAN DESSEL J., *TIS IFD Thema-artikel 1: Wat is IFD bouwen?*, editor: Van Dessel J., 2004, 12p, from: www.IFDbouwen.be, (last consulted in March 2012).

[RUSH, 1986] RUSH R. D., *The building systems integration handbook*, John Wiley & Sons, New York, USA1986, 445p.

[SLAUGHTER, 2001] SLAUGHTER E. S., *Design strategies to increase building flexibility,* Building Research & Information Volume 29 Issue 3, 2001, p208-217.

[SURKYN & WILLAERT, 2008] SURKYN J., WILLAERT D., *Bevolkings- en huishoudensprojecties, en schatting van de toekomstige woningvoorraad in het Brussels Hoofdstedelijk Gewest*, Interface Demography, Vrije Universiteit Brussel, Brussels, Belgium, 2008, 175p.

[TULP, 2009] TULP D., *De mogelijkheden voor het Cradle to Cradle concept in de Nederlandse woningbouw – Een verkenning van de huidige bouwmaterialen voor Nederlandse eengezinswoningen in relatie tot de Cradle to Cradle criteria*, Master dissertation, Technische Universiteit Eindhoven, Eindhoven, the Netherlands, 2009, 60p.

[VANDENBROUCKE, 2011] VANDENBROUCKE M., *Ontwerpend onderzoek van de Cradle tot Cradle benadering binnen kantoorbouw – haalbaarheidstudie op vlak van bouwmaterialen en technieken*, Vrije Universiteit Brussel, Brussels, Belgium, 2011, 144p.

[WTCB GROENDAKEN, 2006] Work group GROENDAKEN (president LOUWERS F.), *Groendaken technische voorlichting 22ç*, WTCB, Brussels, Belgium, 2006, 78p.

Interviews

[Int. Navez, 2011] Interview with Guénaëlle Navez, Brussels, 15 November 2011.

[Int. Brigittinnen, 2011] Interview with inhabitants Brigittinnen, Brussel, 16 December 2011.

[Int. Debacker, 2012] Interview with Wim Debacker, Mechelen, 27 January 2012.

[Int. BECKERS, 2012] Interview with Steven Beckers, Lateral Thinking Factory architect/consultant, from: IFMA (International Facility Management Association) Newsletter, January 2012.

Websites

[HCLA, 2012] HORDON CHERRY LEE ARCHITECTS, Yacht House, http://hcla.co.uk/oldsite/projects/?pid=61, (last consulted on 14 april, 2012).

[OVAM, 2012] OVAM, Afdeling Afvalstoffenbeheer wordt nieuwe afdeling Afval- en Materialenbeheer, http://www.ovam.be/jahia/Jahia/pid/2365, (last consulted on March 2012).

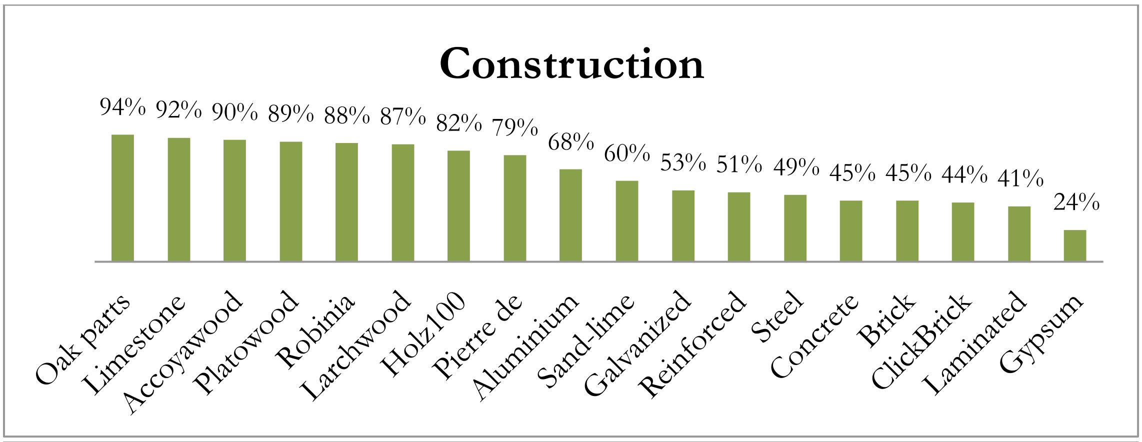
[STATISTICS BELGIUM] STATISTICS BELGIUM, Bebouwde gronden en aanverwante terreinen per gewest - in absolute cijfers (1985-2011), http://statbel.fgov.be/nl/statistieken/cijfers/leefmilieu/geo/bebouwde_gronden/, (last consulted on January 29, 2012).

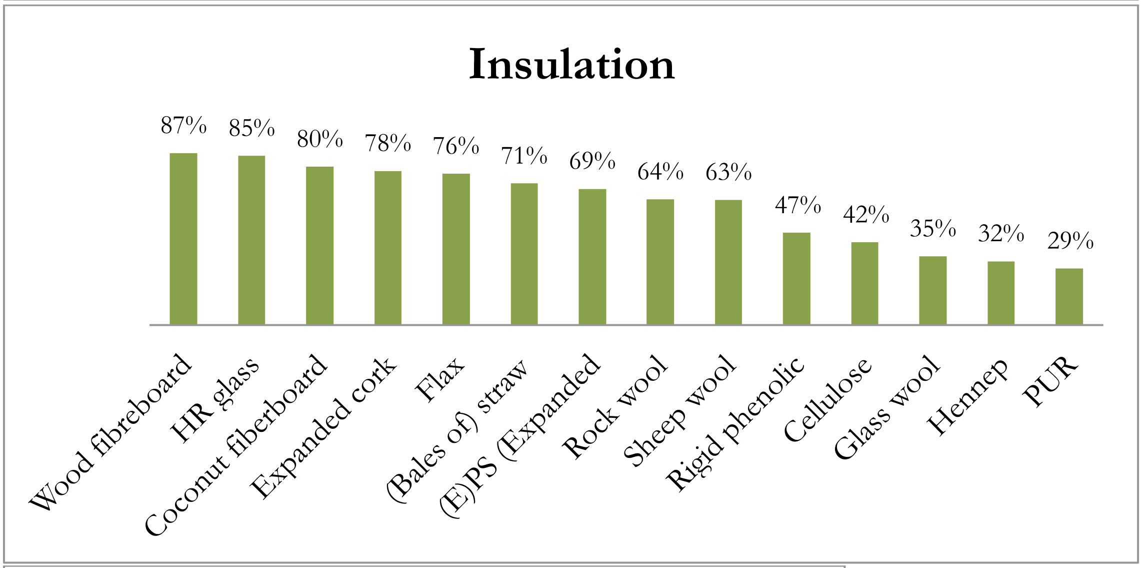
[USGBC, 2012] U.S. GREEN BUILDING COUNCIL, LEED, http://www.usgbc.org/, (last consulted on 22 April 2012).

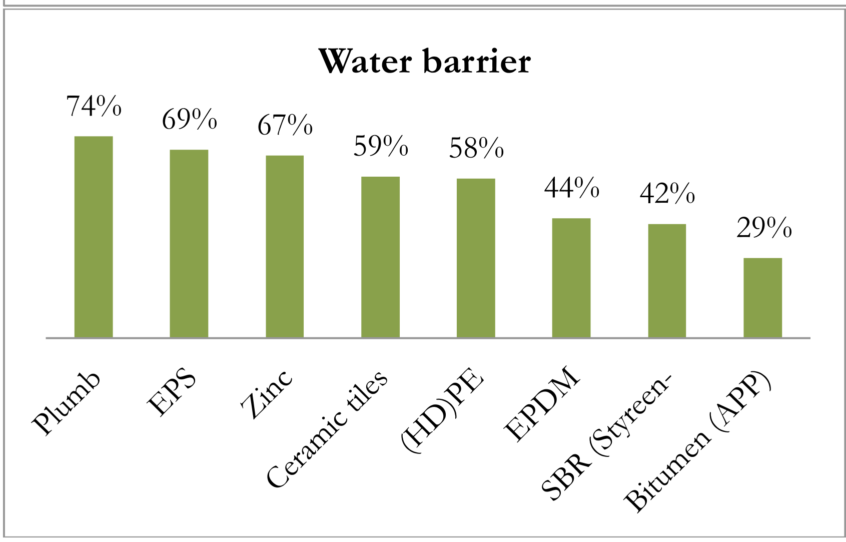
Appendices

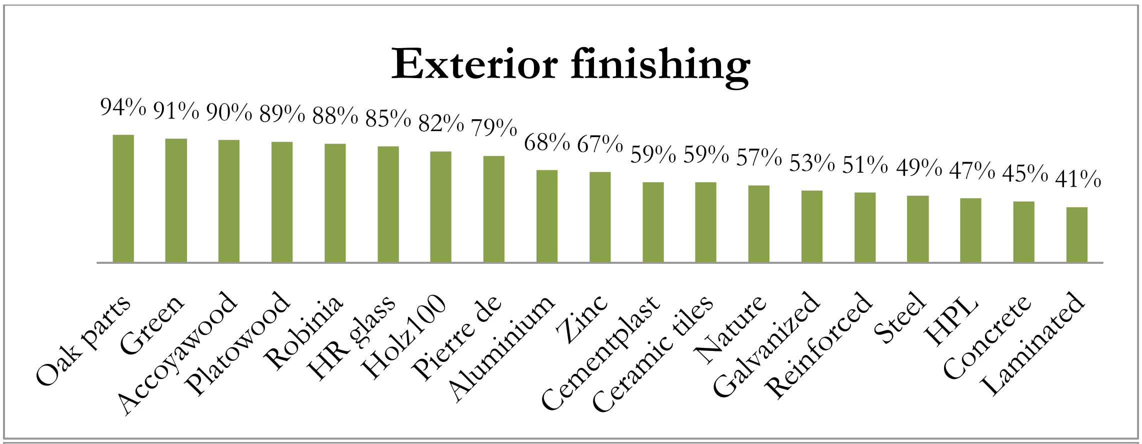
Appendix 1: Material scores – Tulp

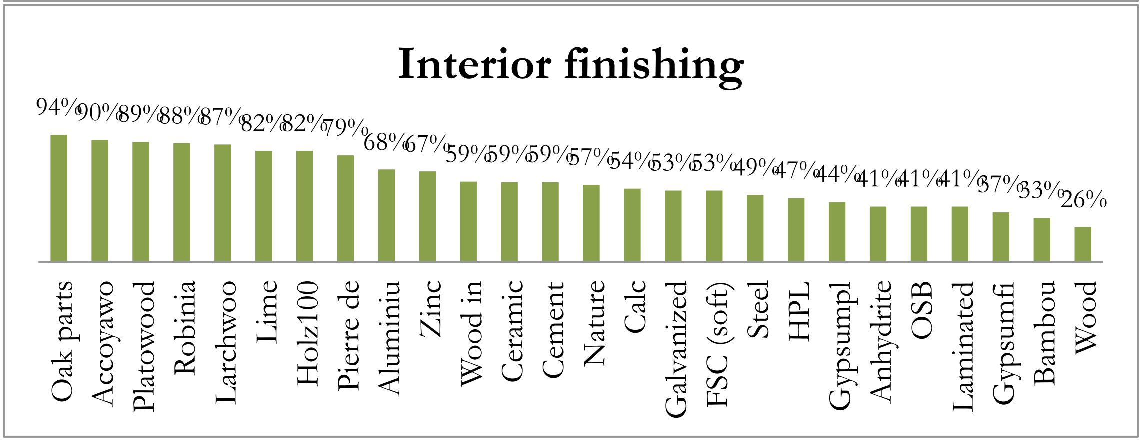
[TULP, 2009, p 45-47]








Exterior finishing
94% 91% 90% 89% 88% 85% 82% 79% 68% 67% 59% 59% 57% 53% 51% 49% 47% 45% 41%
Oak parts
Green
Accoyawood
Platowood
Robinia
HR glass
Holz100
Pierre de
Aluminium
Zinc
Cementplast
Ceramic tiles
Nature
Galvanized
Reinforced
Steel
HPL
Concrete
Laminated


Interior finishing
94% 90% 89% 88% 87% 82% 82% 79% 68% 67% 59% 59% 59% 57% 54% 53% 53% 49% 47% 44% 41% 41% 41% 37% 33% 26%
Oak parts
Accoyawo
Platowood
Robinia
Larchwoo
Lime
Holz100
Pierre de
Aluminiu
Zinc
Wood in
Ceramic
Cement
Nature
Calc
Galvanized
FSC (soft)
Steel
HPL
Gypsumpl
Anhydrite
OSB
Laminated
Gypsumfi
Bambou
Wood

Appendix 2: Cradle to Cradle Material list – Vandenbroucke

FOUNDATION
- Steel: Broken recycled crushed stone
- Poles: Wood from sustainable category 1

Ground improvement
- Sand
- Condensing
- Vertical drainage
- Electro-osmose

STUCTURE

Ground level
- Wood
- Lime
- Aluminium
- (Galvanized) steel

Floor level
- Wood
- Lime
- Aluminium
- (Galvanized) Steel

Pitched Roof
- Wood
- Aluminium
- (Galvanized) Steel

Walls
- Timber (Frame)
- Bales Of Straw Walls
- Straw Lime
- Limestone
- Pierre De Roches
- Aluminium
- (Galvanized) Steel

CLADDING
- Green Façade
- Wood
- Pierre De Roches
- Aluminium
- Zinc
- (Galvanized) Steel
- Copper

ROOFING
- Wooden slates from sustainable forestry
- Cane
- Aluminium
- Zinc
- Copper
- Flat roof: green roof

WATER BARRIER
- Polystyrene
- Zinc
- Polyethylene
- Bitumen
- EPDM

WIND BARRIER
- Wood fibreboard

INSULATION
- Wood fibreboard
- Coconut fibreboard
- Expanded cork
- Flax
- Bales of straw
- Hennep
- Cane
- Chafing
- Shells
- Cellulose
- Polystyrene
- Vermiculite
- Silicate – foam grains
- Expanded clay grains

ACOUSTIC INSULATION
- Elastic or vibration absorbing layer
- Wood fibre
- Flax
- Coconut matt
- Hard wood fibreboard
- Interior: Self-supporting steel floor system

SCREED
- Biofib

INTERIOR FINISHING
- Wood
- Wood panels without glue
- Cork
- Lime plaster
- Pierre de roches
- Aluminium
- Zinc
- Linoleum
- Galvanized steel

FLOOR CLADDING
- Wood
- Linoleum
- Expanded cork panels
- Matts from vegetable fibres

RAIN WATER DISPOSAL
- Zinc
- Aluminium
- Copper (also for pipelines)

SUNSCREEN
- Wood
- Aluminium
- Stainless steel

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