RE-DESIGN FOR CHANGE

a 4 dimensional renovation approach towards a
dynamic and sustainable building stock

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a 4 dimensional renovation approach towards a dynamic and sustainable building stock

Anne Paduart

Thesis submitted in fulfilment of the requirements for the award of the degree of Doctor in Engineering (Doctor in de Ingenieurswetenschappen) by

Anne Paduart

April 2012

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Abstract

A large amount of (social) housing projects was built on large scale before the 1970s, in a time where fossil fuels were still cheap and abundant and global warming was unheard of. This explains why today, in an era in which we have to face up new environmental challenges, these residential buildings are well-known for their excessive energy consumption in addition to their outdated living comfort. Since the number of new buildings annually constructed barely corresponds to 1,5 % of the building stock, it would take from 50 to 100 years to respond the necessity for more sustainable buildings exclusively with new construction. Hence, *renovation* of our existing building stock is a key strategy towards sustainability of our built environment.

During today's renovation buildings are being upgraded according to environmental and health problems known today: whilst the operational energy consumption is currently pushed down to near-zero and passive standard levels, the user comfort is upgraded to contemporary norms by adding the best technical solutions available. However, the lack of a holistic renovation approach may cause this short-term problem-solving to encounter several future setbacks. First, the question arises if these generally applied 'best solutions' necessarily enclose all answers to tackle future environmental problems concerning resource depletion and waste production? Next, recently developed technologies are being extensively applied while the long-term side-effects on the user's health and the environment are not yet fully understood. In addition, future building upgrade, functional alterations and radical building transformations are not anticipated although they inevitably take place due to demographic changes - such as fluctuating size, family composition and age structure of the average household - and future policy revisions in the framework of the European Energy Performance of Buildings Directives.

To anticipate these uncertainties and tackle the environmental impacts associated with each of these intervention processes *dynamic renovation concepts* must be incorporated, moving away from the current once-off design of finished building 'end' products. As a

main objective this PhD proposes an alternative renovation approach based on a *4 Dimensional Design Strategy* (4D) developed and investigated at the ARCH department of the Vrije Universiteit Brussel (VUB). Accordingly, the concept of '*Re-design for Change*' was introduced in this PhD dissertation, in order to enable buildings to deal with change over their building life cycle thereby tackling the excessive resource consumption and waste production - typical for the contemporary way of building. By incorporating the *time parameter* as variable design parameter future building scenarios can be better anticipated.

The research illustrates that re-design of buildings for change is a complex topic influenced by *design* factors (e.g. reversibility of assembly techniques, selection of reusable materials, preassembly of components), *evaluation* factors (environmental impacts and financial cost) and *contextual* factors (e.g. regulatory framework of residential buildings, dimensional grids in existing building context).

As an overview, currently applied renovation solutions are analysed and evaluated based on *reuse and disassembly design strategies*, revealing their restrictions when it comes to dealing with change in a (near) future. An alternative design and materialisation of building assemblies is proposed using reversible detailing techniques and introducing disassembly and component reuse in compliance with the current legal framework. These solutions are composed using basic building elements, which are standardised as in a kit-of-parts system like Meccano®. This makes any future replacement or upgrade process possible in a non-destructive way without adding to the waste stream such as conventional building solutions.

The influence of a 4D approach is evaluated over the total life cycle of a building with an integrated approach for both environmental and financial aspects. The developed research methodology is applied on a representative case study for renovation of social housing of the 70s in Brussels. The results of this analysis reveal that 'Re-design for Change' *can* be a crucial addition to energetic renovation of today. As a result, the 'Re-design for Change' approach in this study reveals and illustrates how future resource demand and waste production can be reduced over the total building life cycle as a complement to current low carbon strategies.

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01

INTRODUCTION

"Never demolish, never subtract, but add, transform and use always".

Anne Lacaton & Jean-Philippe Vassal

1.1 PROBLEM STATEMENT

1.1.1 BACKGROUND

Building activities and their daily use are unmistakably influencing the rational consumption of non-renewable resources, generation of pollutants and spoiling of land [The Worldwatch Institute 2009]. The construction sector uses more raw materials than any other sector of activity: half of the worldwide material flows are directly or indirectly connected to the building industry due to new construction, renovation and maintenance processes, while buildings are responsible for 40% of the energy consumption, and 36% of EU's CO_2 emissions [Roodman and Lenssen 1995, van den Dobbelsteen 2004, European Commission 2010].

The inevitability of declining production and usage of fossil fuels, resource depletion and effects of global climate change, has made reduction of energy consumption of buildings a first essential strategy to deal with the environmental burden of our building stock. Based on European directives to achieve Climate & Energy objectives, national governments have launched high goals on energy efficiency to reach targets the EU has set itself: by the year 2020, the EU wants to cut energy consumption by 20%, reduce greenhouse gases emissions by 20% and introduce 20% of renewable in the energy mix [EU 2010]. These standards, called the *20-20-20* objectives, led to the foundation of different national directives all over Europe. For instance, in the Belgium region of Flanders, the federal government has the ambition to improve energy efficiency by 20% in 2020 compared to 1990's values [Flemish Parliament 2011]. In other countries, like in the United Kingdom, the British government aims to reduce its carbon dioxide emissions by 34% from 2009 to 2020, whereas Germany's objectives are to reduce the greenhouse gases by 40% by 2020 compared to 1990 [UK Government 2009; Deutsche Bundesregierung 2007].

Clearly, such high objectives are not realistic when only new construction is being addressed. Since the annual number of buildings constructed in developed countries barely corresponds to 1-1,5% of the renewal of existing building stock [BBRI 2011], at current construction rate it would take from 50 to 100 years to replace the present stock of buildings entirely with new and more energy efficient buildings [The Sustainable Construction Task Group 2004]. Under the previously referred European 20-20-20 objectives, the Flemish Energy Agency has therefore developed an Energy Renovation strategy [Flemish Parliament 2011]. This program focuses on the existing building stock and has three objectives: replacing all single-glazing, insulating roofs and installing efficient heating systems. In 2020, these measures will become mandatory for all existing buildings.

At present, around 75-80% of the residential building stock in Belgium was built before 1980 [Belgian Federal Government 2011]. The multi-storey building stock constructed in the 1960-1970s, in a time of economic prosperity, holds a large share of the existing stock (25%). In today's framework, these typically poorly insulated buildings show to be highly energy-consuming while they are characterised by low contemporary user comfort and a negative social connotation. Moreover, apartment layouts and technical facilities of this post-war construction era are generally outdated by far and urgently demand for a radical update according to today's building standards.

1.1.2 TOWARDS ZERO ENERGY BUILDINGS … WHAT HAPPENS AFTER?

Present *revisions* of the Directive on the Energy Performance of Buildings (EPBD) suggest that all EU member states should support national plans and targets in order to promote the uptake of very *low and close to zero energy buildings*. As a result, in Belgium, the energy performance regulated by means of the Energy Performance and Interior Climate regulation – the so-called EPB - which sets up requirements with respect to thermal insulation, overall energy performance level and indoor climate (e.g. ventilation, overheating) is revised in upcoming years [EPB 2010, EPB 2012, EPB 2014]. These revisions resulted from recent studies which indicated that the thermal transmittance of the building skin - formulated as a restricted value in EPB-regulation in order to increase thermal building performance - was not sufficiently stringent to tackle environmental burden of buildings [3E et al. 2008].

We are therefore facing the challenge to renovate buildings according to contemporary EPBD policies, with the pre-knowledge that revisions are on their way. Static properties of building design in current building practice, however, do not anticipate future thermal upgrade. One can argue that this will eventually lead to the consequence that buildings renovated today will be highly energy-consuming in the near future.

On the other hand, another crucial question arises: will today's interventions - tackling energy reduction of operational energy consumption related to building occupation - be sufficient to deal with environmental problems of tomorrow? We can certainly imagine a future scenario in which each building is zero-carbon and energy self-sufficient, and existing buildings are retrofitted including enhanced insulation measures, energy efficient heating systems, and contemporary cooling and ventilation systems, while using the most efficient lighting and appliances available. But won't additional measures be needed after this, in order to reduce further resource depletion related to our future living behaviour and changing socio-economical needs?
Indeed, research has indicated that as gains in operational energy reduction have been maximised, embodied energy related to replacements, maintenance and end-of-life phase will become increasingly important in the future in order to make further progress in

reduction of energy consumption [Thormark 2001, Debacker 2009, Grinnell 2011]. However, the current tunnel vision on low carbon technologies to reduce operational energy requirements overlooks these small-scales, though, equally important opportunities in relation to *reduction of embodied energy of buildings* over their *total life cycle*.

For instance, for public housing owners, life cycle building costs of maintenance and replacement interventions, deconstruction and end-of-life costs, are more important than benefits of reduction of energy costs - merely attributed to occupants of buildings. The short-sighted view on building renovation today may consequently result in much higher building costs and higher environmental impacts than those initially expected: important contributions due to unexpected interventions and end-of-life costs are overlooked, while these may play a crucial role in overall building impacts. This can be the case if, for example, future end-of-life (EoL) practice introduces higher taxes for landfill and incineration. These overall life cycle concerns of buildings are not (yet) taken into account by present-day Flemish policy.

In this PhD research it is therefore argued that a dynamic approach for renovation of buildings, namely a **Re-Design for Change** approach, can complement the low carbon agenda of today: by providing 'dynamic buildings' incorporating a life cycle design approach, **future alterations, upgrade or transformation processes** can be anticipated and sustained by including an approach that deals with the environmental burden of **resource depletion and waste production** over the total building life cycle.

1.2 RESEARCH MISSION

1.2.1 TOWARDS A LIFE CYCLE APPROACH OF BUILDINGS

It was only until recently that the building sector started to recognise the environmental impacts related to the use of building materials. Today, we are witnessing a growing interest of building materials developers for environmental impacts related to *production* of building materials, together with optimisation of *recycling processes*. Several reasons lie on the basis of this change, amongst which identification of the extensive amount of energy required to extract, manufacture and transport building materials to the construction site – i.e. the embodied energy- and use of non-renewable energy resources.

A common approach towards sustainable resource management concerns the usage of so-called 'sustainable materials': alternative 'green' materials are becoming a common strategy in order to reduce the overall embodied energy, carbon emissions and associated environmental effects. Nevertheless, these materials in general merely deal with *one aspect* of the life cycle: the initial environmental impact. Uncertainties about the recently developed building materials may cause even higher overall impacts than conventional products in the future. In addition, due to unexpected component replacements, upgrade of building layers or required layout adaptations during a building's life, use of components may add up multiple times their initial material impact if no attention is given to design in terms of future *need for change*.

Consequently, in an age of sustainability focused on short-term aspects of carbon reduction, it is therefore crucial that we maintain an understanding of the broader characteristics which make a building sustainable over time. Our society is rapidly progressing through economic prosperity and technological innovations, while our way of building is not supporting these evolutions. Designers tend to ignore the temporal aspects of buildings, focusing on ad hoc building design which represents the aesthetic and functional aspirations of the time of construction.

Therefore, as a reaction to this static building design, this PhD research aims to encourage a more dynamic and long-term understanding of the built environment which anticipates *change* [Schmidt 2010]. Consequently, the important question arises: *how does one design for change*? And more relevantly for this research: *how does one design for change in existing buildings?*

1.2.2 RE-DESIGN FOR CHANGE OF EXISTING BUILDING STOCK

To achieve building design that supports **change** requires a shift, away from current emphasis in building design on *form* and *function*, in response to immediate priorities in the current-day context, towards a 'time-based' view on building design.

A **4 Dimensional Design strategy** anticipates the need for change by creating a conceptual shift in building design, from *static end-products* to *transitory* building products with continuously evolving configurations to match with functional, technological, and aesthetic trends in society [Hendrickx 2002, Debacker 2009]. Therefore, it adds the 'time' as additional design parameter, which designers should consider during the initial steps of design, to ensure that buildings can adapt to challenges we will be faced with in the future. **Adaptability** of buildings in this work relates to the definition given by Schmidt (2010) as *the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life.* Main objectives to design adaptable buildings today are to lengthen the service life of the building itself and its components, and to minimise energy and material resources required over the building life cycle. In order to do so, a key strategy is to **reuse** building materials, components and buildings, in other words: applying a *Design for Disassembly* approach (DfD) [Durmisevic 2006, Nordby 2009, Debacker 2009].
Design for Disassembly, deals with the optimisation of construction methods and assembly techniques facilitating *reuse* of (sub) components, while it is also viewed as a strategy to facilitate *maintainability* and *adaptability* during the building's operation period whilst increasing the ease of non-destructive *deconstruction* [Nordby 2006]. A growing amount of literature has been developed over this issue the past few years showing that, through recommended measures, DfD is believed to assist future environmental savings [Berge 1997, Thormark 2001, Sassi 2002, Crowther 2003, Durmisevic 2006, Debacker 2009] as well as reduce life cycle costs [Chini et al. 2003, Sassi 2004, Durmisevic 2006]. By striving to capture the value embodied in building products, the goal is to eliminate the mismatch between building components´ service life and technical life [Nordby 2006]. By moving away from rigid construction methods towards dynamic design, developers can start building truly sustainable constructions supporting the life cycle of buildings.

But what about existing buildings? Should new dynamic buildings replace entirely old constructions to ensure that our built environment is more sustainable in the future? Or should we incorporate the same dynamic design vision in the existing building stock? Renovation of existing buildings - particularly as a result of performance upgrading - has been identified to have an important impact on sustainability of the built environment [Bromley 2005, Sustainable Construction Task Group 2004]. International research concluded that the existing building stock has the greatest potential to lower the environmental load of the built environment over the next 20 to 30 years while the reuse of buildings prolongs the large extent of inherent materials present in the building structures

[Rover 2004]. Therefore, the economic, social and cultural importance of the building stock for upcoming generations should be completely understood. Since it has been identified, and it is also desirable, that the existing building stock will remain for next decades, a dynamic approach must be applied during renovation. In this context, the concept of **Re-Design for Change** was developed in this PhD dissertation in order to answer the question of how to deal with dynamic design in the framework of renovation.

Re-design for change covers design strategies in the context of renovation with the objective to transform buildings outdated today to buildings that can be more easily be adapted tomorrow, bypassing the wasteful processes of demolition and reconstruction, therefore becoming an essential complementary keystone for sustainable renovation. In this line of thought, the research focuses on **developing a dynamic renovation methodology**, as a response to the current environmental problems and the urge to update existing buildings to modern standards, whilst incorporating **design for change** as a strategy to tackle unpredictable future scenarios.

1.3 SCOPE OF RESEARCH

The PhD dissertation was developed in the framework of renovation of Flemish social housing. At present, the social housing sector is confronted with the objectives of the Flemish Government to diminish energy consumption of existing buildings. At the request of the Flemish Minister for Housing, all social housing organisations submitted data about the current state of their building stock, indicating that 45% of the buildings need energy renovation measures formulated in the Renovation 2020 call [VMSW 2011]. Therefore, a large-scale renovation of the existing social stock needs to take place in upcoming years.

The focus of renovation of social housing in this research is narrowed down to **multi-storey apartment buildings** constructed in the wake of exemplary post-war projects according to progressive modern architecture - introducing new housing concepts and urban programs. The buildings constructed in later years often did not reach the same initial qualitative standards due to limited financial means of investment and were characterised by a wide range of deficiencies according to modern standards, and excessive energy consumption. For these buildings, the level of analysis for the Re-Design for Change approach is restricted to building and component/material level. The urban level was not included in the scope of the research.

In the text case studies of post-war buildings in Belgium are used in order to analyse building characteristics that influence building flexibility, amongst which some of the initial exemplary modern projects, well-known today for their architectural patrimonial value. However, these projects are only used to illustrate the building typologies; renovation of buildings with patrimonial value is not within the scope of this research.

1.4 OBJECTIVES OF THE RESEARCH

The objectives formulated in this PhD research in the context of Re-Design for Change of the post-war social housing stock are multi-layered. Nevertheless, the main objective of this research is to develop a methodology for Re-Design for Change - as a complement to the low carbon policy – and to evaluate if this approach enables to decrease the energy embedded in renovated buildings over the total life cycle. Consequently, an alternative 'dynamic' design of buildings solutions is proposed in the context of renovation of buildings, which, complementary to the energy consumption reduction during the occupation phase, incorporate a broader and long-term design vision. To deal with the use of our natural resources in the future and to avoid further environmental degradation, a dynamic view on renovation is being developed, which anticipates changing inhabitants' needs and evolving buildings standards.

Therefore a dynamic design approach of building components is being developed in the context of renovation according to a Hendrickx-Vanwalleghem (HV) design strategy [Hendrickx 2002, Henrotay 2008, Debacker 2009]. Benefits and drawbacks of these components in a dynamic building environment are consequently being compared to the standard solutions, according to different assessment scenarios.

Since environmental impacts of buildings reach further than merely energy-related topics, **Life Cycle Assessment (LCA)** is used to evaluate environmental impacts related to the life cycle of building components throughout their life cycle. A methodology for LCA is set up that incorporates occurrence of changing demands over time. Consequently, the evaluation of benefits/drawbacks of reuse strategies over the total life cycle of buildings becomes possible.

Besides environmental issues, an important decision criterion in a renovation project is the optimal spending of the available budget, or the cost efficiency of the measures taken. This criterion becomes even more important when one decides to go further than standard building practice. Additional financial investments need to weigh up against expected savings and/or other future benefits. In the context of this PhD, this means that the investment costs of dynamic building solutions are compared to the costs that will occur in the future: maintenance, replacement, transport and end-of-life costs are therefore incorporated in **Life Cycle Costing (LCC)** analysis. Similar to environmental impacts, the benefits/drawbacks of dynamic design are revealed when compared to standard solutions.

1.5 OUTLINE OF THE THESIS

To respond the aims of the research, a range of sub-questions is addressed along the thesis. The following questions are dealt with in successive chapters:

- *What are the main renovation challenges of social housing? Which building types are in an urgent need for renovation? What are the preconditions of renovation today? Is a dynamic re-design approach needed for these buildings?* **(Chapter 2)**
- *What is a 4 Dimensional Design approach, and what are DfD strategies? What is the state-of-the-art in research concerning DfD and what are opportunities for renovation? How can a building be (re)-designed for change? (***Chapter 3)**
- *Which building layers are indicated to have a high need for flexibility? Do current building solutions exhibit dynamic properties? What is the space for improvement in existing building solutions used in upgrade of buildings?* **(Chapter 4)**
- *Which building parameters define the future opportunities for change? Which building types of the post-war construction era exhibit a high degree of flexibility for re-design today and in the future?* **(Chapter 5)**
- *How does one design dynamic building solutions? How can building solutions be designed according to a dynamic approach, while complying with thermal, acoustic and fire resistance standards?* **(Chapter 6)**
- *How can different building solutions for renovation be evaluated and compared, in environmental and financial terms, over the entire life cycle of buildings? Are there guidelines a designer can follow to gain insights if building solutions necessarily need to be designed according to DfD?* **(Chapter 7)**
- *Does dynamic design adds up environmental impacts/ financial costs in comparison with tradition building products? Do dynamic building solutions result in environmental/financial benefits over entire life cycle of buildings? Is dynamic design desirable for all building layers?* **(Chapter 8)**
- *Does Re-Design for Change of existing post-war residential buildings offer benefits as a complement to performance upgrade of buildings today? Are additional environmental / financial investment costs acceptable?* **(Chapter 9)**

Chapter 2 delivers the necessary background information on the topic on renovation of social housing, indicating which buildings are in an urgent need for renovation today. The chapter contains a brief description about the development of post-war residential buildings and the motivation for renovation in the current-day context. On this issue - in order to identify if a Re-Design for Change approach is desirable for these buildings as a complement to current renovation practice - a survey was set up in Chapter 4, this last one based on the preconditions for renovation set up in this second chapter.

In **Chapter 3** it is explained what exactly are 4 Dimensional Design strategies, and how design for change can be included at different levels of building design. The state-of-the art of these strategies is shortly discussed concerning Design for Disassembly (DfD) and Design for Reuse (DfD) strategies. Consequently, it is identified which are opportunities in this framework for renovation of buildings, leading to the conceptualisation of Re-Design for Change.

Chapter 4 takes a closer look at the actual market situation for existing building solutions used in renovation. A qualitative multi-criteria assessment was made of existing building solutions used to upgrade buildings today, i.e., facade, vertical partitioning, roof and floors. It was evaluated to what extent these widely applied solutions comply with three main renovation criteria: upgrade of building performance, life cycle design, and (de)construction criteria. The results of this analysis reveal opportunities for improvement concerning dynamic life cycle design of building solutions.

An additional point of focus when re-designing buildings for the future is the inherent flexibility exhibited by the building itself. Therefore, **Chapter 5** determines which building parameters determine the flexibility of post-war buildings at present, and to what extent building typologies can be re-designed for a dynamic future. The analysis of four recently renovated post-war building case studies illustrates the relation between determining building parameters (e.g. load-bearing structure, circulation, technical clustering) and opportunities for re-design.

Chapter 6 was derived from the revealed missing aspects in design of building solutions in the fourth chapter. In this chapter building systems are developed in accordance to the desired degree of change and reuse of components, in compliance with specifications of the regulatory context of residential buildings. The conflicts that take place when a high capacity for change and reuse is pursued combined with stringent building standards are also addressed in this chapter. A methodology to design, materialise and detail main building layers balancing both of these aspects is described. Consequently, design catalogues are set up, from which solutions can be selected according to the context of building solutions.

To assess environmental gains/losses attributed to dynamic design, a comparison between the proposal of dynamic building solutions and their current application is needed. **Chapter 7** explains methods of calculating quantifiable aspects such as environmental impacts and life cycle costs related to building components. The methodologies are based on Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), together with the selected assessment options. In addition, an extension of the assessment matrix of Norby (2009) for DfD design is presented, which can be used as a guideline for designers to evaluate when DfD is required and suitable.

Chapter 8 uses the notions of LCA and LCC methodologies to evaluate dynamic building solutions discussed in Chapter 6, and compare them to traditional building solutions using different assessment scenarios. Consequently, benefits and drawbacks related to dynamic design approach are revealed in this chapter at component level.

The analysis of case studies discussed in Chapter 5 led to the selection of a representative post-war case study of social housing currently under renovation for analysis in **Chapter 9**. Building IX at the Model City in Laeken (Belgium) – exhibits flexible building properties, which create opportunities for re-design for change. Consequently, a dynamic re-design approach is developed for this case study which is compared in environmental and financial terms with renovation practice taking place today as a reference.

In the two next figures (Figure 1.1 and Figure 1.2) an overview is presented of the principal questions answered in each research part. These questions are directly related to the chapters of this research.

Figure 1.1: Structure of the thesis based on main questions

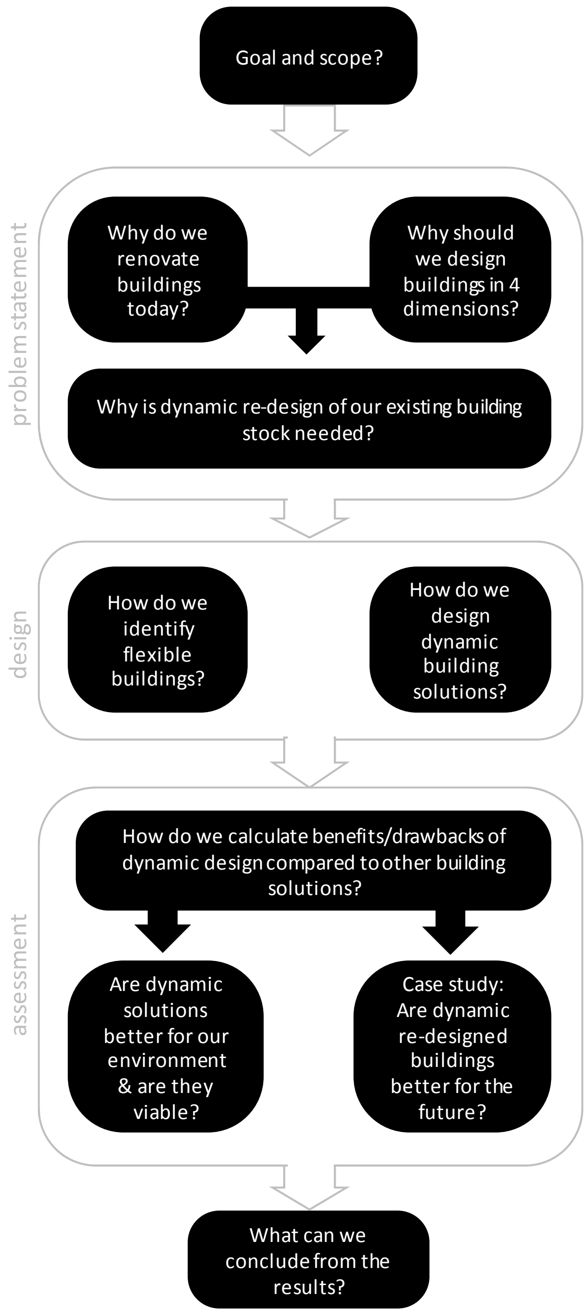
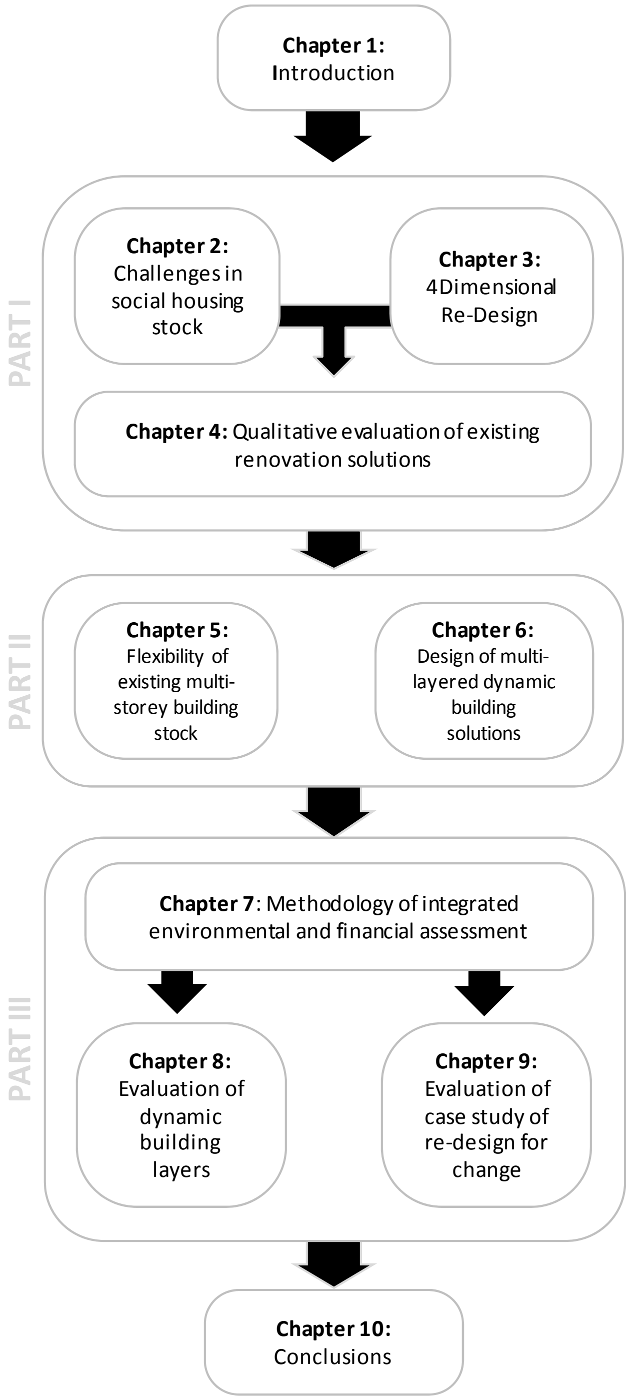


Figure 1.2: Overview of the thesis structure



1.6 CONTRIBUTIONS OF THIS PHD RESEARCH

The specific contributions of this PhD research, in the described framework of dynamic re-design of the post-war building stock, can be summarised as following:

- *Development of the concept and the methodology of Re-Design for Change;*
- *Development of a survey that aids the identification of the need for flexibility in the context of social housing renovation;*
- *Multi-Criteria Analysis (MCA) of standard building solutions, revealing their shortcomings from a life cycle perspective on building design;*
- *Determination of building parameters influencing flexibility of post-war buildings;*
- *Visualisation of flexibility of post-war buildings to incorporate a dynamic re-design;*
- *Determination of building typologies with high potential for dynamic re-design;*
- *Development of dynamic building solutions as an alternative for standard solutions used in renovation, according to the Hendrickx-Vanwalleghem approach;*
- *Development of building solutions anticipating future alterations with reuse of sub components;*
- *Development of preassembled building components that deal with tolerances inside existing buildings;*
- *Comprehension of contradictions between principles for DfD and dry design principles that enhance building physics performance (relating to thermal and sound performance and fire resistance);*
- *Development of detailing and design catalogues in order to select dynamic building solutions that compromise DfD design principles with regulatory building design;*
- *Modelling of LCA and LCC evaluation in one single software program (SimaPro);*
- *Modelling of reuse loops of components in static software; modelling of dynamic discounting method for LCC analysis in static software;*
- *Extension of the DfD matrix to form guidelines for designers in the DfD framework;*
- *LCA and LCC evaluation of standard and dynamic building solutions, revealing benefits and drawbacks of dynamic solutions;*
- *Demonstration of the DfD features responsible for initial increase of environmental impact of dynamic building solutions;*
- *Development of a Re-Design for Change approach for a case study at Model City; LCA and LCC comparison between dynamic re-design approach and reference renovation.*

1.7 TERMINOLOGY

Renovation and *refurbishment* - two often used terms to indicate the same building interventions - are often erroneously employed as synonyms while they can have quite different meanings. In the framework of this research, a clear definition is therefore proposed in order to make a clear distinction between "renovation" from "refurbishment", and other terms that describe interventions on the existing housing stock at different scales, e.g., *renewal, renovation*, and *retrofit*.

In this research *renovation* is regarded as the global intervention at building level, using the definition of Thomsen (2001) as the *transformation process of the physical, functional, financial, architectural and ecological characteristics of a building product or project to realise a comprehensive and useful extension of the life span*.

Refurbishment is then defined as being a subpart of the renovation, which only involves certain building layers, such as the facade, floors, or the roof. Refurbishment means the process of major maintenance and repair of components that are either technically or aesthetically out of date [Ebbert 2010, Giebeler 2009].

According to Ouwehand and van Daalen (2002) *renewal* is a radical approach at neighbourhood level where dwellings are made available for middle and higher income households.

Retrofit is generally used as a technical term to identify actions required to bring a building into the framework of new building performance requirements, referring to the addition of new technologies or features to older systems, for example the upgrading of technical installations, such as water, electricity and HVAC installations [Ebbert 2010]

Finally, the concept of R*e-Design for Change* was developed in this PhD research, with *re-design* referring to the *design approach* dealing with *renovation* of buildings. Consequently, 'Re-Design for Change' refers to the inclusion of a dynamic design approach during renovation.

PART I

02

CHALLENGES IN EXISTING SOCIAL HOUSING STOCK

A large amount of the current urban building stock in Europe was designed and constructed in a time where fossil fuels were cheap and abundant and global warming was unheard of [UN-HABITAT 2008; The Worldwatch Institute 2009]. As a result, buildings predating the oil-crisis of the 70s have been identified to deal very inefficiently with the consumption of fossil fuels in the current-day context. Consequently, the European post-war building stock accounts for alarming rates of the global energy and material consumption at present-day.

A considerable part of the social building stock was constructed during this period and it is currently under wide discussion if these buildings should be retained or not. Nevertheless, the pressing lack of social housing in Belgium is one of the main motivations today to renovate these buildings instead of demolishing and replacing them by new construction. In this chapter some of the benefits and drawbacks related to the renovation and demolition of post-war residential building in the framework of social housing are discussed. Renovation of post-war buildings is clearly a challenge for architects and investors since a long list of deficiencies need to be improved in order to make these building liveable tomorrow while the significant carbon footprint of these buildings must be reduced. Although many deficiencies have been identified in these buildings recent renovation projects of the post-war building estate have given reasons to believe that with a holistic sustainable approach renovation of these buildings may still offer various qualities for the future.

This chapter explains why - as a complement to the focus on low carbon-policy and user comfort today - a dynamic design must be incorporated during renovation today in order to enable these building to adapt themselves more easily to future needs in contrast with the situation today. This forms the point of departure of this research, i.e. the renovation as an extension of the service life of buildings, not only today, but also in the future. Approaches that enable change - enhancing a more dynamic variant of current renovation practice - will therefore be discussed in the next chapters.

2.1.1 LACK OF SOCIAL HOUSING IN BELGIUM

At present day, as a result of historical events social housing in Belgium is currently pressed to catch up with the private housing sector when compared to the surrounding European countries. While the number of candidates-renters for social housing is rapidly increasing each year, the number of social rented dwellings has reached a stagnation point. The last survey on residential building in Belgium in 2005 indicated that the social housing market in Belgium accounts only for 6% of the total housing stock in Flanders [Woonsurvey 2005, Vrancken et al. 2009].

This low number can be explained by the approval of several laws in the housing policy in Belgium. The housing market in Belgium was strongly determined by national policies since the late 19th century. The Housing Law of 1889 introduced a first range of financial measures to persuade the working classes to buy or to build their private homes [Declerck 2004]. Around this time, the Socialist party started propagating the construction of social rental housing. The first social renting companies were established and in 1919 a first umbrella organisation was founded responsible for the financing of social housing. The impact of the renting sector in the total building stock however was limited and the focus more and more evolved to private property stimulated by subsidies.

After a period of relative socio-economical stability Europe and part was thrown into the Second World War. By the end of the war Europe was facing severe challenges to rebuild itself. Entire cities had been destroyed, infrastructures were wrecked and economies ruined. This had a tremendous humanitarian impact from a construction view point: many cities were destructed by bombardments resulting in an overwhelming lack of housing [Turkington 2004]. To add to this situation, by the 1950s family formation and the post-war 'baby boom' had placed even greater demands on Europe's housing stock and a drive to meet housing shortage and improve dwelling conditions gained priority throughout Europe [Van Herck 2006].

The role of the state as institution was central in financing and organising residential building. It took the Belgian government several years to work out a new national housing policy for the estimated shortage of about 200 000 houses [Goossens 1982]. The main reason for the delay was an ongoing conflict over social housing between the Catholic and the Socialist parties in government. Two visions co-existed on how to plan the scattered Belgian urban space resulting in two housing subsidy acts [Declerck 2004, De Naeyer 2007b].

In contrast with other European countries which opted for social housing to reconstruct the building stock after the war, Belgium diminished the subsidies for social housing by promoting new construction through the private sector. The "De Taeye" Act (1948) - supported by the catholic parties - continued to offer financial contributions to those buying or building their own private homes preferably on separate parcels of land. This act gave a major boost to the individual property in the Belgian landscape until the day of today at the expense of the social housing sector [Declerck 2004, De Naeyer 2007b].

The Socialist party, represented by politicians and architects such as Fernand Brunfaut and Renaat Braem, predicted that private initiative would transform the country into obstructive spatial chaos [Declerck 2004, APA 2010]. In response to the "De Taeye" Law they plead for a fund - known as the Brunfaut Law (1949) - that would realise collective projects of housing companies. A precondition for using this fund was that the urban layout of the new quarters would be financed within the project and that the architectural construction and planning would be rationally guided. The initial objective to stimulate large qualitative social housing projects at low price was, however, restricted to financial support for the infrastructure and the layout of public areas in social housing projects [Vanderleyden 2009].

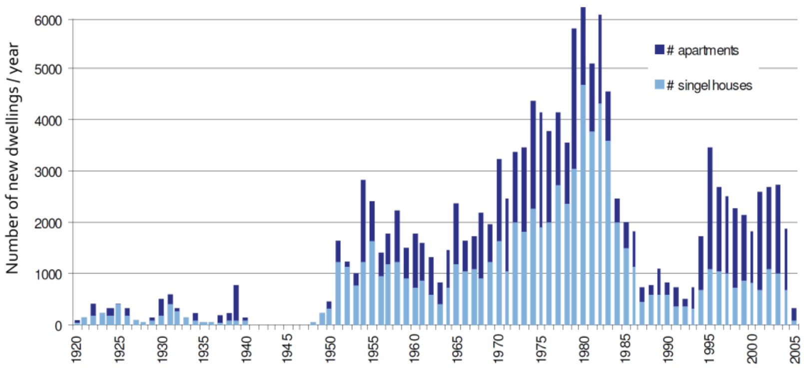
Nevertheless, in this period, architects and housing associations let themselves be inspired by the modern visionary ideas to develop large scale modernist high-rise estates inspired by CIAM. Following CIAM principles, Renaat Braem pioneered the construction of free-standing social high-rise complexes with the Kiel estate in Antwerp (1949-1958) [Braeken 2010]. After, Braem began his 'Model City' at the Heysel in Brussels in 1956, presented at the 1958 Brussels World Exhibition. The quarter represented new housing of the future, and from the early sixties on, many modernist architects began to imitate his ideas [Declerck 2004].

However, in the end it was the De Taeye Act that, from 1950 on, had the most overall influence on the residential landscape and it remained an instrumental factor in urban development in Belgium until the early 1990s. This led to an increasing number of owner occupiers in Belgium from 39% to 65% over the past 50 years [Declerck 2004].

Between 1950 and 1980 a relatively high segment of post-war construction consisted of social rental housing [Vanderleyden 2009]. However, from the 1980s on, problems caused by the approaching federalising of Belgium and the oil crisis of the 70s caused a collapse in housing construction, especially in the social-housing sector [Declerck 2004]. The long and radical process of reformation of the Belgian state, high impact of loans admitted in the past and high inflation together with high interest rates during the economic crisis caused a first period of strong decline [Vanderleyden 2009]. As a result, construction of social high-rise estate came to an end.

It was only in 1995 that as a result of the "Urgence Program for social housing" - the so-called Domus Flandria[1]- a transitory increase of construction in social housing was again visible. In contrast to earlier construction periods, Figure 2.1 shows that apartment typologies became more important than one family dwellings.

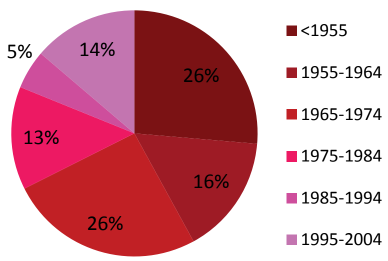
Figure 2.1: Evolution of constructed social dwellings in Belgium (1920-2005)



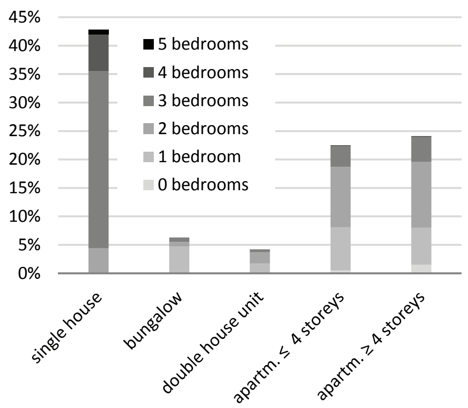
Source: [Wallyn 2008]

Figure 2.2: Social patrimony according to construction period and typologies in Flanders [VMSW 2010]

Dispersal of social patrimony in Flanders according to construction period



Dispersal of the social rented dwellings according to the number of bed rooms and building typology



[1] Domus Flandria was an emergency program of the Flemish government in the period 1992-1995 organised to catch-up with the low number of social houses built in the 1980s. It involved an ambitious campaign for 10.000 additional social housing. The program was Public-Private Partnership in which construction of social housing was co-financed by financial partners.

While in the end of 2010 about 95.000 candidate-renters were counted on the waiting list Flanders only accounts for 140.000 social dwellings [VMSW 2010]. In Wallonia and Brussels respectively 100.400 and 39.000 social dwellings are counted, with respectively 33.000 and 38.000 candidate-renters on the waiting list [SWL 2010, Luyten et al. 2011]. This means that a total amount of social candidate-renters of 165.000 whereas only a limited offer of 280.000 social dwellings exists.

It can be concluded that there is a significant demand for social housing in Belgium which cannot be coped neither only with new buildings, neither only with the existing building stock. Therefore, for a long time social housing policy was oriented on the creation of additional dwellings at the expense of the upgrade of the existing building stock [Wallyn 2008]. Nevertheless, the slow rate of current new construction has led to the conclusion that the existing building stock will play a key role for the future in order to respond this excessive demand of social candidate-renters. The focus of attention in current social housing therefore started to diverge towards renovation of the existing social patrimony, along with the European trend to renovate the abundant existing building stock in the environmental framework of today [Turkington 2004, Andeweg 2007, Riccardo 2007]. Since the Flemish umbrella organisation of social housing (VMSW[2]) was concentrating all of her activities on the expansion of its building stock, the instruments to support sustainable upgrade of its existing building stock urgently need to catch up with established renovation practice of surrounding countries.

2.1.2 TOWARDS AN ENERGY EFFICIENT SOCIAL HOUSING STOCK

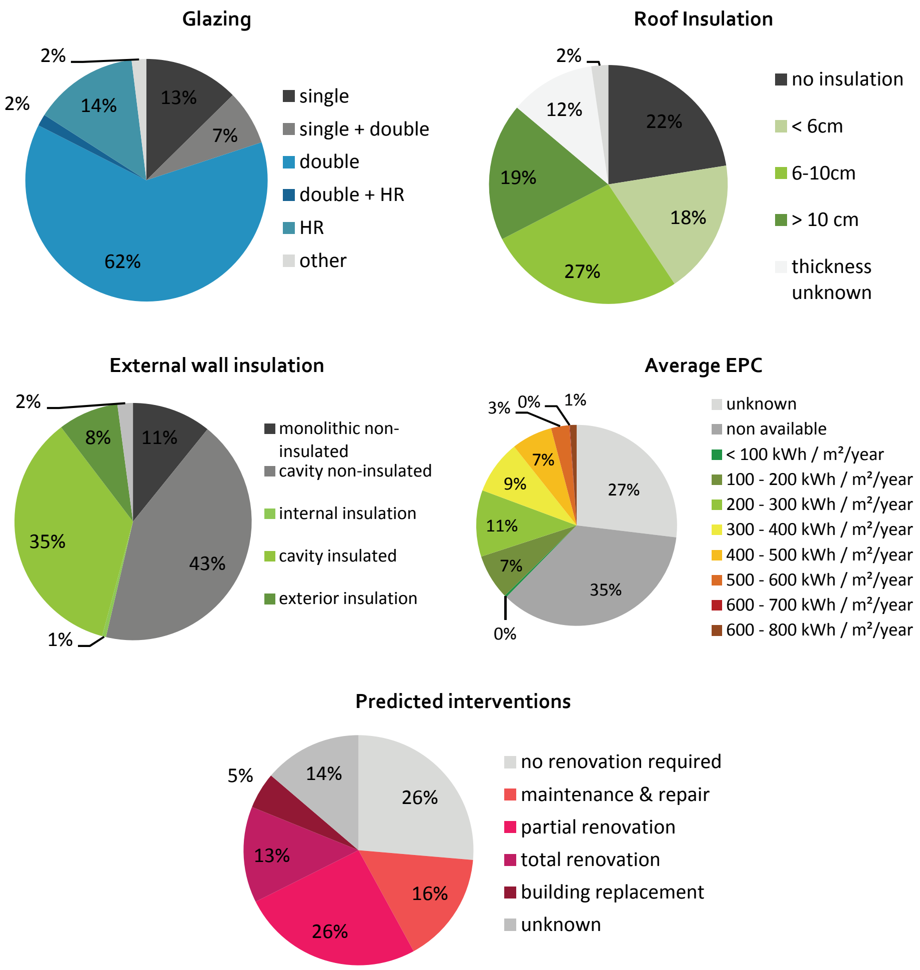
In recent years, the social housing sector has been confronted with the objectives of the Flemish Government to drastically diminish the energy consumption of existing buildings, under pressure of the EPBD (Energy Performance Building Directive) implementation and Kyoto engagements [European Commission 2010, EPB 2010].

Under the European objectives towards 2020, the Flemish Energy Agency has therefore developed an *Energy Renovation 2020* strategy [Flemish Parliament 2011]. In the framework of this renovation call in 2010 the Flemish Minister for Housing requested that all social housing organisations would audit the current state of their building stock. Subsequently, an extensive inquiry was held in Flanders which resulted in a database of around 130.000 of the social dwellings. As a result, information was included in a new

[2] VMSW (Vlaamse Maatschappij voor Sociaal Wonen) is mainly charged with implementation of the Flemish housing policy priorities. It does so by assisting, and financing the activities of 120 social housing companies which build, promote, construct, refurbish, let and sell social housing, both rental and ownership. It also provides technical, legal and financial assistance and collects existing data in order to assist in the future policy making.

database about the number of dwellings per building, type of dwelling (single family house or apartment), number of building storeys, composition of the roof, type of heating (collective or individual, energy source), state of the facade insulation and glazing (single or double glazing) [Bosmans 2010]. The information was subsequently used to classify buildings in categories to develop renovation strategies for improvement. In Figure 2.3 some overall results of the audit are shown of the current state of the Flemish social housing stock.

Figure 2.3: Outcome of the audit in the Flemish social housing societies [VMSW 2010]



The overall summarised results of the inquiry concluded that social housing built before 1985 - or 72% of the total social stock - are indicated as a priority in the current renovation strategy. The results revealed that for *apartments* and *houses* **built before 1985** (33% and 38% of total social housing stock) respectively 60% and 80% lacked facade insulation, 25%

and 38% lacked roof insulation and 25% and 30% made use of single glazing [Bosmans 2010]. Therefore, these buildings were indicated to be the least energy efficient residential buildings of the social patrimony of the VMSW and consequently requiring energy measures during renovation.

The scope of this research is defined as the renovation of the first group of buildings, i.e. apartment blocks built before 1985, and, more specifically, the **multi-storey** buildings constructed in the **post-war** period. We are assisting today to an overall European tendency to renovate the buildings since they are causing a wide range of social, functional, technical, thermal and acoustic problems [Turkington 2004, Andeweg 2007, Riccardo 2007, Denaeyer 2007a]. A renovation strategy that focuses on a wide range of similar apartment building types in social housing can lead to a holistic renovation approach of the building stock. In this perspective, the aim of this research is to develop overall dynamic and sustainable concepts that can be applied on a large scale, simultaneously and complementary to the energetic upgrade of buildings that is planned for upcoming years.

In the next paragraphs, it is discussed which problems need to be tackled during renovation of these post-war apartment buildings, revealing that thermal upgrade of buildings to reach EPB standards in Flanders is not the only main concern in renovation for the future.

2.2 POST-WAR SOCIAL HOUSING ESTATE

2.2.1 INDUSTRIALISED BUILDING: AN ANSWER TO HOUSING SHORTAGE

Whilst most multi-storey residential buildings in Belgium were constructed in the 1950s and later, their origins date back to the second half of the 19th century. From 1928 onwards the Congrès International d'Architecture Moderne (CIAM) organised - as the name eloquently states it - international congresses which influenced to a large extent the high-rise construction in the 1950s [Turkington 2004]. As a honorable example, Le Corbusier introduced his famous free-standing high-rise block Ville-Radieuse concept in 1930 as a universal solution to the European housing problem. Although most Belgian architects had accepted the CIAM ideals and many master plans had been drawn up, it was only after the Second World War that - for more pragmatic reasons - high-rise was finally promoted as an important housing type and a solution for the working classes in order to give a concrete answer to the lack of adequate housing [Declerck 2004, De Naeyer 2007b].

Due to the necessity to produce a large number of dwellings in a short period of time, many countries experimented with new construction methods and non-traditional building materials [Declerck 2002, Andeweg 2007]. *Industrialised buildings* were introduced based on the principle of transferring work from the site to the factory as much as possible, in order to simplify assembly carried out on site [Turkington 2004]. Many industrialised building systems employed the large 'closed' panel method of construction comprising factory-made pre-cast concrete floor and wall panels, replacing laborious work with bricks and mortar.

High-rise housing represented the ideal housing of its era, with egalitarian and modern dwellings which were spacious, comfortable, well-designed and suitably located [APA 2010]. However, a large section of the public remained suspicious about modern high rise construction, which would eventually lead to the questioning of the initial qualities in further years.

2.2.2 RENOVATION OR REPLACEMENT OF POST-WAR BUILDINGS?

Since the demand for post-war housing necessitated rapid production of large numbers of living units the emphasis was put on time. This signified that quality was significantly deprecated in view of quality [Riccardo 2007]. Consequently, the quality of a large part of these buildings is esteemed quite poor for today's patterns while the functional standards have changed significantly over the years [Andeweg et al. 2007]. In recent years, several researchers have attempted to classify the range of problems affecting post-war residential estates, amongst which Declerck (2002), Skifter Andersen (2003), Turkington

(1997, 2004), De Naeyer (2007), COST C16[3], Power (2008) and Ebbert (2010), and have identified several problems, represented in Table 2.1.

Given the inevitability and the prevalence of these problems, the question insinuates the following: should outdated post-war buildings be demolished rather than renovated?

Figure 2.4: Demolition of les Minguettes near Lyon (France)

Source: Mairie de Vénissieux

There are several motivations to reconsider existing post-war buildings which can result in different opinions considering the renovation or replacement of these buildings extensively discussed in literature [Turkington 2004, Andeweg 2007, COSTC16 2007, Power 2008, Thomsen and van der Flier 2009, Verbeeck 2011]. A summary is proposed of the main reconsiderations of buildings in Table 2.1.
Affirmative answers could be based upon the fact that the exhibited qualities have decreased to such an extent that these buildings have become impossible places to live in, or, that new construction would result in more energy efficient buildings. One could also argue that the financial costs to upgrade buildings are too high compared with new construction. Indeed, an often argument used for demolition is that the cost and impacts related to renovation do not weigh up against the benefits of new construction which results in more energy-efficient buildings than for energetic upgrade of existing buildings. However, research of Verbeeck (2011) has proven that this is a discussable argument. Regarding the specific issue of financial costs related to energy-efficient measures in renovation, Verbeeck (2011) concluded that financial savings as such are not a sufficient argument to promote wide-scale demolition of existing buildings. From a strictly financial cost point of view, the results indicated that it is only worth to replace existing building by

[3] COST stands for the European COoperation in the field of Scientifical and Technical research, and falls under the Urban Civil Engineering Technical Committee (UCE). The ACTION C16, "Improving the quality of existing urban envelopes", was developed in the COST UCE Programme.

new ones if no significant energy savings can be made with renovation and if the building is of such poor quality that renovation costs would be excessive.

Table 2.1: Motivations to reconsider post-war multi storey buildings

building & design	**Site**	Urban design	*Need for improvement for the urban quality;*
			High building density;
			Traffic and noise pollution;
			Absence of communal facilities;
			Inadequate external space;
	Building	Architecture	*Outdated appearance;*
			Decay of valuable architectural heritage;
		Building physics	*Lack of insulation;*
			Overheating in summer, overcooling in winter;
			Cold bridges (e.g. cantilevering balconies);
			Poor ventilation;
			Wind & water leaks, condensation problems;
		Acoustics	*Poor sound insulation;*
		Fire safety	*Fire protection deficiencies;*
	Structure		*Poorly executed building structure;*
	Services	Technical installation	*Outdated heating systems;*
			Outdated electrical installations;
			Outdated sanitary equipment;
			Need for updated elevator;
	Spatial infill	Plan layout	*Outdated plan layout;*
			Uni-lateral apartments;
			Small surface rooms;
			Lack of storage room;
	Material	Hazardous materials	*E.g. asbestos pollution;*
legislation	**Environment**	Energy consumption	*Energy Renovation Program (Flanders);*
	General	Fire regulation	*Compulsory fire safety improvements;*
		Building Safety	*Danger of damage to third party;*
social housing	**Management**	Operational cost	*High energy demand and associated charges;*
			High maintenance costs;
		Renting	*High rent arrears and vacancies;*
	Organisation	Typologies	*Unadapted offer for the individuality of candidates-renters;*
			Unadapted offer for elderly;
			Over and under occupancy of living units.

In the context of social housing main motivations *at benefit of* renovation are determined in Table 2.2, resulting from literature studies, case studies of current renovation of social housing and the communication with different stakeholders involved in social housing.

A crucial argument which may be pleading for renovation concerns the ratio between the demand for social housing in Belgium and the slow pace of new construction: demolition and replacement of buildings is not likely to be the most aspired or even rational option if it is still possible to make major improvements at reasonable cost. Nevertheless, new construction is a necessity *in addition* to the renovation of the existing building stock, to catch up with the increasing demand for social housing.

Table 2.2: Decisive factors for renovation instead of demolition of a building and replacement

general	**Building**	Architecture	*Identification with the building*
			Preservation of socio-cultural heritage
	Services	Technical installations and structure	*Load-bearing structure still in good condition*
			The technical components have not reached their end of life span
		Building permit	*Permit for a new construction would allow less building height /surface/ volume*
		Monumental protection	*The building is listed*
	Environmental factors	Life cycle thinking	*Renovation of a building enables a high level of reuse in the life cycle of buildings, i.e. reuse of the building*
social housing	**Economic factors**	Construction cost	*Lack of investment means for new buildings*[4]
		Operational cost	*The interior fitting-out has been renovated recently and is still up to date*
		Life cycle costs	*The life cycle costs of renovation of a building are lower than demolition and new construction*
		Loans	*Repayment term: 66 year loan period for public housing is not yet reached*
	Organisation		*In case of low-scale renovation inhabitants can stay in their dwellings during renovation*
		Speed	*Renovation can provide 'new' accommodation in only 50%-75% of the time needed for the alternative demolition and new construction [Highfield 2000]*

In addition, renovation has other pragmatic arguments in its favour. As an example, a problem that often occurs when replacing existing building with new ones is that the permit for new construction allows less building height/surface/volume than the initial buildings. New construction in this case gets less attractive since fewer dwellings can be provided than was initially the case.

The specific context of social housing under the formal supervisory of the VMSW - maintaining by 120 social housing societies (SHS) - is a good illustration of the complexity of the discussion about renovation *or* replacement of the existing building stock. In Flanders, the legal framework for social housing is described by a code – the Flemish Building Code [5] - upon which the federation for social housing (VMSW) has based a formal

[4] Renovation has been indicated by Highfield (2000) to amount only for 50-80% of new construction cost.

[5] The central point of the Flemish Building Code is the right on decent housing for all citizens. The aim is to promote and guaranty the availability on the market for rent and sale of adapted housing, of good quality,

supervisory and financing role towards the 120 local social housing societies owning the social housing stock in Flanders. Based on this Building Code social housing societies receive technical, financial and administrative support from the Flemish Social Housing Society (VMSW) to provide and maintain affordable and qualitatively sound housing for low income groups. The local social housing societies (SHS) are primarily responsible for maintenance and renovation of their local social housing stock. Consequently, they buy, renovate, build and also sell social housing to low income groups.
A regional social correction introduced by the VMSW makes the selection between renovation and replacement quite complex. The GSC (Gewestelijke Sociale Correctie) - the so-called 'regional social correction' - is a financial compensation to which each social housing association can make an appeal when it lacks of financial means, i.e. when the difference between the incomes and the revenues of the housing associations is negative. This financial measure for housing associations, however, can be held responsible for a paradox in current renovation of the social housing stock. Social housing associations which cannot claim this financial subsidy - implying a good management of their social housing patrimony - have to carry out renovations at their own expenses. Therefore, as in the concept of the 'pater familias', these housing associations maintain well their building stock by renovating it until the loans of the initial construction are paid off. Housing associations with financial difficulties, on the contrary, have the right to reclaim new made debts from this subsidy in case of new construction and may consequently be motivated to demolish their existing building stock and replace it with new construction for personal motives. New construction clearly offers a better comfort for the user and reduces the energy costs in the short term, while the maintenance costs for the housing association are diminished as well. Consequently, this social correction influences to a high extent in what way social housing associations deal with the financial question between constructing new building or renovating their existing social housing stock.

On the other hand, another important barrier for renovation in social housing can be identified as benefits-related issues. Social housing societies must make high financial investments for renovation determined by the VMSW with limited financial means, while currently the tenants have all the advantages of the renovation related to comfort and reduced energy costs. Therefore, a new rent law will be introduced in 2012 including an energy correction factor in the rent calculations; EPC (Energy Performance Certificate)[6] will become the basis for a practical calculation method [Flemish Parliament 2011].

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in an adequate environment and at an affordable price. The VMSW and the local social housing societies (SHS) are the privileged executers of the Flemish housing policy [Wallyn 2008].

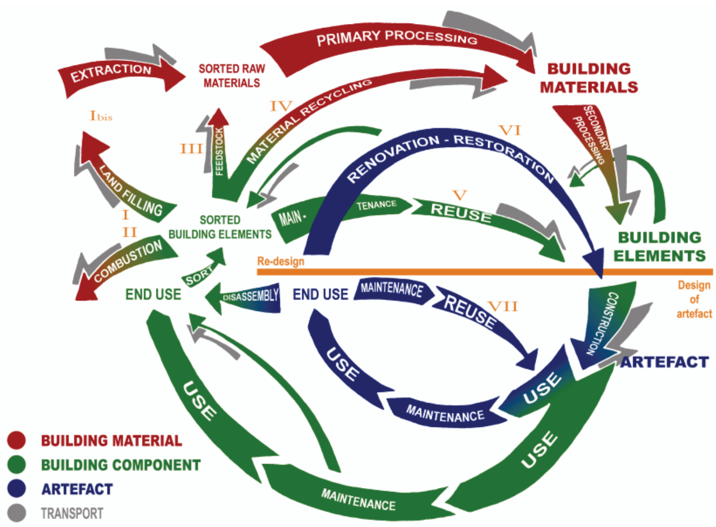
[6] The Flemish Council decided by resolution to introduce the energy performance certification end 2008 for sale of dwellings and begin 2009 in case of rent. This is called the EPC-rule.

It is clear that the issue of renovation versus replacement is a complex issue which must be balanced for each considered case study. All these considerations show that decision-making about demolition of existing buildings is not always about the structural performance of buildings and that not all motives are often outspoken. However, in many cases literature concludes that renovation is the most appropriate for financial, social and environmental reasons and should receive priority to replacement if buildings are still in good structural conditions. The scope of this research however, does not include the determination of which of both strategies is more adequate for a case study. This research departs from the concept of renovation as an extension of the building life cycle, as will be discussed in the following paragraph.

2.3 RENOVATION AS EXTENSION OF THE BUILDING LIFE CYCLE

The perspective on renovation in this PhD research departs from a life cycle perspective on the built environment. Debacker (2009) developed an integrated life cycle model, representing the contemporary built environment according to three life cycles in which reuse can take place: the cycle of the *building*, the cycle of its *components* and the cycle of *materials* used to manufacture components (Figure 2.5).

Figure 2.5: Integrated life cycle model [Debacker 2009]



The life-cycle of buildings is described as a cyclic revolving process of building initiative, design, construction, use and redevelopment/renovation and reuse represented by the model in Figure 2.5 [Debacker 2009]. The model gives a good representation of life cycle thinking in the built environment since it can be used to compare different paths with each other. It shows that for a total picture of the material and energy flows (and their side effects) it is crucial to take all cycles into account. By staying in one of the three loops waste and extraction of new resources is avoided or minimised. Materials, components or buildings are in such cases re-invested in another life minimising environmental and socio-economical loads over the entire life cycle [Debacker 2009].

The numbering of the paths in the life cycle model represents the decreasing impact of end-of-life or reinvestment solutions on the depletion of material resources and waste accumulation. The model shows that path VII - the *reuse* of buildings - shows to have the lowest impact of reinvestment. However, in today's context residential buildings – in this case post-war residential buildings - usually need a minimum degree of change due to the low versatility of the initially designed buildings as will be further be elaborated in Chapter 5. To be able to respond the contemporary standards and modern living comfort requirements *renovation* of residential buildings is indispensable. This is the second best option according to the model – i.e. path VI - showing to be of significant priority to keep reinvestment impacts low. This is where this PhD dissertation is situating itself, i.e. at the re-design level of buildings after a first period of use.

Therefore, it is relevant to point out again that for each building that is renovated - and thus reused - the extraction of raw materials and the manufacturing processes and energy involved with new construction can be partially avoided to the benefit of the environment.

2.4.1 CONTEMPORARY UPGRADE IN POST-WAR SOCIAL STOCK

2.4.1.1 *RENOVATION VERSUS EPBD POLICY*

In Europe, a legislative milestone for the improvement of the energy performance of buildings was the adoption into the European legislation of the 2002 Energy Performance in Buildings Directive (EPBD) [EU 2002]. A total of 30 European (EN) and 24 international (EN ISO) standards were drafted or updated including those relating to minimum energy performance levels, calculation methods and inspections of heating and cooling equipment [Roulet and Anderson 2006]. As a result, in Belgium the energy performance is regulated by means of the Energy Performance and Interior Climate regulation - the so-called EPB - which sets up requirements with respect to thermal insulation, the overall energy performance level and the indoor climate (e.g. ventilation, overheating) for those buildings that use energy to create specific indoor climate conditions.

This EPB policy formulates requirements in new construction and renovation for:

- the thermal insulation, through defined minimum and maximum levels for the *K-level*, the *U-values* and *R-values*[7];
- the energy performance, according to a *E-level*[8];
- interior climate: for *ventilation* through a minimal *flow of air (m³/h), and for overheating* through the proposition of design rules.

2.4.1.2 *NEW ACOUSTIC STANDARDS VERSUS SOCIAL HOUSING*

In order to comply with the European standards and customer expectations a new standard with even more strict requirements became a necessity in Belgium. Consequently, in 2008 a new acoustic paradigm was introduced in the Belgian standardisation. NBN S01-400-1:2008: 'Acoustic criteria for residential buildings' replaces the older standards NBN S01-400: 1977 and NBN S01-401: 1987[9]. The new criteria

[7] With K-level = general insulation level; U-value = thermal transmittance (at component level) (W/m²K); R-value= thermal resistance (m²K/W).

[8] With E-value = primary energy consumption.

[9] The old requirements for sound insulation were determined based upon parameters which designate the sound insulation of components independently of their surface area and volume. In order to take into account that large surface areas can transmit more sound than small areas the new requirements depend on the weighted standardised sound level difference $D_{nT,w}$ for the airborne sound insulation and the weighted standardised impact sound level $L_{nT,w}$ for the impact sound insulation [Ingelaere 2005].

concerns the airborne and impact sound insulation between dwellings, facade sound insulation, limitation of equipment noise and an imposed minimum absorption in entry halls and common spaces of multifamily housing. The requirements are given in a Belgian standard but act as rules of good practise and function as such as real obligations for the building industry [Ingelaere 2005]. This new standard has a great impact on the sector of social housing [Paelinck 2008]. This sector uses the standard values as their minimal demands to reduce the sound pollution and guarantee the comfort of the occupants. However, social housing is a sector in which a living unit is usually closely clustered. If we attend to this and to the fact that the separation of elements between these dwellings are of crucial importance to enhance a positive experience of cohabitation, we understand that the new acoustic standards are quite a challenge for social housing with average requirements having increased significantly with plus 7 dB.

Nevertheless, in current renovation practice the major focus still lies upon energy savings. Although energy related interventions and acoustic interventions can often be combined the acoustic aspect is often given less importance. This can lead to serious problems during the use phase: privacy and adequate protection against external noise are basic needs of the inhabitants. Upgrading the acoustic performance does not necessarily require a great deal of additional effort when it is simultaneously considered with increasing the thermal comfort. Therefore, for the reasons mentioned above, renovation of buildings should integrate thermal upgrade *together* with acoustic considerations and, at its best, providing solutions that are upgradable for both future standards and needs.

2.4.1.3 SUSTAINABLE RENOVATION STRATEGIES AT BUILDING LEVEL

According to the SHC Task 37[10] for *Advanced Housing Renovation by Solar and Conservation* sustainable renovation embodies a strategy to extend the service life of existing building by introducing opportunities to re-initiate a second building life while limiting the building's future impact on the environment. Therefore, the formulated aims in the SHC task are to introduce the following renovation strategies during the re-design, construction and use phase of existing buildings [Trachte & De Herde 2010]:

- *Increase the comfort and health issues;*
- *Reduce the energy consumption;*
- *Reduce tap water consumption;*

[10] Solar Heating and Cooling Program, implemented by International Energy Agency (IEA).

- *Increase the water resources;*
- *Reduce waste production, and*
- *Reduce resource consumption.*

These strategies for sustainable renovation incorporate a wide range of sub strategies at building level represented in Table 2.3.

Table 2.3: Subtopics of sustainable renovation strategies according to SHC Task 37 [Trachte & De Herde 2010]

Sub strategies for sustainable renovation	
Increase comfort and health issues	*Increase the quality of outdoor areas* *Increase the quality of indoor air* *Increase the respiratory comfort* *Increase the acoustic comfort* *Increase the thermal comfort* *Increase the visual comfort*
Reduce energy consumption through increased thermal performance	*Optimise the building skin performance* *Add/increase the insulation level* *Reduce thermal bridging* *Improve air tightness* *Use thermal inertia strategies* *Optimise solar protection* *Introduce concept of natural night cooling* *Optimise window conception*
Reduce fossil energy consumption	*Optimise the heating system, use heat pumps* *Optimise the use of domestics hot water* *Optimise the lighting system* *Use renewable energy* *Introduce ventilation system with heat recovery* *Introduce pre-heated air by air-ground exchanger*
Reduce water consumption	*Rational use of tap water* *Recovery and use of rainwater*
Reduce waste production	*Reduce construction and demolition waste* *Reduce domestic waste*
Reduce resource consumption	*Reduce embodied energy consumption* *Reduce environmental impact of building materials*

This clearly requires from architects/designers/engineers active in the renovation field to face several challenges in order to boost up problematic buildings of today to the sustainable buildings of tomorrow.

2.4.2 NEED FOR FUTURE UPGRADE

2.4.2.1 FUTURE EVOLUTION OF BUILDING PERFORMANCE

Now that is presented to what challenges post-war buildings are placed today, a preview of what is to come is presented; this is the storyline of buildings that most designers tend to overlook during renovation today.

A clarifying example of this concerns the context of the EPBD policy. Whilst the EBPD stipulated minimum energy performance standards during the last years, many EU member states have gone beyond its requirements and building standards are being nationally revised including more stringent requirements. Governments are agreeing to develop policies and take measures such as targets to transform existing buildings into near-zero-energy buildings. Consequently, the further evolution and the extent of these evolving building policies are difficult to predict. Trends in sustainable building - as in our daily society - come and go.

Moreover, literature and investigation in general on the field of renovation and, in specific, on the energy performance of buildings are quite recent. There is a lack of cumulated knowledge on this subject which implies that new technologies and sustainable targets can only be evaluated after some years of practice and experience and new developments must therefore first prove their effectiveness.

In Europe, for instance, the Passive House standard is currently being under discussion as a reference for the energy performance of buildings. Although it has demonstrated to reduce space heating demands by up to 90% compared to conventional dwellings [Feist et al. 2005], research of Allacker (2010) has revealed that dwellings according to the passive standard should not always be strived for since they require a high extra investment for only a limited reduction of the life cycle impact compared to low-energy buildings.

At the same time, zero-carbon and zero-energy building standards and demonstration projects are emerging all over Europe. However, the monitoring of actual performance of these buildings indicates that most do not actually achieve zero-carbon standards, usually due to underestimation of loads and poorly performing energy systems [Borg 2010].

As a result, since the current energy performance standards are expected to evolve, dwellings that are being built or renovated today may not be in accordance with future standards. This forms a first crucial motivation to introduce building systems in renovation which can anticipate these unknown future evolutions.

A second example for the need of future building upgrade can be found in the field of sound insulation of buildings. In order to improve the sound insulation of buildings (during the renovation stage today) the plans and detailing can only be adapted in the *initial* design stage. However, it is only *after* the execution of the renovation that in situ measurements can evaluate the overall sound performance. When acoustic solutions are applied in renovation, there is little margin for deficiencies. If the acoustic performance of the solution does not perform as expected, the combination of restricted storey-height and conventional static design result in buildings, difficult or impossible to be reversed to better performances.

Adaptable solutions can offer important solutions in this matter. When the final result does not meet the targets, the solutions are still reversible and upgradable to achieve satisfactory properties. The weak points can be evaluated and ameliorated in a second phase without need for entire demolition of the created building solutions.

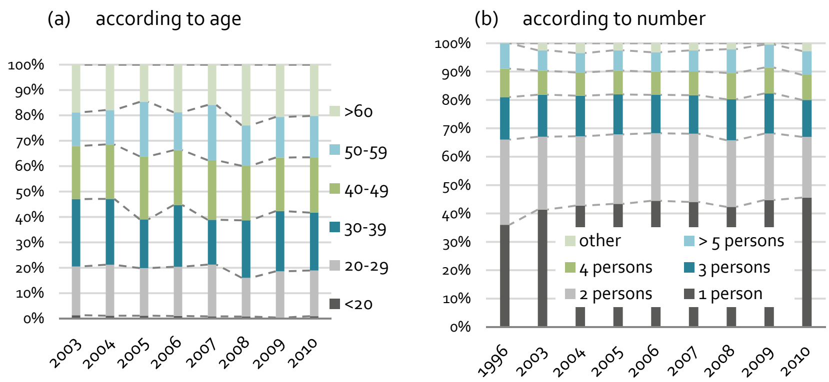
2.4.2.2 ANTICIPATING SOCIO- CULTURAL AND DEMOGRAPHIC TRENDS

Albeit that construction and living standards and society in general have changed rapidly in the last two or three decades, housing typologies and the accommodation in social housing tend to remain stable meaning that inhabitants are forced to adapt their living comfort to the provisions present in their dwellings. Some building typologies have proved more flexible than others but in general, the response to contemporary standards was not well-suited due to the restricting static construction techniques applied in post-war buildings.

Demographic trends such as ageing are among the more predictable future trends. For instance, the well-known baby boom that took place after the Second World War is at present creating a parallel 'boom' in the percentage of aged persons with retirements [Turkington 2004]. This brings along a first concern: this important group of the population places distinctive housing needs and preferences on our current building stock, which need to be met by adapted secure and manageable dwellings fitted to their profile.
On the other hand, the growth of personal choice and individualisation is a post-modern key trend at work in contemporary Europe [Turkington 2004]. A growing series of social groups - from young people to elderly, single parents, migrants and those with a physical disability - have established distinctive needs. Whilst conventional family households have been a majority for years, an extremely visible effect of this process of individualisation is the number of growing smaller households in all Western Europe, especially in cities. Among the main changes in many countries there is a growth in relationship breakdown and the postponement of family formation, resulting in single, childless couple, divorced, elderly and single parent households.
This falling average household size and the emergence of more diversified households, imply an urge for a *higher* number of dwellings together with a *variable* offer of configurations and sizes. As a result, the demand for varied typologies increases, currently characterised by a faster turnover than in the past.

For the specific context of social housing, Figure 2.6 (b) shows an increase of 10% of the total demand by candidate-renters for dwellings consisting of one family member considered over the last 15 years (from 36% to 45%).

Figure 2.6: Distribution of candidate-renters for social housing in Flanders



Source: Statistical Bulletin of candidate-renters (1996-2010) [VMSW 2010]

As will be illustrated in Chapter 9, the actual offer of social housing associations in existing post-war buildings often cannot respond the actual demand for a varied and adapted offer of typologies conform to modern standards.

Therefore, an update of dwelling typologies to contemporary minimum comfort standards including a variety of configurations responding the individuality of a wide social mix of inhabitants is urgently required. Nevertheless, crucial during renovation today is the anticipation on these evolving socio-cultural and demographic trends in the future. Dwellings conform to contemporary requirements today will, again, rapidly become outdated when new trends come along if no attention is paid on the temporary aspect of dwelling typologies and their internal partitioning. It is therefore concluded that a dynamic renovation approach is crucial to anticipate evolving spatial needs to ensure that buildings will not face the same problems of today in the future.

03

4 DIMENSIONAL RE-DESIGN

The *4Dimensional Design Research Group* (VUB) is investigating how buildings and their composing elements can be designed and detailed in order to respond to the increasing need for change in the future by introducing more adaptable features. It therefore adds the 'time' parameter to the initial conception of buildings [Hendrickx 2002, Henrotay 2008, Debacker 2009]. "Time" as a design parameter conceives buildings as dynamic systems that constantly interact with evolving building parameters in order to respond to the socio-economic progress of our society and evolving trends.

Today, a growing amount of research is being done about the building capacity to accommodate spatial, functional and technical change through the design of dynamic systems in *new construction* [Douglas 2006, Henrotay 2008, Debacker 2009, Schmidt 2009, Till 2009]. Nevertheless, what is consistently forgotten is that the environmental challenge of today will be how to deal with *existing* buildings. These buildings are habitually overlooked since architects and designers seem to be more intrigued by the more challenging opportunities of designing dynamic buildings from scratch.

In analogy with the majority of buildings constructed today, buildings of the post-war construction period were designed and built to suit a particular purpose at a certain time, with relatively little thought about future use or lifespan of the materials. Today, the need for renovation of these buildings calls for a dynamic approach in order to reuse the best of what still exists, whilst incorporating an overall strategy that results in more adaptive constructions in the future. Therefore, in this chapter, the strategies to deal with change are analysed in three design levels - *building*, *component* and *material level* – and are re-interpreted in the context of renovation of buildings. Subsequently these strategies form the starting point of the research question of this PhD dissertation: is a Re-Design for Change approach beneficial for the renovation of our post-war social building stock?

3.1.1 SUSTAINABLE RESOURCE MANAGEMENT

Today's design of buildings has become a burden to the vibrant and fast-changing society of the 21st century. The lack of anticipation of flexibility and adaptability causes buildings to be partially or entirely demolished for the failure of each building or building component [Durmisevic 2006, Debacker 2009, Paduart 2010]. As a result, our conventional building design is responsible for a vast amount of redundant construction and demolition waste - an amount that is still increasing, as the number of building activities increases yearly. New construction, maintenance and renovation of buildings, including the production of building materials, generate 45% of the European waste [EEA 2001, EuroSTAT 2006]. In Belgium, construction and demolition waste represents the largest fraction of the total waste disposal composition [EuroSTAT 2006] with a value of 15 million tons per year [Vrijders 2011]. Moreover, demolition processes are responsible for 47% of the total waste composition, whereas renovation generates 24% of the total waste.

Table 3.1: Source of Construction and demolition waste in Belgium [Vrijders 2011]

Construction & Demolition Waste	Fraction
Demolition	47%
Refurbishment buildings	24%
Construction (buildings)	8%
Roads	18%
Production waste	3%

Nevertheless, contemporary building design still does not anticipate the final deconstruction of buildings, neither unpredictable circumstances which naturally take place and cause interventions during each building's life cycle. Changing patterns of household typologies in our society, the proportional increase of ageing people in developed countries, and the rising worldwide population pressure our buildings to adapt themselves in the future to respond these socio-economic changes. The lack of design for deconstruction at the end-of-life of a building implies that components and materials are difficult to recuperate, even though they still may incorporate a long remaining service life. On the other hand, besides the generation of building waste, this means that for each intervention new materials need to be addressed. This partially explains why 35% of the materials flows can be attributed to the construction sector [UN-HABITAT 2008].

Therefore, and as stressed before, there is an urgent need to apply design strategies that transform our existing inflexible building structures into dynamic buildings, in order to reduce the environmental burden of buildings not only today, but also in the future. However, the question insinuates by itself: How can we deal with these aspects of time and uncertainty when we are re-designing buildings today?

4Dimensional design (4D) refers to a design attitude that conceives building artefacts from a life cycle perspective, therefore integrating the fourth dimension, i.e. *time*, from the initial stage of design [Hendrickx 2002, Debacker 2009]. 4D strategies conceive building 'products' that support evolving processes in life and society in contrast to predetermined design of finished end products, resulting from a pre-programmed end state [Debacker 2007 b, Henrotay 2008]. The response to change lies in a re-conceptualisation of time to a more nuanced view of a building as a socialised product constantly on the move [Schmidt 2010].

Re-design for change covers design strategies in the context of renovation with the objective to transform buildings - outdated today - to buildings that can be more easily be altered tomorrow. The applied definition of **adaptability** of buildings is related to the definition given by Schmidt (2010) as *the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life.* A dynamic design approach is thereby essential - together with reuse strategies - to ensure that buildings that will remain for the next decades are able to respond our rapidly changing society during their entire life span while they extend the service life of all inherent materials.

Therefore, it is crucial to introduce design strategies that enable change, applied at three levels of the building (excluding urban level), namely the *material*, *component* and *building* level [Debacker 2009].

3.2.1 DESIGN FOR DISASSEMBLY AND REUSE

The motives to introduce adaptability in order to give response to a need for change in buildings differ considerably throughout history. Habraken (1961), for example, introduced adaptability in the 60s as a *social* reaction against monotonous and repetitive post war building structures ignoring individual preferences.

In contrast, the urge for dynamic building design strategies today is driven by *environmental* concerns. One of the main objectives to design adaptable buildings today is to lengthen the service life of the building itself and its components in order to minimise the energy and resources required over the building life cycle. In order to do so, a key strategy is to *reuse* building materials, components and buildings, in other words, applying a Design for Disassembly approach (DfD) [Crowther 2002, Durmisevic 2006, Nordby 2009; Debacker 2009]. Design for Disassembly (DfD) deals with optimisation of construction methods and assembly techniques facilitating *reuse* of (sub) components, while it is also viewed as a strategy to facilitate *maintainability and adaptability* during the building's operation period and increases the ease of non-destructive *deconstruction* [Nordby 2006].

An increasing amount of literature has been developed over this issue the past few years showing that - through recommended measures - DfD is believed to assist future environmental savings [Berge 1997, Thormark 2001, Sassi 2002, Crowther 2003, Durmisevic 2006, Debacker 2009] as well as reduced life cycle costs [Chini et al. 2003, Sassi 2004, Durmisevic 2006]. By striving to capture the value embodied in building products, the goal is to eliminate the mismatch between building components´ service life and technical life [Nordby 2006]. Reclaimed building components may then re-enter the metabolism of the building industry or other industries (e.g. furniture) if attention is given to the non specificity of the sub components. This will be discussed in 3.2.3, at component level.

Studies and exemplary projects have also pointed out that DfD can meet market needs for flexibility, for example in the IFD (Industrial Flexible and Demountable buildings) Program developed in the Netherlands [Durmisevic 2006, Henrotay 2008, Debacker 2009] and also provide social benefits [Chini et al. 2003, Sassi 2004, Henrotay 2008]. The existing research field of DfD provides basic information required as a starting point for this PhD thesis.

Design for Reuse (DfR) can be taken into account by closing the three life cycles of Debacker (2009) in an effective way. Design strategies exist that deal with these three building levels [the Dorsthorst and Kowalczyk 2002; Debacker 2009]:

1. *Design for dismantling*, wherein **building materials** are technically easy to separate according to their waste or reinvestment treatment. If possible, down-cycling wherein the initial material is used for a lower grade function must be avoided. Biodegradable materials can be brought back into the natural cycle;
2. *Design for deconstruction*, wherein **building components** should be technically demountable. To reuse building elements multiple times they must be designed in such a way that during handling damage is prevented as much as possible;
3. *Design for adaptability/versatility*, wherein **buildings** should be technically easy to adapt to changing constraints.

To better situate the context and the scope of this research, each of the design levels for reuse is briefly discussed in the next paragraphs, pointing out which strategies are incorporated further in this work.

3.2.2 BUILDING LEVEL

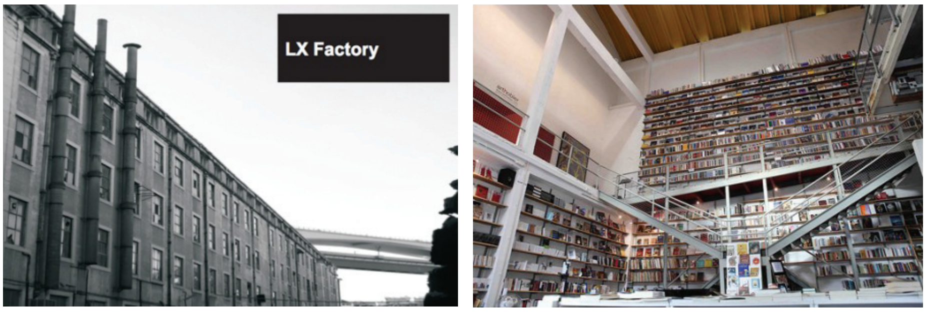
According to Leupen (2005) there are three possible ways to deal with time and uncertainty at building level:

- *Make buildings versatile;*
- *Make buildings partially permanent and partially changeable; and*
- *Make buildings semi-permanent.*

3.2.2.1 VERSATILE BUILDINGS

The first approach *-versatility of buildings-* implies that buildings may be applied in different ways without adjustments to the way they were initially built. This means that whereas polyvalence of offices, commercial spaces or industrial buildings may be ensured by providing proper dimensions, versatility in the context of housing relates primarily to spatial exchangeability of activities between different rooms. In this case, dwellings must be able to provide an appropriate space for a wide range of activities which may take place at the same time [Leupen 2006]. Examples of this building approach are consequently more likely to be found in industrial than in residential buildings regarding the rapidly changing individual styles and preferences, and contemporary comfort standards in residential buildings compared to the industrial sector.

Figure 3.1: LX Factory in Lisbon



Source: LX Factory

For example, in Lisbon, an old industrial site which was originally occupied by a threads and fabrics company called "Companhia de Fiação e Tecidos Lisbonense", recently became the new setting for a diverse set of commercial spaces and happenings related to fashion, publicity, architecture, bookshops, music and concerts, and many more. This illustrates that versatility of buildings maximises the reuse of buildings since little or no radical changes are needed in the building fabric to accommodate adapted functions.

3.2.2.2 PERMANENT VERSUS CHANGING BUILDING LAYERS

The second approach to enhance buildings capability to deal with time may well be the best known approach, in which it is assumed that there exists a permanent part of the building, which remains unchanged over the total building life cycle while the remaining building parts may adapt and transform over the years. This approach includes both the *support concept* and the *frame concept.*

The **support concept** refers to the well-known *support-infill* approach of Habraken (1962) in which it is argued that support systems should be provided in such way that they offer people the freedom within the structure to build their personalised houses (infill). Providing such support systems would be the task for the community: the house itself would become the result of a process. This concept was developed by Habraken for the Dutch Foundation for Architectural Research (SAR). The SAR 65 approach is based on three main pillars: the concept of 'support and infill', a modular coordination system and the use of zones and margins [Debacker 2009].

Leupen (2006) more recently introduced the **frame and generic space concept** in which the emphasis is not on what can be changed but on what is permanent and lasting inside a building. By determining what can be permanent today, i.e. the nature of the *frame*, opportunities can be created to deal with future unpredictability. A building can be divided in a number of layers of which each layer - or combination of layers - can be seen as the

frame - the permanent part of the building. The remaining layers are considered as the evolving *generic space* subject to frequent update.
The most obvious illustration of the framing concept is the example of a load-bearing skeleton structure in which massive load-bearing walls are avoided and subsequently the floor plan is liberated. According to this principle the permanent part of the building can be thought of as the frame which creates freedom and enables various adjustments to be made without requiring such adjustments to be precisely determined in advance [Leupen 2005].

This concept of *layering* of buildings can be found back in literature in several variations [Habraken 1961, Duffy 1990, Brand 1995, Leupen 2005]. Layers provide a way of thinking about the building that link both time and the building's material form, conceiving components as different layers of longevity [Duffy 1990, Brand 1995, Leupen 2005, Schmidt III 2009].

Table 3.2: Layers of a building deriving from literature (adapted from [Schmidt 2009])

Source	Habraken (1961)	Duffy (1990)	Brand (1995)	Leupen (2005)
Building layers			Site	
	Structure	Shell	Structure	Structure
	Infill		Skin	Skin
		Services	Services	Services
				Access
		Scenery	Space Plan	Space Plan
		Set	Stuff	

The Quinta Monroy Housing project (2005) in Chile designed by the architecture office Elemental - headed by Alejandro Aravena and Andrés Iacobelli – is a good illustration of the *frame and generic space* concept.

Figure 3.2: Quinta Monroy (Elemental)

Source: Elemental

With a minimum construction budget, the think tank of Elemental together with the community for which the housing was intended started a concept for living units based on the traditional row house. This 'row house' was conceived to be possibly expanded and modified with time according to each family's individually changing needs and fluctuating incomes. The designers provided a building lot that contains a building structure including circulation elements and technical provisions - forming the frame - with a physically vacant zone between adjoining dwellings. This void allows residents to adapt and expand each property themselves to suit their individual needs in the future, i.e. the generic space. The initially provided building structure acts as a visual frame, giving a face to constantly changing individual infill of inhabitants [Leupen 2005].

3.2.2.3 SEMI-PERMANENT BUILDINGS

The third approach to make buildings respond to change departs from the perception that buildings have a limited building life span due to our rapidly changing society and are thus not permanent. In practice this implies designs of buildings which enable a total disassembly of components. In the Netherlands the IFD concept has been introduced which stands for an *Industrial, Flexible* and *Demountable* way of building. Initiated by the Dutch government, IFD tries to improve the way of building in such a way that it results in a rapid, economically viable, qualitative and environmentally building solutions. IFD projects which are entirely demountable however are still exceptional, especially in the residential building area. The IFD concept is usually applied for only one aspect of the buildings, e.g. demountable floors, and partitioning.

A good example of an entirely demountable residential building is the Cellophane House of Kieran Timberlake architects (2008) in New York. The Cellophane House demonstrates a holistic approach departing from the preservation of the energy embodied in building components, through recovery of all components for reassembly elsewhere. The aluminium structural frame of the building provides a substructure against which factory made components - forming floors, partitioning and enclosure - can be mounted. Due to the nature of the reversible connections there are no specialised tools or facilities required and the construction can be built in sixteen days while it can be dismantled and re-erected elsewhere using the same building components. Inside the Cellophane House interior floor plans can be rearranged and the building materials can be substituted by other materials based on varied budgets and desired standards.

Figure 3.3: Cellophane House

Source: Kieran Timberlake architects

In the three global strategies over building design it is clear that the more 'temporarily' buildings are perceived the greater the need for strategies at component level that enable these changes without adding to the environmental issues of today.

3.2.2.4 EXISTING BUILDING STRUCTURES

In the context of renovation of existing buildings we have to deal with the settings of building structures which have already been designed and constructed in the past. The need for renovation of multi-storey residential buildings today - in which new spatial lay - outs are often required illustrates that what was thought to be an expression of modern flexible standards in a specific building was not sufficient to resist the test of time.

Depending on the construction techniques, the post war building stock may still incorporate flexibility for future use. This issue will be later discussed when, in Chapter 5, flexibility of the main typologies of post-war construction in the social housing stock is analysed for a selection of case studies. Regarding this question, however, it is important to note that even though not initially designed for change, buildings may still exhibit flexibility for the future. In analogy with the frame concept of Leupen (2005) the permanent layer can be redefined in these post-war multi-storey buildings by removing oppressive and/or outdated parts. The remaining *permanent* part may then form the base for a **dynamic re-design** of these buildings.

When designing for the new *generic space*, i.e. the new parts in the existing building, the designer should strive to introduce DfD and reuse strategies ensuring that each addition is "layered" for easy replacement, adaptation or removal [Morgan and Stevenson 2005]. Therefore, when departing from the permanent elements of a structure, the design of the new infill can use design strategies at component level aiming to prolong their life cycle.

Instead of making similar mistakes as in the initial 'static' design of buildings, a re-design approach is therefore applied with the main premise of a future need for change. This point is one of the touchstones of the DfD approach and is, as a matter of fact, the starting point that led to this research.

3.2.3 COMPONENT LEVEL

3.2.3.1 OPEN SYSTEM APPROACH

In the period after the Second World War the building sector shifted to prefabrication techniques in order to respond the urgent need for new dwellings, inspired by the automobile and aeronautics industry. The post-war mass-production, replacing traditional craftsmanship by machines while using materials and assembly techniques [Habraken 1972, Frampton 1995], has led to the development of many construction systems - most of them using large prefabricated elements. Due to the limited variation of frequently large 'panel' elements used, these building solutions used in post-war residential buildings often resulted in repetitive modular architecture. Today, we find ourselves with an abundance of these 'closed', incompatible modular systems that often generate uniform structures and a stockpile of fairly useless modular pieces after deconstruction [Lommée 2010].

In consequence, *open system building* was developed as a reaction to this post war housing boom, aiming to empower the user [Bosma 2000, Kendall 2004, Schmidt III 2010]. In open systems buildings are seen in the form of an *open structure* which is a result of disciplined integration of independent sub systems [Durmisevic 2006]. As a resulting physical object, open system buildings bolster the capacity for change to take place, while variety is also being provided through greater functional decomposition so that different requirements can be met during a system's life cycle. The main characteristics of such dynamic systems are separation of functions, open assembly, flexible production processes and standardisation on sub assembly level which connect mass production to small size components [Durmisevic 2006].

These open system principles have paved the way for system development, shifting the focus in buildings from predefined static elements to complex components defined by dynamic configurations [Durmisevic 2006, Henrotay 2008, Debacker 2009], while opportunities for reuse and recycling are created. However, in order to facilitate compatibility of building components and enhance flexibility we need to synchronise current dimensional frameworks and define universal standards [Debacker 2009, Lommée 2010].

3.2.3.2 HENDRICKX – VANWALLEGHEM APPROACH

The architects H. Hendrickx and H. Vanwalleghem developed a design approach in the framework of open system building to stimulate reuse in the built environment while providing diversified building artefacts. The Hendrickx-Vanwalleghem design approach (H-V design approach) departs from the objective to create a built environment that *supports* the dynamics of life instead of *obstructing* it [Hendrickx 2002].

The approach therefore encloses guidelines to design multiple construction systems, all compatible to each other, by which a variety of adaptable and reusable construction elements can be composed. Each construction system is made of a minimum number of basic elements and a set of combination rules. They allow the conversion of each artefact to a different configuration by means of adding, removing or transforming the basic elements it is made of. It offers a high potential of recycling and (direct) reuse. The outcome can be compared with kit-of-parts systems of which Meccano® or LEGO® building sets are good examples [Henrotay 2008, Debacker 2009].

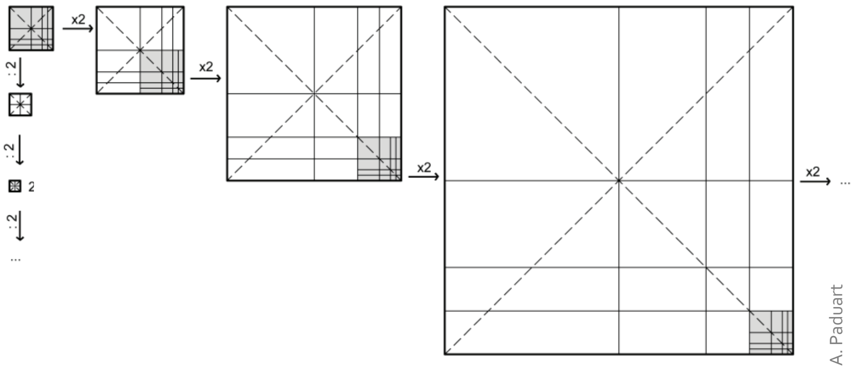
In order to design compatible construction systems, the HV approach provides two design tools: firstly, a *generating system* that produces form and dimensioning of basic elements and, secondly, a method for developing *design catalogues* for standardised and compatible elements.

TOOL 1: A GENERATING GRID

To develop compatible basic elements standardisation rules are required through which form and dimensions of basic elements can be regulated. In the HV-approach, therefore, a simple and comprehensible concept was introduced namely the "generating form and dimensioning" system [Hendrickx 2002, Debacker 2009, Henrotay 2008].

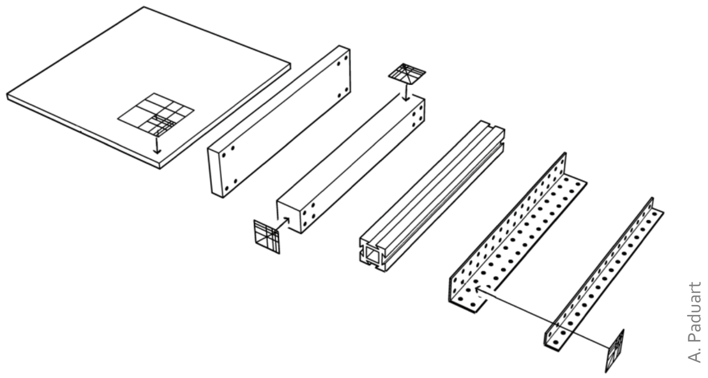
In these standardisation rules Hendrickx and Vanwalleghem presume that any tangible basic element can be approximated with a minimal diversity of basic forms derived from a fractal model: the *square*, its *diagonals* and the *inscribed circle*. The set of basic forms should then be provided with basic dimensions resulting from rules of either halving or doubling of a basic unit. Series of a lower standardisation level are set up by adding up values of the primary series [Debacker 2009, Henrotay 2008].

Figure 3.4: Design of basic elements according to the fractal model



The fractal model can be projected on all materials and all scales and can therefore define the basic elements for different material types, for linear, planar or volumetric elements.

Figure 3.5: Morphology of basic elements according to fractal model



Using a fractal model offers benefits designing at different levels, i.e. structural, spatial, functional and technical. This is an efficient alternative to conventional superposition of different modular design grids for each design level that may result in dimensional problems where different grid lines intersect [Debacker 2009]. The single operator in the fractal model (e.g. divide or multiply by two) makes a shift to different design levels possible, without putting the compatibility at stake between each basic element [Debacker 2009].

A good example of the use of a fractal model is illustrated by a research project in 2009 initiated by Thomas Lommée about open modularity in the artefacts we use in our everyday life, the so-called OpenStructures (OS) project. The project was originally conceived at the Institute without Boundaries and further developed and tested by Intrastructures in collaboration with the 4Dimensional Design Research group (VUB).

Figure 3.6: OpenStructures artefacts designed according to the OS design grid [OpenStructures 2009]

This project explores the opportunities of a generic construction model for artefacts in which *everyone designs for everyone* on the basis of one shared geometrical grid [OpenStructures 2010]. An Open Structure is defined as an assembly of components mostly consisting of a frame which supports additional functional elements. These frames and elements were designed making use of the fractal design grid - based on a 4cm x 4cm base unit - and are assembled and connected using reversible joints. This open grid is used as the tool which allows each designer to develop compatible parts, components and structures independently from each other. The research project illustrated that a more dynamic and scalable built environment can be developed based on a generating grid;

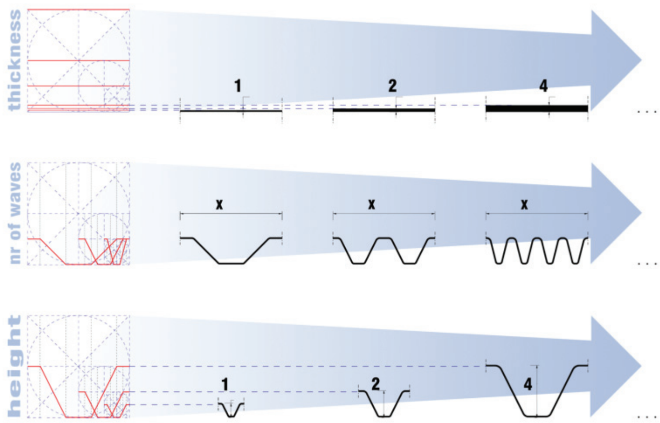
dynamic patchworks worked better rather than rigid, monolithic blocs [OpenStructures 2010].

TOOL 2: DESIGN CATALOGUES

The second tool in the HV approach to enhance an open building approach is the systematic development of design catalogues, in which basic elements are based on combinations of selected parametric rules. An aid to develop construction systems with compatible basic elements is achieved by developing theoretical design catalogues. These design catalogues enable to set up catalogues of basic elements of which different characteristics are varying, but of which all dimension and form is derived from the same fractal grid. This development is carried out in a particular way that can be apprehended in the lines that follow.

Design catalogues allow description of an adaptable artefact, through translation of one or more properties series [Debacker 2009; Henrotay 2008]. In a first step, each of the composing elements of a building product is objectively and verbally described based on characteristics, strengths and weaknesses [Debacker 2009]. Each characteristic has one or more parameters as a counterpart, all bracketed between predefined limits. This can be illustrated with a simple construction element, e.g. a steel corrugated plate for application subject to transverse loads illustrated in Figure 3.7 [Debacker 2009].

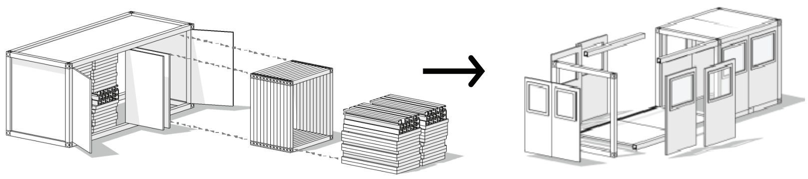
Figure 3.7: Theoretical design catalogue of a load-bearing corrugated plate [Debacker 2008]



The bearing capacity of a steel corrugated plate can be described with three main parameters: its thickness, the number of waves per unit length and the height of the waves [Debacker 2009]. These parameters can be entered into series as represented in Figure 3.7 by defining extreme values, e.g. the ultimate steel plate thicknesses possible (i.e. the smallest and largest value). All variants should lie between the defined limits. A thin plate is the opposite of a thick one: this means that there is a limit for the ratio thickness-span. Whereas the thickness of the plate is defined by the production process of steel, the number of waves per unit length and the height of the waves are limited by plate thickness and fabrication process [Henrotay 2008; Debacker 2009]. Hence, theoretical[1] design catalogues can be established combining and juxtaposing elements. From this catalogues simple systematised elements can be selected to match the specifications of a building product in a certain context.

A practical example of a construction kit derived from selection of several design catalogues is given by Debacker (2009) who designed multiple use construction kits for PSO (Peace Supporting Operations) accommodation. These construction kits are composed of versatile and compatible (sub) components designed according to the HV-approach. Instead of using a fixed building module which can only be lined up and stacked - such as existing containerised solutions - a transformable unit was proposed.

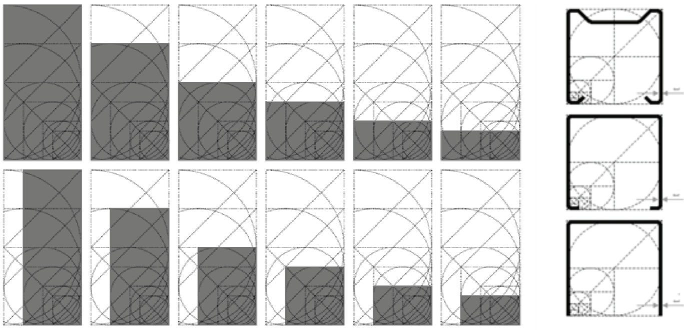
Figure 3.8: Conceptual drawing of multiple use construction kit for PSO [Debacker 2009]



The main objective of this design is to create a construction module, of which the three dimensions - *height, width* and *length* - can be changed over time, in relation to different applications or dwelling configurations that also change over time. Consequently, the sub components of the building module sustain the transformative character, following the HV design approach. Like in a Meccano® box only a limited number of different component types were selected. The compatibility of these components was based on a generating form and dimensioning system.

[1] The emphasis has been put on "theoretical" as in practice not all combinations are possible or technically sound, meaning that they are not considered in a practical catalogue.

Figure 3.9: Geometrical standardisation of components based on fractal model [Debacker 2009]



Moreover, transformation of constructions and components is done by changing the position of (sub) components or by replacing them with other compatible elements derived from the design catalogues. By using a limited set of sub components a varied set of configurations can be assembled with similar or totally different applications, including an ISO 20ft container to transport and store all elements to the construction site [Debacker 2009].

3.2.4 MATERIAL LEVEL

3.2.4.1 CRADLE TO CRADLE IN THE BUILDING WORLD

The last level to apply reuse strategies in the scope of this research is the *material* level. Building products need to be materialised and designed in an intelligent way in order to possess a form that allows their contents to continue to be applied in repeated cycles according to the motto "from cradle to cradle" instead of cradle to grave.

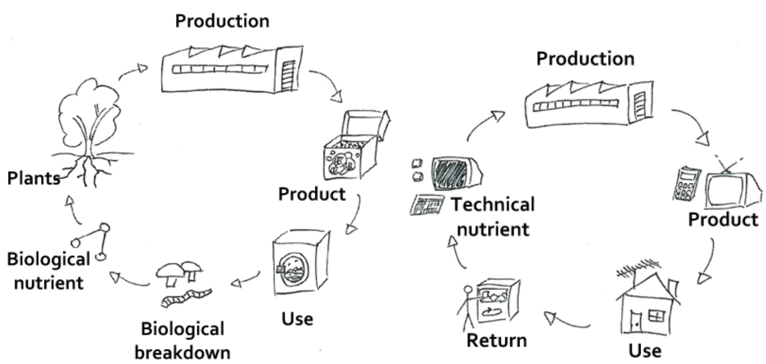
An important strategy that includes a life cycle design view on material level is the Cradle to Cradle® (C2C) concept. C2C includes an approach to design products, processes and systems taking into account the entire life cycle of the product, optimising material health, recyclability, renewable energy use, water efficiency and quality, and social responsibility [McDonough et al. 2003].

Three basic principles guide implementation of the C2C philosophy:

- *Waste = Food (everything is a nutrient for something else);*
- *Use current solar power income;*
- *Celebrate diversity (biodiversity, conceptual diversity and cultural diversity).*

At material level of the design of building products, C2C therefore defines parameters for development of products and industrial processes in which materials become forms of nourishment within a *biological* or *technical* cycle at material level.

Figure 3.10: Biological and technical circulation of consumables and products [EPEA 2010]



A *biological* nutrient can consist of biodegradable materials that do not cause damage to the living systems after use and can be passed back to nature for biological processes. According to McDonough and Braungart (2007) biological nutrients are ideal for products that are gradually used up during their usage, such as for instance textiles, brake discs, or shoe soles [Braungart et al. 2007].

Figure 3.11: 100% compostable Trigema t-shirt

Source: Cradle-to-Cradle

A *technical* nutrient is defined as a material with potential to be safely reused in a closed, industrial reuse cycle [Debacker 2011]. It is crucial that the quality of the technical nutrients is maintained or upgraded throughout the numerous cycles of manufacture, recuperation and reuse. Consequently, negative effects of down-cycling can be avoided. For example, in the context of construction steel, at present, valuable non-ferrous metals are lost through a primitive recycling of used cars [Braungart 2010].

The milestones to achieve C2C in the building world according to the manifesto 'Cradle to Cradle in architecture' [c2carchitecture 2009] at material level are shown in Table 3.2.

Table 3.3: Milestones to achieve C2C in the building world according to the manifesto 'Cradle to Cradle in architecture' [c2carchitecture 2009]

	C2C strategies to achieve C2C in the building world at material level
Material Level	- Eliminate waste: only use materials that will become resources for further biological or technical production loops; - Only use materials of which the impact is measurably beneficial for human health and the environment; - Design buildings free from radioactive and toxic "off-gassing" materials; - If hazardous materials are necessary, they must not be released into the environment and are completely recoverable in technical pathways.

Buildings have a high potential in terms of biological and technical nutrients since they are made up of a wide variety of building products and materials while they have significant influence of energy and water consumption [Debacker 2011]. Due to the long service life of buildings components generally have to be replaced or repaired on numerous occasions during their period of use.

The additional requirements according to C2C design demand for an extended range of building materials/products which can ensure that embedded substances/elements can circulate in biological/technical nutrient cycles. Only with appropriate building materials the concept of nutrient cycles can be achieved in the built environment. For instance, building materials such as cement and concrete should be conceived in such a way that no harmful or problematic additives increase the contamination of the biosphere [Braungart 2010].

3.2.4.2 *STATE OF THE ART IN FLANDERS*

Until now, only a very limited number of building materials on the Flemish building market have a so-called C2C-certificate[2]. However, the Flemish Government has started to stimulate the Cradle-to-Cradle principles in 2010, when it allocated 5 million euro to research institutions and companies for the development of sustainable technologies and products [Debacker 2011]. This simulation program includes the closure of material and process reuse cycles according to the Cradle-to-Cradle philosophy.

Although increasing numbers of Flemish companies are starting work on the Cradle-to-Cradle concept, such as *Gyproc* (gypsum based products) and *Wienerberger* (bricks), the overall increase in number of C2C certified products in Belgian remains limited. Of the approximately 300 certified products (2010) products of Belgian origin can still be counted on the fingers of one hand [Debacker 2011]. In Flanders, at present, the general selection of 'sustainable' building product is not based on C2C labeling, but relies on other certifications/labels like the European data label, NIBE's reference work for Environmental Classification Building Products, FSC and BRE environmental profiles.

[2] The C2C design principles on material level lead to a certification system for products, according to different degrees of performance (from basic to platinum).

3.3.1 NEED FOR UPGRADABLE, ADAPTABLE AND REUSABLE SOLUTIONS

In the previous chapter it was explained how evolving building standards, fluctuating occupation of social housing by different household types and evolving comfort standards require renovation approaches that anticipate the need for change in the future. Therefore, as a complement to the upgrade of buildings according to EPBD standards, additional criteria must be set in order to evaluate to what extend building products today introduce a dynamic life cycle design.

Therefore, criteria were selected deriving from literature, esteemed appropriate in the scope of this research project. Although elaborate evaluation tools to 'calculate' the transformability of building solutions exist [Thormark 2001, Sassi 2002, Durmisevic 2006], the complexity of these models to collect all relevant information for evaluation generally requires expert skills and professional software, which cannot be easily performed by stakeholders in the context of social housing. In order to reach out criteria which are more usable and comprehensible for all stakeholders it is esteemed more suitable to propose a selection of straightforward criteria to gain overall insights about dynamic properties of building systems - almost in an intuitive way[3].To provide an overall view about building components used in renovation it must consequently be analysed if building solutions integrate an integrated life cycle design, if they deal with (de)construction and replacement issues, and if opportunities for alterations with reuse of components is addressed. The selection of criteria was based on literature of Design for Assembly (DfA) and Design for Disassembly (DfD) principles [Crowther 2002, Sassi 2002, Durmisevic 2006, Debacker 2009].

3.3.2 EVALUATION CRITERIA FOR DYNAMIC LIFE CYCLE DESIGN

3.3.2.1 DESIGN FOR ASSEMBLY VS. DESIGN FOR DISASSEMBLY

Disassembly of buildings may sound like the opposite of their *assembly* but in practice it seldom occurs in the reversed way [Crowther 2002]. The main difference between Design

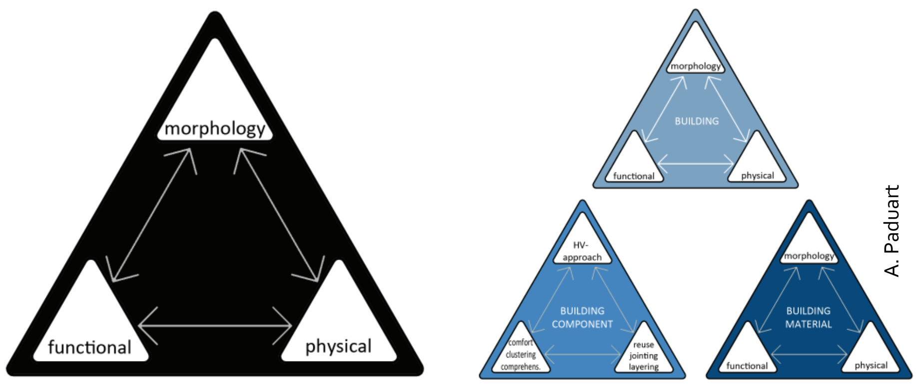
[3] Since it is not the objective to make a quantitative assessment of the dynamic capacity of building products, this approach seems acceptable. The focus of the research, i.e. the detailed environmental and financial information of these products over a dynamic building life cycle will then be further elaborated in detail in Chapter 8.

for Assembly strategies (DfA) and *Design for Disassembly* (DfD) mainly relate to their primary *objectives*.

Design for Assembly (DfA) was initiated by Boothroyd (1989) in the 80s introducing a process for improving product design for *easy* and *low-cost* assembly, thereby focusing on functionality and ability to assemble concurrently in *economic terms*. By simplifying handling of parts and improving product assembly, reducing the number of parts, optimising manufacturing processes and consequently reducing the assembly duration the overall labour costs could be reduced [Boothroyd 1989, Boothroyd 2002, Baizura 2007]. Furthermore, implementation of Design for Assembly encouraged product design in order to manufacture (building) products with maximum quality and reliability [Baizura 2007, Boothroyd 2002].
On the contrary, Design for Disassembly (DfD) originated from *environmental* concerns in the end of the 1990s. Principles of Design for Assembly - or *ease of construction* - were adapted towards principles for Design for Disassembly [Crowther 2002]. As a result, strategies and principles of *Buildability* – a concept introduced by CIRIA (1983) to represent the ease of assembly in the building environment - were translated and adapted for Design for Disassembly by simple extending responsibility for the building beyond its service life and using similar design techniques that promote good assembly to promote good disassembly [Crowther 2002].

In the framework of this research study criteria were selected from DfA and DfD and subdivided according to physical, *functional* and *morphological* design concerns. The selected criteria can be related to each design level - *building*, *component* and *material* level. In this chapter, however, only criteria at *component level* are discussed since the qualitative assessment in Chapter 4 deals with criteria at component level.

Figure 3.12: Evaluation criteria at different building levels



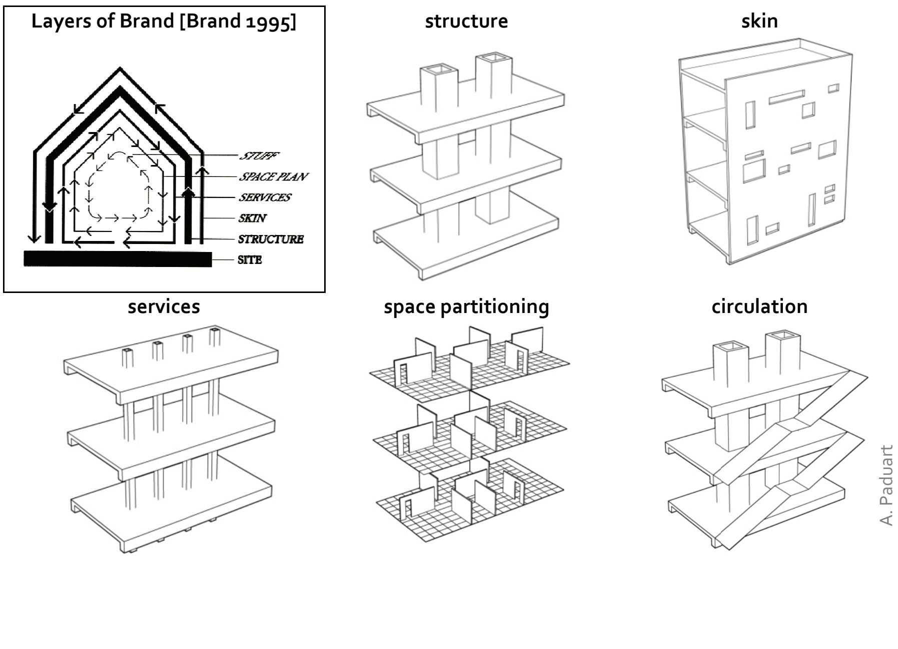
3.3.2.2 *PHYSICAL CRITERIA*

LAYERING

When designing for flexible structures the introduction of the concept of *layering* is a crucial initial design step. Brand (1995) introduced a conceptual framework at building level to subdivide a building into functional layers with typical service lives (Figure 3.13) characterised by the anticipated need for modification. It is at the junctions of these layers with varying service life expectancies that disassembly will need to occur during a building life cycle. Consequently, the physical separation of constructions in six **shearing functional layers** allows layers or systems to be replaced, altered are taken away without affecting the other layers. Facilitating disassembly of each layer will therefore allow buildings to naturally evolve over time in an environmentally and socially responsible way. Brand (1995) defines six *shearing layers* as following [Brand 1995, Morgan and Stevenson]:

1. **Site**: the geographical setting, the ground on which buildings are constructed;
2. **Structure**: the foundations and load-bearing components of buildings;
3. **Skin**: the cladding and roofing system that excludes (or controls) the natural elements from the interior;
4. **Services**: electrical, sanitary and technical appliances;
5. **Space Plan**: the internal vertical and horizontal partitioning systems;
6. **Stuff**: the furniture and other non-attached space defining elements.

Figure 3.13: Selection of building layers according to Brand (1995) with addition of circulation



In addition, a seventh building layer is included in this study in analogy with Leupen (2005), namely the **Circulation** layer. In general, the *circulation* is closely related to the load-bearing structure but it may also feature in buildings as an independent entity.

Consequently, in this research study the term **building layer** is applied to refer to the layers of Brand, including the Skin (*facade and roof*), Space Partitioning (*vertical partitioning and separating floors*), Services and Circulation. In the framework of this work, the Structure is already determined by the existing load-bearing structure.

The same concept of 'layering' can be implemented for design at component and material level. Components can be physically sub layered in sub components, whereas basic material element can be sub layered using different materials. Consequently, **sub layering** is referring to additional layering of principal 'building layers' of Brand at lower level, i.e. component and material level.

REUSE AND REVERSIBLE CONNECTIONS: KEY FACTORS

The choice of connections is incontestably one of the most crucial aspects of DfD [Durmisevic 2006, Debacker 2009]. The type of connections between construction elements is determinant for whether or not deconstruction or dismantling can take place successfully. Dry connections that are reversible and can be applied without damaging parts are the most preferable. This will be illustrated in Chapter 4.

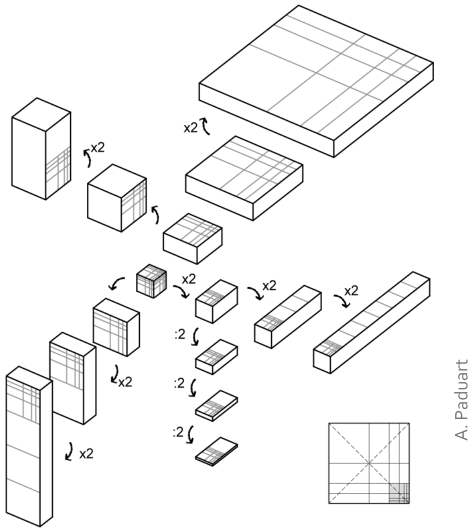
The type of connection is, among other criteria, strongly related to the materialisation of components [Debacker 2009]. Dry joints and indirect connections are not always feasible with the traditional building materials. A fundamental constraint when reuse of components is taken into account is the durability of the components: to optimise reuse and repair with minimal cost and labour components need to exhibit durability.

In addition, the service life of components is also a fundamental requirement of components to maximise the benefits of reuse; the benefits of reuse related to components with a short service life are clearly less interesting than materials that last for many decades.

3.3.2.3 MORPHOLOGICAL CRITERIA

The morphological criteria for components relate to the form and dimensioning of (sub) components (elements) in order to enable a wide variety of applications by enhancing the compatibility between the elements.

Figure 3.14: Compatibility of basic elements according to fractal model



The approach in this dissertation is based on the Hendrickx-Vanwalleghem (HV) approach, using a fractal grid in order to ensure that all basic elements are simple and straightforward and have a high capacity to be applied in current application while they enhance a future second life in a wide range of other applications after deconstruction due to their simplicity and ease of understanding.

3.3.2.4 FUNCTIONAL CRITERIA

ACCESSIBILITY

Visually, physically, and ergonomically accessible connections will increase efficiency and avoid requirements for expensive equipment or extensive environmental health and safety protections for workers [Guy 2006]. Therefore, good access to components and fasteners should be integrated. Consequently, the ease of access will enhance the ease of disassembly and allow for components to be recovered from the building site without destructive techniques if other physical criteria are responded.

INDEPENDENCE

The independence of components relates to the relation with its surrounding parts: independence is crucial so that components or materials can be removed without disrupting other components or materials. If it is not possible to make all elements independent from each other in one component, the most reusable or 'valuable' parts of the building must be made most accessible to allow for maximum recovery of these components.

CLUSTERING

Limiting the number of different connection types and base elements simplifies to a great extent the assembly. Pre-clustering - of preassembly - of assemblies will reduce the site work and allow greater control over component quality and conformity. This will more extensively be discussed in Chapter 6.

COMPREHENSION

Specialist technologies complicate the assembly as they call for specialist labour and equipment which increase the complexity and results in added labour time and increased financial costs. In order to make a good understanding of the assembly of building systems becomes possible one must apply standardised components and fasteners compatible with other systems both dimensionally and functionally.

COMFORT

The comfort relates to a number of assembly concerns, amongst which ease of handling components, understanding and simplicity of connections, and use of tolerances to facilitate the assembly.
First, clearly, using components with limited dimensions and weight, makes these components easier to handle on site during assembly. Secondly, using simple and straight-forward connection types together with assembly tolerances adds up to the comfort of assembly and disassembly.

3.4 DISCUSSION

In the construction industry - which is responsible for a large section of our resource use and waste production - Design for Disassembly (DfD) strategies have become crucial to tackle the environmental burden of our way of designing buildings. Design for Disassembly may in the short term add economic and possibly environmental costs (see Chapter 8) but on the much larger scale of the life cycle of material resources, the long term benefits are potentially much greater.

The opportunities of introducing DfD strategies in the context of renovation of (social) housing are apparent, considering the rapidly evolving society and policies, and the growing importance of these buildings in the future. Building standards are expected to become more stringent in the near feature, which explains why a dynamic approach to the design and materialisation of building solutions today is so pertinent.

To further investigate the benefits of DfD strategies in the context of renovation of (social) housing, first, the need for change of each *building layer* according to the vision of each stakeholder in renovation of social housing must be identified. Secondly, standard solutions applied in renovation need to be evaluated in order to determine if a life cycle vision is incorporated dealing with all life cycle phases amongst which construction, maintenance, replacements, alterations, deconstruction/demolition and end-of-life of building products. Hence, missing opportunities in current building product design can be revealed, which will eventually lead to a range of alternative proposals, discussed in Chapter 5.

04

QUALITATIVE EVALUATION OF STANDARD RENOVATION SOLUTIONS

In the previous chapters, it was identified that existing buildings have difficulties coping with change, due to their initial rigid design and the materialisation of sub components. A dynamic renovation approach was in introduced, i.e. Re-Design for Change, based on a 4 Dimensional design approach. At component level, this implies that buildings systems must provide flexibility to deal with changing needs over the building life cycle, while reuse potential of components is crucial to reduce the environmental burden associated with the built environment. The question that arises is therefore: Do building solutions introduced during renovation of our existing stock today incorporate this flexibility for future adaptation? And are they designed from a life cycle view, in which the composing building elements can be easily deconstructed and reused if needed?

The aim of this chapter is therefore to respond if there is a need for design of alternative building solutions which improve the life cycle design of building products today. A global evaluation and comparison of building systems for renovation is, however, difficult to undertake since buildings are complex systems including a wide range of subsystems all together influencing the global performance. Throughout a multi-level approach, i.e. Multi-Criteria Analysis (MCA), a nuanced picture about interferences between diverse goals and requirements can be developed, set up by different key actors in renovation projects. The qualitative criteria in the MCA were based on a survey developed in this PhD thesis, combined with literature study. Together, this enables to gain insights into the criteria which architects, social housing societies and members of the VMSW (Flemish umbrella of social housing societies) apply in order to evaluate renovation alternatives.

Financial costs and environmental impacts related to the life cycle of building products are important quantitative aspects, therefore requiring an additional detailed assessment; therefore Part III of this PhD thesis is dedicated to a detailed evaluation of these aspects.

4.1 MULTI-CRITERIA ANALYSIS

4.1.1 METHODOLOGY

In order to perform a complete study of building systems a complex evaluation would be required including a wide range of building characteristics amongst which contextual, financial, technological, environmental, climatic and social conditions. Multi-Criteria Analysis (MCA) allows an evaluation of qualitative criteria in conformity with prerequisites set up by the main stakeholders in renovation of social housing, i.e., occupants, social housing societies, the VMSW (Umbrella for Flemish Social Housing Societies) and architects. Diverse perspectives on the approach for renovation and the aspired performance can be expressed through 'weighting' of a range of qualitative criteria, which enables to score and compare building products.

In multi-criteria analysis (MCA) a hierarchical approach is applied, arranging key criteria of a stated 'problem' into a hierarchical structure of *criteria*, *sub criteria*, *indicators* and *verifiers*. These hierarchical levels are defined by Mendoza [1999]:

- *Criteria & sub criteria*, which indicate principles or standards by which the subject of assessment is judged by (1st and 2nd level);
- *Indicators*, which give a specific description of a (sub)-criterion through single qualities (3rd level);
- *Verifiers*, which provide specific details indicating a condition of the indicator to assess that indicator (4th level).

The following consecutive methodological steps are necessary to undertake multi-criteria assessment [Mendoza 1999]:

1. Definition of goal and scope of the qualitative assessment;
2. Identification and selection of criteria, sub criteria, indicators and verifiers;
3. Determination of the weighting of each assessed element;
4. Scoring of criteria, sub criteria and indicators based on verifiers;
5. Assessment of alternatives (aggregation of weighting factors and scores) at all levels of the hierarchy;
6. Interpretation of results.

All verifiers, indicators, sub criteria and criteria need to obtain a value according to their hierarchical importance in the multi-criteria assessment to define weighting sets. To identify and express the relative importance of each (sub)-criterion, indicator and verifier, there are two simple techniques in MCA methodologies, i.e. ranking and rating [Mendoza 1999]. *Rating* is a technique where experts are asked to give each decision criteria a rating or percentage score, between 0 and 100. The scores for all the elements being compared must add up to 100. *Regular ranking* assigns each element relevant to the decision process a 'rank' depending on its perceived importance.

Figure 4.1: Ranks assigned to a 9 point-scale

To give each criterion an accurate measure of cardinal importance would require an expert team that has access to large amounts of relevant information [Mendoza 1999]. Since it is perceived as a barrier for non-experts to give objective rates to subjective criteria as in rating, a combination is made of both techniques. Therefore, first, the ranking method is used as an intuitive technique to help different key actors to attribute a value to proposed criteria and sub criteria derived from literature. In a second step these criteria are then relatively compared to each other, based on the attributed level of importance. For instance, if two sub criteria are both perceived as moderately important (ranking 5) this means that both sub criteria are esteemed of equal importance, and each account for equally 50% of the weighting of that criterion. The ranking, i.e. five, relates to the relative importance of the criteria itself. A total value of 100% will be subdivided amongst the relative importance of criteria/sub criteria attributed by the stakeholders in the survey.

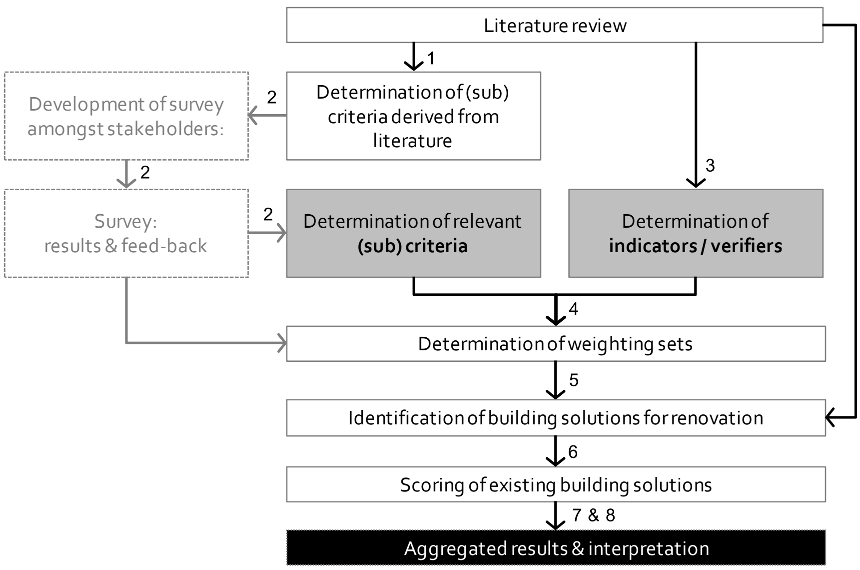
4.1.2 GOAL AND SCOPE

Qualitative assessment with MCA is a powerful tool which can indicate how alternative renovation solutions are valued, not only in terms of today's requirements but also in a future context. Chapter 2 suggests that the main focus in building renovation in Belgium lies upon initial energetic building upgrade to comply with EPBD policies. Through the MCA it can be revealed if the solutions introduced in this framework simultaneously integrate a future life cycle perspective of building products. Therefore, this analysis examines to what extent renovation measures of today respond overall life cycle issues, and, if alternative/complementary solutions for renovation practice of today are requested.

The multi-criteria analysis is performed at **component level**, for a selection of building layers (facade, partitioning, separating floors and roof). Consequently, selection of (sub) criteria is based on physical, technical or functional characteristics at *component* level, and does not include interventions at building level. For example, in order to improve the user comfort, thermal upgrade can be achieved by means of a wide range of interventions: replacement of heating installations and ventilation systems, renewal of electrical appliances, and/or thermal upgrade of the insulation of the building skin. Global interventions which do not affect the component level of, in this case, the facade and roof – i.e. the modernisation of technical installations - are not included and are assumed equal for all compared solutions. The thermal performance of the facade and roof, conversely, is included at component level, since it prevents excessive heat losses through the facade and roof - leading to higher thermal comfort. It is then compared how a *functional unit* of a range of facade solutions with equal performance for the criterion indicated as the most crucial/compulsory one - in this case the thermal U-value for facade - scores on the overall set of criteria in the MCA analysis. For instance, facades may all comply in the same way with the compulsory thermal U-value, but the assembly techniques and sub layering used result in a wide range of properties when it comes to acoustic performance, life cycle design (e.g. maintenance and replacements) and construction aspects (e.g. construction speed and ease of deconstruction).

The consecutive steps that were followed in this research for the development of the qualitative assessment based on multi-criteria analysis are summarised in the flowchart, represented in Figure 4.2.

Figure 4.2: Methodological steps for the qualitative assessment in this research



The structure of the following paragraph is based on this flowchart:

1. Collecting data from literature to identify main criteria and sub criteria for the qualitative assessment;
2. Development of a survey based on (sub) criteria, including feedback and selection of relevant (sub) criteria for the qualitative assessment;
3. Collecting data for identification of indicators of the (sub)-criteria;

4. Determination of weighting sets for the criteria defined by the type of participants of the survey;
5. Identification & selection of alternative upgrade solutions for renovation;
6. Scoring of alternative solutions;
7. Aggregation of weighting sets and scoring;
8. Interpretation of results.

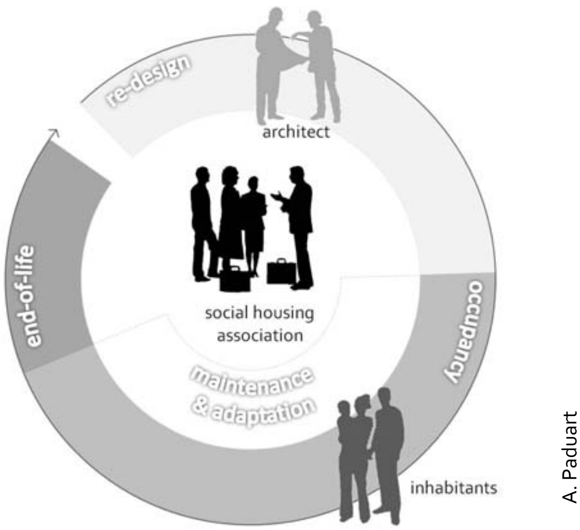
4.1.3 SURVEY

4.1.3.1 OBJECTIVES AND SCOPE

Weighting sets in a MCA depend on the individual viewpoint of all actors/stakeholders. Architects, engineers, social housing societies, members of the VMSW and inhabitants have different individual priorities/preferences according to their degree of participation in the renovation of buildings.

Criteria based only on literature do not necessarily reflect the aspirations of the every-day life of inhabitants or the perspective of decision-making housing societies confronted with the daily reality to implement a wide set of requirements in practice.

Figure 4.3: Stakeholders in the context of renovation of social housing



Therefore, a survey was developed to:

1. Indicate additional (sub)-criteria for inclusion in the assessment;
2. Check the relevance of preliminary criteria and sub criteria based on literature;
3. Value the importance of each (sub-) criterion to evaluate solutions according to the perspective of each stakeholder in renovation.

To take into account and understand different viewpoints concerning renovation of social housing, all participants were split into three different groups. Through the answers of each group separate weighting sets were established. The survey was separately held in the following groups:

- *Architects working within the field of residential renovation;*
- *Members of the VMSW involved with renovation;*
- *Social housing societies (SHC).*

Clearly, the participation of inhabitants of (social) housing is an important aspect of renovation. However, due to the boundaries of this study their participation in the framework of setting up qualitative criteria for renovation was not explicitly evaluated. By enclosing the aspect of increased user comfort and adaptability of typologies - to give answer to changing inhabitants' needs - their interests are represented to an important extent. The participants were selected based on their experience, executed projects, and/or function. In total 10 architects, 13 members of social housing societies and 6 members of VMSW participated in this survey.

4.1.3.2 CRITERIA AND SUB CRITERIA BASED ON LITERATURE REVIEW

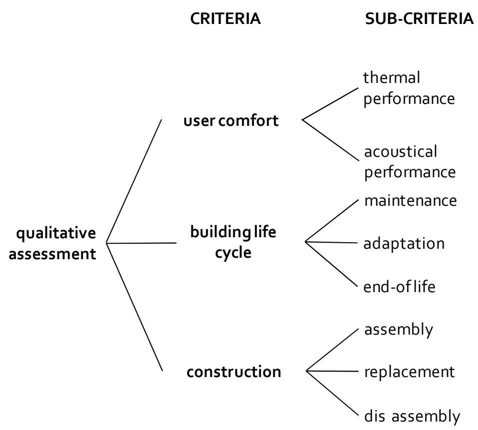
The preliminary literature study focused on renovation of residential buildings [MATRIciel 2009; Trachte 2010, EPDB 2010], a life cycle approach of buildings [Kohler et al. 2009], adaptability of building components [Durmisevic 2006, Morgan 2005, Addis 2004, Sassi 2002, Debacker 2007], (dis)assembly [Boothroyd 1992, Crowther 2002, CIRIA 1983], the normative framework of buildings and reports related to social housing renovation [VMSW 2008]. Three main qualitative criteria were derived from the study, which were in the next step presented and discussed with stakeholders involved with renovation of (social) housing. These initial criteria relate to initial user comfort, the life cycle of buildings and construction issues, leading to the definition of three main criteria for the MCA:

- *User comfort: thermal and sound performance*[1]*;*
- *Building life cycle: maintenance, adaptation & end-of life;*
- *Construction: (dis) assembly and replacement of components.*

[1] Visual comfort was discarded since this applies on the design of buildings, and not at component level. Visual comfort is defined by the facade layer, as an interchange of different building facade parameters, such as size and number of openings in the facade. Therefore, it is assumed that the building design sets the visual comfort equal for all analysed facade solutions.

The hierarchical structure of the (sub)-criteria is represented in Figure 4.4. These criteria and sub criteria formed a starting point for the development of questions in the survey, discussed in the following paragraph.

Figure 4.4: Criteria and sub criteria for qualitative assessment of facade solutions



4.1.3.3 RELEVANCE OF (SUB) CRITERIA

For the survey, a questionnaire form was selected that could easily reflect the importance which participants attribute to different topics based on their experience in the renovation field. Therefore, a survey with numerical scale from *1 to 9* was applied to indicate the scale of importance of a presented range of topics. These values can be understood as following:

- A *value of 1* means that the respondent considers the proposal not important (or unaccepted);
- *A value of 9* means that the respondent considers the proposal extremely important (or accepted);
- *A value of 5* means that the respondent is undecided about the relevance.

Table 4.1: Numerical scale from 1 to 9 to indicate scale of importance

Criterion	Scale of importance								
	not important				*important*				*extremely important*
criterion 1	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐
criterion 2	1☐	2☐	3☐	4☐	5☐	6☐	7☐	8☐	9☐

The content, formulation of questions, range of responses and sequence of questions are based on the preliminary discussions with stakeholders in renovation of social housing in Flanders. The resumed survey can be consulted in Appendix I. The results of the survey are used to indicate both the *relevance* and *weighting* of criteria attributed by different sub groups.

4.1.3.4 RESULTS FOR RELEVANCE OF CRITERIA

Agreement about the relevance of criteria among the respondents is defined on the basis of distribution of all the values obtained and the median of the values. For this research (sub) criteria are deemed:

- *relevant*, when the value of the median is ≥ 7 (with strong agreement if less than 10% of all scores is ≤ 5);
- *non relevant*, when the value of the median is ≤ 3 (with strong agreement is less than 10% is ≥ 5);
- *uncertain* when the median is between 4 and 6.

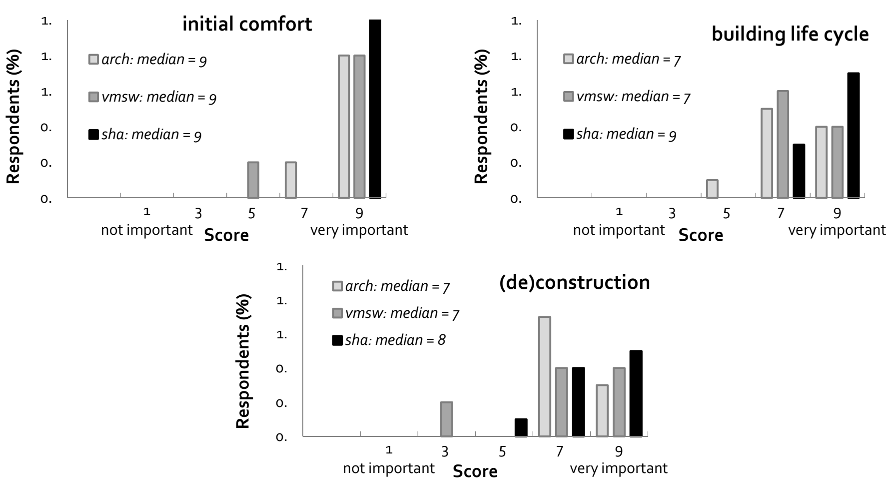
Table 4.2: Classification of criteria according to the value of the median and distribution of the scores

(sub)-criteria proposal	degree	distribution of scores	median (m)
relevant	strong agreement	7 to 9[1]	m ≥ 7
	relative agreement		m ≥ 7
non relevant	strong agreement	1 to 3[1]	m ≤ 3
	relative agreement		m ≤ 3
uncertain	undecided	1 to 9	4 ≤ m ≤ 6

([1] minimum 90%)

The outcome of the survey confirmed the relevance of each preselected criterion, for each sub group (architects, VMSW and SHC). The median *m* of each evaluated criterion always revealed scores of *m ≥ 7* with only 6% of the values attributed to the main criteria with a value *m ≤ 5* (Figure 4.5). This leads to the overall assumption that there is a *relative* to *strong* agreement of the relevance of all selected criteria.

Figure 4.5: Results of survey for *main criteria* for three participant sub groups



In particular, a strong agreement was revealed about the importance of upgrade of *initial user comfort* as a main motive for renovation. The median for each sub group indicated a value of $m = 9$, confirming the important attributed to this criterion. The values of medians of $m \geq 7$ for both the building life cycle and aspects of (de)construction show that these criteria are also esteemed relevant by all sub groups.

In addition, the final formulated question in the survey, i.e. "*Which qualitative aspects do you additionally assess when considering the renovation of residential buildings?*", aimed to reveal essential missing criteria for the qualitative assessment in the framework of this study. The outcome of this question did not lead to identification of unknown additional criteria; the added topics dealt with overall building design and performance of technical installations similar to the renovation topics discussed from literature in Chapter 2, which confirms the reliability of the literature study.

Social housing societies discern an overall picture of pragmatic issues at different levels, e.g. management, building, environmental, social and financial level. Most topics are closely related with comfort of future inhabitants, including user-friendly technical installations, energy-efficient installations (to reduce costs for the user) and qualitative organisation of the living units.
The architect group formulates relevant additional topics for renovation in terms of 'design quality' of buildings and their environment. Topics relate to the urban, building, system and material level. The topics fit in an overall framework of renovation of buildings, since most questioned architects were not exclusively active in the specific case of renovation of social housing.

Table 4.3: Additional renovation criteria quoted by the participant sub groups in survey

Level of intervention		Topics
architects	urban level	Quality of public space.
		Mobility at urban level.
	building level	Conservation of architectural and historical value of the residential building.
		Natural daylight in spaces.
		Quality of living spaces and optimal functional organisation at building level.
		Accessibility of the building.
		Flexible and versatile organisation of the building.
	system level	Quality labels of building systems.
	material level	Use of sustainable materials with low environmental footprint.
		Life expectancy of building components.
VMSW	management	Inconvenience for inhabitants during renovation works.
		Control over state/performance of building elements.
	building level	Aesthetic aspect of the building.
		Architectural value of the renovation.
	system level	Simplicity of technical systems.
local social housing societies	management	Inconvenience for inhabitants during renovation works.
	building level	Building regulation (EPB, fire safety, etc.)
		Optimisation of the plan organisation to improvement of the internal living quality for inhabitants.
		Enlargement of the surface of living units.
		Addition of qualitative spaces in buildings (balconies, terrace, communal space.
		Rate of interventions to reduce the inconvenience for inhabitants.
	system level	Central heating system with individual counters.
		User-friendly technical installations (heating systems, ventilation)
		Energy efficient electrical appliances.
	material level	Use of materials with easy maintenance.
		Use of sustainable materials with low environmental footprint and health risks.
	social level	Use the renovation as opportunity to improve living environment for inhabitants and eliminate the stigma of social housing.
	financial level	Reduce the financial renovation costs.

RESULTS FOR RELEVANCE OF SUB CRITERIA

The overview of the medians of values attributed by each sub criterion for each group (and for each building layer) is represented in Appendix I. These tables show that although in some cases one group estimates a criterion as non relevant, this is not confirmed by the other two groups. Therefore, all sub criteria were supposed relevant (or undecided) and were subsequently kept for comparison of the building layers.

For the *initial comfort* criterion the thermal comfort was valued most important for the facade and the roof whilst for the space partitioning (walls and floors) the acoustic comfort is esteemed most crucial. This is confirmed by literature and current building regulation. For the *building life cycle* criterion it was expected that maintenance would be valued as the most relevant sub criterion for most building layers, since the social housing companies indicate that this is a crucial concern for them. This assumption was validated by the outcome of the survey, especially for the group of the social housing societies which valued this sub criterion more relevant than the architect group. Also in the line of expectations was the lower importance that society currently gives to the end-of-life phase of buildings and selected materials. This criterion was valued as irrelevant or undecided for most building layers, though, not by all sub groups. The architects clearly gave more attention to the aspects of the after-life of buildings and materials, influenced under the current trends of sustainable construction.

4.1.3.5 NEED FOR DYNAMIC RE-DESIGN

An additional question narrowing down on adaptability concerns calls for a more nuanced valorisation of the *adaptability sub criterion*. The questions at sub criterion level dealing with adaptation scenarios show the great interest for change-related design issues - higher than would be expected from the survey results at criterion level. The medians of the values attributed to questions relating to future adaptation issues, such as future thermal upgrade and future flexibility of technical systems, are shown in Table 4.4. This table shows that 95% of these adaptation-related aspects are valued with a median of m ≥ 7, which implies that these aspects are valued of strong relevance. Future alterations and adaptability requirements are more requested at roof, facade and wall partitioning level.

Table 4.4: Medians of adaptability sub criterions per building layer per participant sub group

Building layer	Criterion	Median group 1 (arch)	Median group 2 (VMSW)	Median group 3 (SHC)
Facades	*future thermal upgrade*	7	9	9
	future aesthetic upgrade	7	7	4
Partitioning walls	*adapted typologies*	8	7	7
	future functional upgrade	7	7	7
Internal walls	*internal flexibility*	9	7	7
	future technical upgrade	9	9	9
Floors	*future technical upgrade*	7	7	9
Roof	*future upgrade insulation*	9	9	9

This gives an important sign that future measures in terms of change and adaptation are perceived important, but still, this does not imply that initial (re)design of buildings is taken into account. Integrated Re-Design for Change may therefore prevent that these issues - which are valued important but which are little taken in consideration in the initial phase of renovation - lead to major problems when changes actually need to occur in the future.

4.1.3.6 INCONSISTENCY CHECK

Additional measures in the composition of the survey enabled to check on inconsistencies in responses of the participants data to a certain extent. For instance, the first question was repeated along the survey in an adapted formulation. No major inconsistencies were found. Furthermore, in questions that narrowed down on sub criteria, the scale of value attributed at sub criteria level was checked with the scale of values initially attributed at upper criterion level. For both verifications, the outcome of the survey showed to give consistent results.

An additional remark relates to the scale of values attributed by each sub group: although local social housing societies (SHC) and architects in general give higher values to all questions than the VMSW sub group, the *relative importance* attributed to the topics was of the same order of magnitude. This can be perceived in the analogous weighting set that was derived from the responses of each sub group, represented in Appendix I.

4.2.1 HIERARCHICAL STRUCTURE

The final hierarchical structure of the (sub) criteria for the qualitative assessment of building layers applied for renovation is shown in Figure 4.6.

Figure 4.6: Hierarchical structure for criteria and sub criteria of qualitative assessment

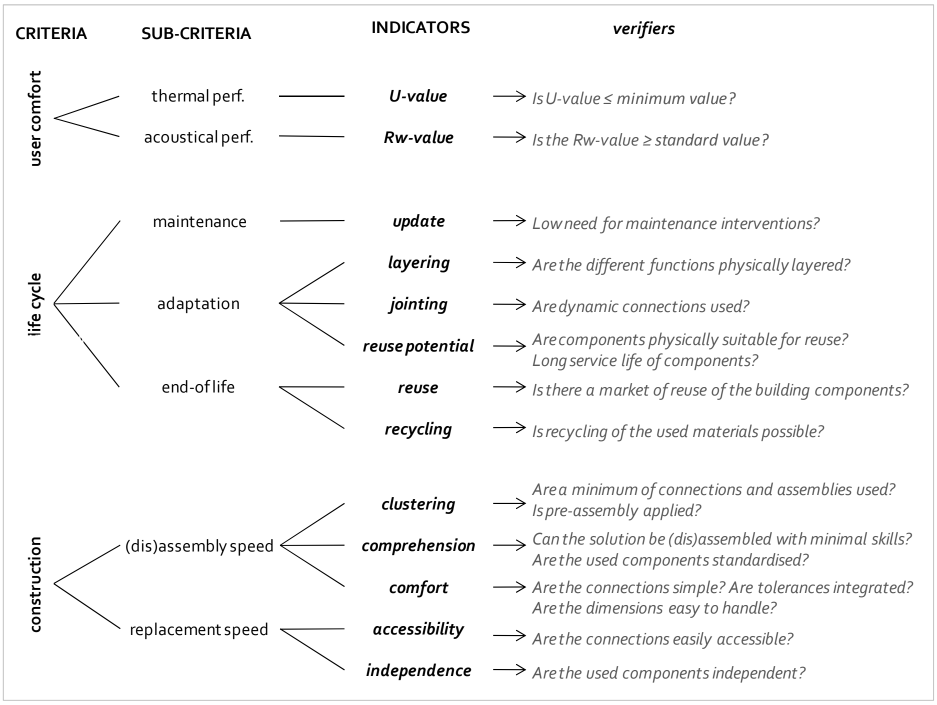


Table 4.5 shows the indicators and verifiers set up to score these (sub) criteria. The indicators and verifiers were based on literature study during the determination of preliminary criteria.

Table 4.5: (Sub) Criteria, indicators and verifiers for qualitative assessment of renovation solutions

(Sub)-criteria	Indicators	Verifiers
A user comfort		
thermal perform.	1.1 U-value	*Can U-value be reached ≤ minimum value for concerning building layer?*
acoustic perform.	2.1 R_w-value	*Can R_w-value be reached ≥ minimum value for concerning building layer?*
B *life cycle design*		
maintenance	1.1 finishing	*Low need for maintenance interventions (i.e. replacements)?*
adaptation	2.1 layering 2.2 jointing 2.3 reuse potential	*Are the different functions physically layered?* *Are reversible connections used?* *a. Are components durable (resistant against damage and wear-and-tear)?* *b. Long estimated service life of components?*
end-of-life	3.1 reuse 3.2 recycling 3.3 down-cycling	*Is there a market for reuse of the building components?* *Is recycling or composting of the materials possible?* *Is down-cycling possible?*
C *(de)construction*		
(dis)assembly	1.1 clustering 1.2 comprehension 1.3 comfort	*a. Are a minimum of connections and assemblies applied?* *b. Is preassembly applied?* *a. Can the solution be (dis)assembled with low skills?* *b. Are the sub components standardised and dimensionally coordinated?* *a. Are complex connection techniques avoided?* *b. Are tolerances integrated?* *c. Are the dimensions ergonomically easy to handle?*
replacement	2.1 accessibility 2.2 independence	*Are the connections easily accessible?* *Are subcomponents independent of each other?*

4.2.2 WEIGHTING SETS

Three main weighting sets were derived from the survey results for each participation group. As an example Table 4.6, gives the three weighting sets for the facade layer. The highest importance is given to upgrade of initial user comfort (36% to 37%). Nevertheless life cycle design (32% to 34%) and (de)construction aspects (30% to 32%) are valued almost equally relevant for all evaluated building layers. In addition, the different weighting sets resulting from the survey did not show inconsistencies between the sub groups. All weighting sets are closely related, and therefore, only one weighting set – *weighting set 1* - is represented for the next evaluated solutions.

The difference between overall aggregated results using different weighting sets only mount up to 2% of difference. This means that the consensus over the qualitative results of the facade alternatives is relatively high.

Table 4.6: Weighting sets for (sub-) criteria and indicators for assessment of *facades*

(Sub) criteria & Indicators		Weighting set set 1 arch.	 set 2 SHC	 set 3 VMSW
A user comfort		36%	37 %	36 %
1.thermal comfort		54%	53%	55%
1.1 U-value		*19 %*	*20 %*	*20 %*
2.acoustic comfort		46%	47%	45%
2.1 R_w-value		*17 %*	*17 %*	*16 %*
B life cycle design		32%	33%	34%
1.maintenance		37 %	48 %	45 %
1.1 finishing		*12%*	*16%*	*15%*
2.adaptation		30 %	29 %	29 %
2.1 layering		*2%*	*2%*	*2%*
2.2 jointing		*2%*	*2%*	*2%*
2.3 reuse potential	a. material resistance	*2%*	*2%*	*2%*
	b. ESLC	*2%*	*2%*	*2%*
3.end-of-life		33 %	23 %	26 %
3.1 reuse		*4 %*	*3 %*	*3 %*
3.2 recycling		*4 %*	*3 %*	*3 %*
3.3 down-cycling		*4 %*	*3 %*	*3 %*
C (de)construction		32%	30%	30%
1.(dis)assembly speed		49 %	50 %	49 %
1.1 clustering	a. # connections	*2%*	*2%*	*2%*
	b. preassembly	*2%*	*2%*	*2%*
1.2 comprehension	a. min. assembly skills	*2%*	*2%*	*2%*
	b. standardisation	*2%*	*2%*	*2%*
1.3 comfort	a. connection simplicity	*2%*	*2%*	*2%*
	b. tolerance	*2%*	*2%*	*2%*
	c. manageable dimensions	*2%*	*2%*	*2%*
2.replacement speed		51 %	50 %	51 %
2.1 accessibility		*8 %*	*8 %*	*8 %*
2.2 independence		*8 %*	*8 %*	*8 %*

4.3.1 FACADES

Once weighting sets have been established the following step is to include scoring of building solutions on the market today applied for upgrade of post-war multi-storey buildings. An overview of the most applied current renovation solutions is given in the next paragraphs for each evaluated building layer, together with scoring attributed to all verifiers. To score the verifiers, three possible values were retained: 'yes' = 1 (+); 'no' = 0 (-); and 'to some extent'= 0,5 (+/-). As an example, the evaluation of the criteria is discussed and clarified for the existing building facade solutions, by means of scoring of a selected number of indicators.

4.3.1.1 POST-WAR BUILDING FACADES

The post-war architecture of social housing has delivered a wide variety of facade compositions present today. In order to get insights into their composition, the main facade compositions of existing facades are systemised in Table 4.7. The external walls are subdivided according to their load-carrying capacity. The second level of determination is defined by the relation between the load-bearing structure and the 'thermal barrier' positioning. The thermal barrier does not necessarily imply the presence of thermal insulation, since it is defined by the enclosing layer of the facade. This subdivision determines the dominance of the structure as a design element and the thermal properties of a facade [Herzog 2004; Ebbert 2010].

Table 4.7: Categories of facade compositions in multi-storey housing

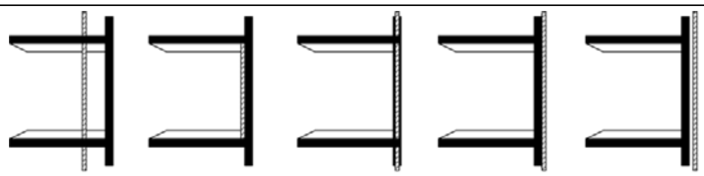
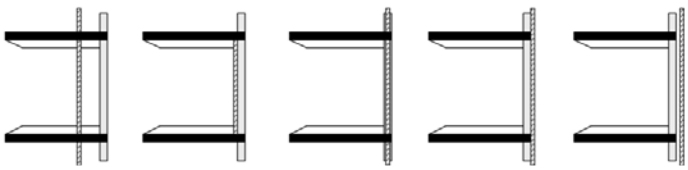
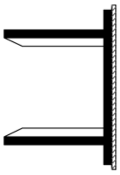
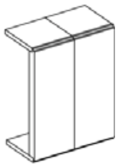
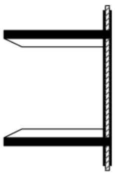
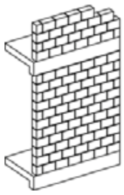
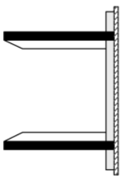
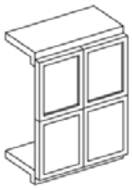
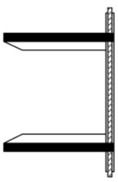
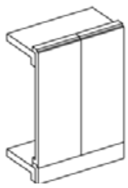
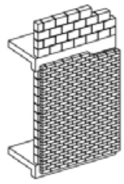
Type	Position of the thermal barrier in relation to the load-bearing structure				
load-bearing external wall					
	corridor	*internal*	*intermediary*	*external*	*extern. + cavity*
non-load beating external wall					
	corridor	*internal*	*intermediary*	*external*	*extern.+cavity*

Table 4.8: Examples of existing multi-storey facades of post-war residential buildings

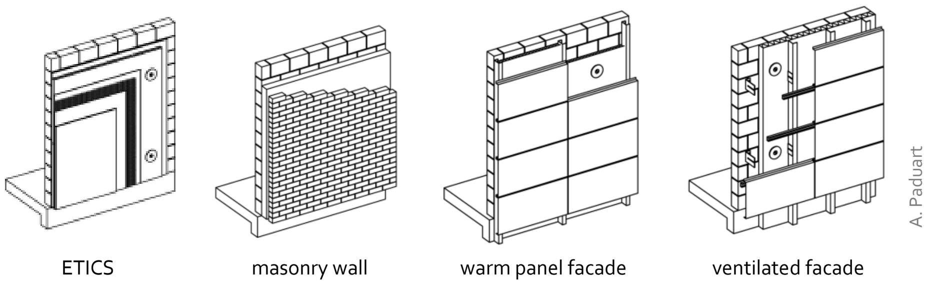
	Facade type	Representation	Examples	Description
load-bearing external wall		**prefabricated** 	**Cité Modèle**  Source: [Simon 1962]	*System of load-bearing prefabricated concrete panels for the external walls.*
		**in situ** 	**Cité Galaxie**  Source : A. Paduart	*External walls built up with load-bearing brickwork, for buildings with a limited number of floors.*
non-load-bearing external wall		**prefabricated**  *light-weight*	**Cité Modèle, Building IX**  Source: A. Paduart	*Prefabricated light -weight unitised curtain wall elements, incorporating windows and sandwich panel fillings.*
		 *heavy*	 Source: A. Paduart	*Prefabricated concrete-based panels, suspended on the load-bearing structure (floor or columns).*
		in situ  A. Paduart	**Het Kiel**  Source: Archive R. Braem	*In-situ 'prefabricated' unitised brick facade panels using thin layer of sliced facing bricks preassembled on site.*

4.3.1.2 OVERVIEW FACADE CATEGORIES IN CURRENT RENOVATION

Facades of post-war multi-storey housing typically mount up prefabricated non load-bearing light-weight or concrete-based modular panels against a skeleton or cross wall structures. Table 4.8 shows some typical examples of facades of post-war multi-storey residential buildings. The retained facade categories for the MCA evaluation of upgrading solutions applied on the external side, frequently applied in renovation practice today are shown in Figure 4.7. The four defined categories are described as following:

- *Category 1* consists of a layer of externally attached insulation covered with rendering - so-called External Thermal Insulation Composite Systems (ETICS). These wall compositions form barrier-wall systems[2].
- *Category 2* is defined as traditional double-leaved walls made from brickwork including cavity insulation.
- *Category 3* consists of (warm) prefabricated facades (non-ventilated) composed by front sealed modular panels which incorporate mineral wool insulation (sandwich panels). These panels are attached to a carrier framework which is fixed to the building structure.
- *Category 4* consists of rain screen (ventilated) facades which mount an outer weather-resistant skin against an underlying structure by means of a supporting grid. This maintains a ventilated and drained cavity between the external facade leaf and the interior leaf (brickwork structure). These facade types mount modular elements (rebating, sheets, tiles, boards or cassettes) in front of a layer of mineral wool insulation, attached to a carrier wooden or aluminium framework. Two types are subdivided; wooden rebating on a wooden framework (category 4a), and sheets/ tiles /board covering on an aluminium framework (category 4b).

Figure 4.7: Overview of four defined facade systemsapplied in renovation practice



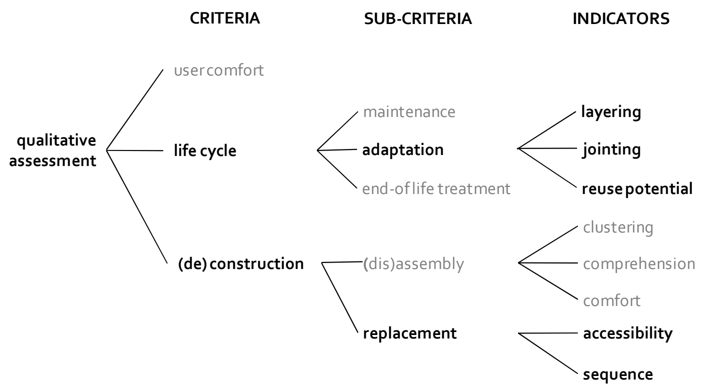
[2] In a barrier wall system, the exterior cladding serves both for the principal drainage as for the primary line of defence against bulk rainwater penetration.

For the MCA of the defined facade categories it is assumed that the four categories can be dimensioned to reach the same level of thermal insulation, according to normative standards [EPB 2010][3]. While providing the same thermal performance, these defined facade alternatives may still incorporate varying performance in terms of sound insulation, thermal heat storage capacity and fire safety, but also differ in terms of composing (reusable) materials, assembly techniques and thus also capacity for change.

4.3.1.3 INDICATORS & VERIFIERS

Figure 4.8 shows a hierarchical overview of the (sub) criteria discussed for the scoring of facade systems in the next paragraphs; the sub criteria '*adaptability'* and '*replacement'* are selected since their scoring needs more illustration then indicators with more straight-forward questions.

Figure 4.8: Overview of discussed facade indicators



4.3.1.4 ADAPTABILITY

Adaptability of building systems is a crucial sub criterion in order to establish an efficient use of resources in a life cycle perspective on buildings. A reversible way of jointing, a careful choice of well-suited resistant materials together with multi-layered compositions of building systems are just small interventions which enable a wide range of adaptations in the future with reuse of sub component, without the need for destructive methods. Therefore, the scoring in the assessment of the three indicators of adaptability - i.e.

[3] The detailed composition of each facade category with a same U-value of 0,3 W/m²K can be found in Chapter 8.

layering, jointing and reuse potential- are illustrated to give a practical understanding of rules necessary to make adaptation possible in the case of the facade layer.

LAYERING

Sub-layering of building products in individually separated functions is a crucial approach for effectiveness of adaptation interventions (replacements, upgrade, or transformation). In the case of facades, it allows the performance profile to be matched with changing requirements during the course of its life as individual layers can be added or replaced by others in the future [Herzog 2004], without having to intervene in each sub layer.

Table 4.9 shows scenarios for sub-layering of the facade, illustrated by representative facade renovation solutions. The figures in the table represent the degree of physical separation of main functional layers present in external walls such as: *external weatherproofing (e), air tightness (a), insulation (i), vapour barrier (v), load-bearing function (l)* and *internal finishing (f).* The compositions are categorised from permanently "fixed" constructions to "dynamic" layered assemblies:

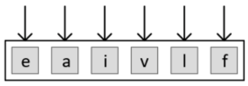
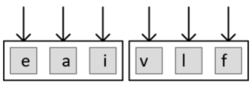
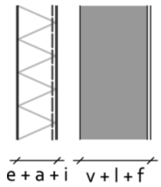
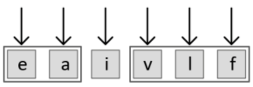
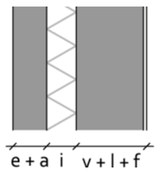
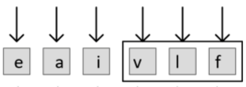
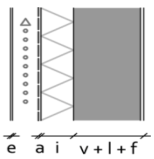
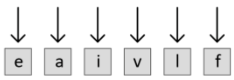
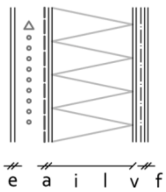
- *The lowest degree of sub-layering (**category 1**) consists of facade systems using adhesive connection techniques, such as glues, plasters and mortars, grouping all functions in one - fixed - assembly with a masonry wall as a base, such as ETICS.*
- ***Category 2** consists of prefabricated panel systems, clustering external functions, e.g. (e), (a) and (i), in one subassembly separated from the building structure.*
- *Cavity walls (**category 3**) subdivide the external wall in two massive leaves[4], clustering the main functions with an insulation layer filling up the cavity.*
- *The most dynamic sub-layering for double-leaved external walls is characterised by physical disconnection of each of the exterior functions, i.e. (e), (a) and (i), namely the rain screen facades (**category 4**).*
- *In the most extreme scenario, the interior leaf is layered in functional subassemblies as well (**category 5**). Examples of the latter are rain screen facades that are assembled on a wooden or steel load-bearing structure, instead of a solid masonry wall. These solutions however or only found back in new construction.*

Subsequently, scoring of the *layering* sub criterion with the verifier '*Are the different functions physically layered*?' results in a *score = 0 (-)* for the first category; and 0,5 (+/-) for categories 2 to 4. Only the 5^{th} category would receive a score equal to 1 (+).

---

[4] Leaves are usually assemblies with load-carrying capacity, partly or completely three-dimensional and/or structurally autonomous. A leaf can comprise several layers [Herzog 2004].

Table 4.9: Sub-layering scenarios of facade systems

Layering	Composition	
fixed 		***one leaf - no ventilation cavity*** Improved thermal performance with rendered layer of insulation; interior benefits from heat storage capacity. **Example**: ETICS
		***two leaves - no ventilation cavity*** Outer leaf provides physical protection to insulation and also protection against driving rain. Outer leaf forms unit clustering the exterior functions. **Examples**: warm panel systems
		***two leaves - no ventilation cavity*** Outer leaf provides physical protection to insulation and against driving rain. **Example:** cavity walls
		***two leaves - ventilation cavity*** Replaceable facing leaf; condensation water and infiltration moisture are reliably removed behind rain screen. **Example**: rain screen facade systems
 dynamic		***two leaves - ventilation cavity*** Ventilated protective and wearing leaf on the outside, diffusion resistance decreases towards outside; separate layer for air tightness; interior lining as separate layer. **Example:** rain screen systems combined with wooden/ steel load-bearing structure

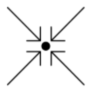
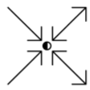
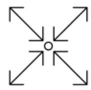
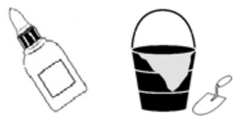
	solid structure		rendering		airtight barrier
	insulation		ventilation cavity		vapour barrier

e = enclosure; a = airtight barrier; i = insulation; v = vapour barrier; l = load bearing; f = finishing

JOINTING

The applied jointing technique is essential to maximise the opportunities of adaptation or reuse of sub components in facades: use of reversible dry connections was revealed as the key to enable reuse strategies [Durmisevic 2006, Nordby 2006, Debacker 2009].Table 4.10 gives an overview of typical connections applied in construction and the associated degree of flexibility, to enable to answer the verifier '*Are there reversible connections applied?*' in this qualitative assessment.

Table 4.10: Typical connections in the built environment

	Connection type	
fixed		***flexible***
irreversible		reversible
		
		
adhesives, cement mortar, welding, resins	*nails, staples, rivets*	*bolts, dowels, screws, pressed metal plates*

The facade categories 1 and 2, the so-called "wet" facade systems typically use irreversible connection techniques reducing the opportunities for reuse. Fixed connections such as adhesives and cement mortars are applied between all layers making non-destructive deconstruction of layers extremely difficult.
On the contrary, facade c*ategories 3 and 4*, the so-called dry facade systems, make use of both fixed connections, and flexible connections such as brackets, linear rail systems and clips depending on the cladding and its assembly technique (for details, see Chapter 6). The connection between the substructure and the cladding is crucial for capacity for change during the life cycle.

REUSE POTENTIAL

The reuse potential of (facade) solutions deals with the materialisation of sub components, relating to its material resistance and useful service life. For this sub criterion two verifiers were set up, i.e. '*Are the sub components suitable for reuse?*', and, '*Do the sub components have long estimated service life*?' to indicate if materials are suitable to be reused.

Reversible connections may enable to dismantle materials, but if these materials are too brittle, reuse is in most cases not feasible. Multiple reuse of building sub components is therefore also based on the durability - the resistance against wear-and-tear of the

materials, in order to resist multiple transport, assembly and handling - based on guidance from literature.
A second important parameter is the service life span of buildings. As discussed in Chapter 3, reuse of elements with a limited service life does not necessarily compensate the environmental benefits that may be related to reuse. Therefore, building materials/components are preferred with a long estimated service life and low environmental and financial impacts. The latter will be discussed in the Chapter 8. The suitability for reuse and the estimated lifetime of the sub component of selected facade categories are given in Table 4.11.

Table 4.11: Aspects influencing the reuse potential of defined facade categories

Facade category	Type	Durability of sub components[5]	Estimated service life[6]
category 1	ETICS	-	+/-
category 2	facing brick wall	+	+
category 3	sandwich panel	+	+/-
category 4	wooden rebating	+	+/-
	metal sheets	+	+/-
	ceramic tiles	+	+/-
	fibre cement	+/-	+/-
	synthetic boards	+/-	-
	glass tiles	+/-	+/-
	wood-based boards	+	-

(-) limited; (+/-) average; (+) substantial.

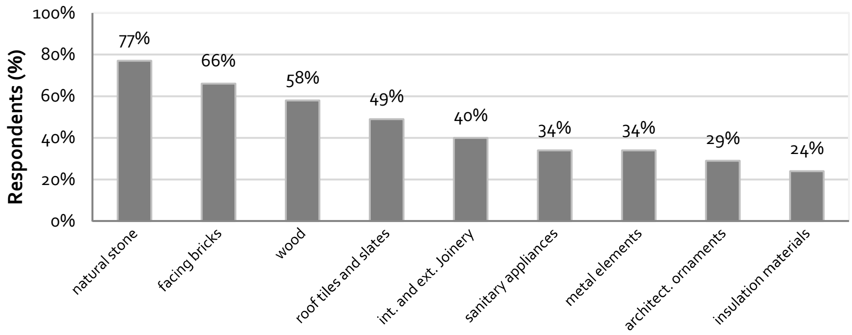
This table shows that the first category of facades - ETICS facade systems - has a low potential for reuse, due to the use of plastering. For dry facade systems, the reuse potential of the components depends on the selection of the covering material and sub frame. Synthetic boards and wood-based boards have a low service life, which limits their chances for reuse. Next, we see that ductile and surface resistant materials such as metal sheets have a higher suitability for reuse than fibre cement boards, synthetic boards or glass tiles.

Market research indicates a second type of suitability for reuse, i.e. the actual demand on the market for second-hand building materials. An overall market study for building materials executed in 2009 in Wallonia and Brussels (Figure 4.9) indicated the high interest from a large audience for reuse of natural stones (77% of respondents) and bricks (66%) [RESsources 2009]. Other second-hand building components in with a high demand are wooden components (58%) and roof tiles and slates (49%). Joinery (40%), sanitary

[5] Based on [Addis 2004] based on material ductility and surface resistance.
[6] Based on technical service life [BCIS 2006].

appliances (34%), metal elements (34%) and insulation materials (24%) were also indicated to be potentially interesting for the reuse market. Together with Table 4.11, Figure 4.9 shows an interesting result. Facing brick walls have high technical reuse suitability together with a high reuse demand on the market. However, the jointing, discussed in the previous paragraph, makes it time-consuming and labour-intensive for traditional brick walls to be easily deconstructed, adapted, and/or reused.

Figure 4.9: Market research on demand for second-hand materials [RESsources 2009]

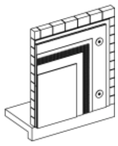
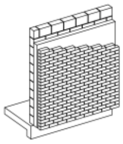
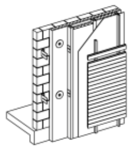
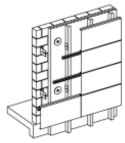


In Chapter 8 it will be shown that a low reuse potential can lead to high environmental and financial life cycle impacts of buildings. As a suitable alternative, brickwork panels consisting of bricks dry assembled in a supporting framework are designed to extend the life span of bricks and their potential for reuse, while they enable adaptations during the building life cycle by using dry reversible connection methods. This means that when adaptation, transformation or removal of the building envelope is needed, the valuable materials can be more easily disassembled and reused.

OVERALL SCORING OF ADAPTABILITY

An overview of the scoring of the sub criterion 'adaptability' of facade solutions is shown in Table 4.12 based on the discussed scoring of indicators.

Table 4.12: Scoring of facade categories for sub criterion 'adaptability'

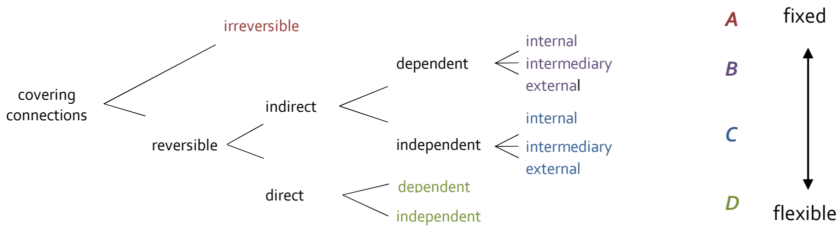
	Facade category				
	cat. 1	cat. 2	cat. 3	cat. 4a	cat. 4b
Indicator & verifiers					
layering Are the different functions physically layered?	-	+/-	+/-	+/-	+/-
jointing Reversible connections?	-	-	+/-	+	+
reuse potential Are components technically suitable for reuse?	-	+	+/-	+	+
Long estimated service life?	+/-	+	+/-	+	+

(-) limited; (+/-) average; (+) substantial

4.3.1.5 REPLACEMENT

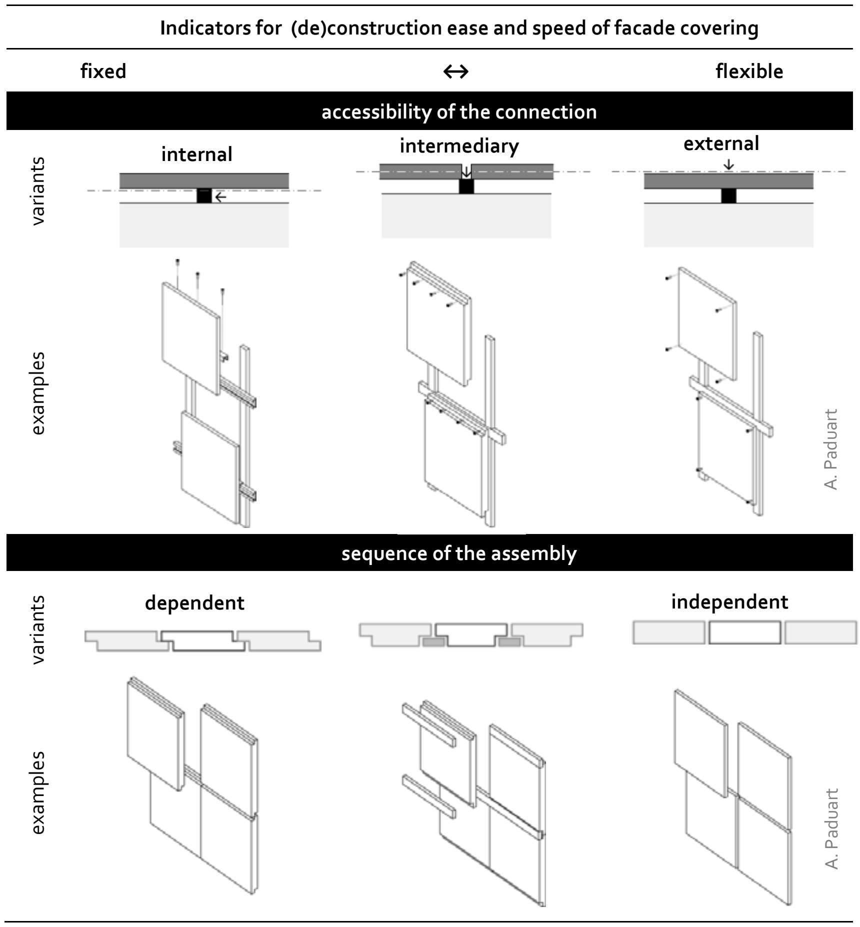
The main indicators, which influence the ease of replacement, are represented in Table 4.14 for the example of dry covering: the *accessibility* and *sequence* (dependence). Together with the type of connections, these define the ease of sub components to be replaced. The type of connection - discussed in the previous paragraph – first determines if adaptation in the facade composition requires destructive techniques or not. This is applied as a first subdivision of the classification of the main connection types for dry covering of facades (irreversible/reversible), represented in Figure 4.10.

Figure 4.10: Connection types of facades of facade systems according to accessibility and sequence of composing sub components and connection types applied



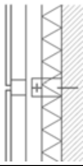
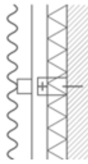
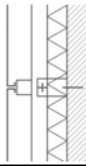
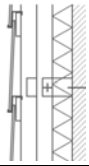
A further subdivision was made according to *additional connection elements* (direct/indirect) with e.g. linear fixing elements, brackets or clips, the *(in) dependency* and the *positioning* of the connection. The following subdivisions are made, based on the accessibility of the connections, and the sequence of assembly, represented in Table 4.13.

Table 4.13: Accessibility and sequence indicators for dry facade covering



Covering solutions that are most easy to replace, are identified as the direct (external) connections (type D) with independent covering (if executed with dry screws or rivets), and independent cladding systems using linear rail systems, brackets or clips (type C) executed from outside. These groups use non-destructive assembly methods which enable easy and fast replacement, while assembly using adhesives makes replacement of components extremely difficult without destructive techniques (type A). Examples of covering systems applying these different covering connection types are represented in Table 4.14.

Table 4.14: Covering types for dry facade systems (adapted from [Rentier 2001])

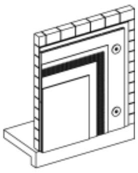
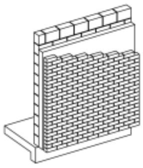
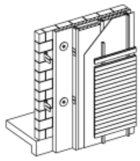
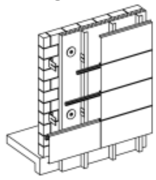
Material type		**Covering type**			
		panel	**sheet**	**cassette**	**rebate**
					
metal	*aluminium*	x	x	x	x
	steel	x	x	x	x
glass		x			
stone-based	*ceramic*	x			
	fibre cement	x	x		x
wood-based	*multiplex*	x			
	wood composite	x			
	wooden element				x
synthetic	*melamine*	x			x
Connection type (Figure 4.10 Error! Reference source not found.**)**					
	fixed	*type A*			
		type B	*type B*	*type B*	
		type C	*type C*	*type C*	
	flexible	*type D*	*type D*	*type D*	*type D*

This means that the score of dry facade systems (category 3 and 4) depends on the selected cladding and connection type applied. It can vary between a positive scoring of the replacement indicator of 'score = 1 (+)', to a negative evaluation due to the use of a covering difficult to disconnect, i.e. score = 0 (-). Wooden rebating of the facade has a relatively high score, since the connections used are directly made at the outside of the facade and thus easily accessible.

Facade categories 1 and 2 (ETICS and brick walls) make use of components of which the connections are not accessible, neither are components applied independent of each other. Therefore, these categories score low according to the replacement criterion.

Table 4.15 shows the overall scoring of the selected facade categories for renovation.

Table 4.15: Scoring of verifiers for each defined facade category

verifiers	facade categories				
	category 1	**category 2**	**category 3**	**category 4a**	**category4b**
					
A	user comfort				
1.1	+	+	+	+	+
2.1	+/-	+	+/-	+/-	+/-
B	life cycle				
1.1	-	+/-	+/-	-	+
2.1	-	+/-	+/-	+/-	+/-
2.2	-	-	+/-	+/-	+/-
2.3.a	-	+	+/-	+	+
2.3.b	+/-	+	+/-	+	+
3.1	-	+	+	+	+
3.2	-	-	-	-	+/-
3.3	-	+	-	+	+
C	(de)construction				
1.1.a	+/-	-	+/-	-	-
1.1.b.	-	-	-	-	-
1.2.a	-	+/-	+/-	+	+
1.2.b	-	+/-	+/-	+/-	+/-
1.3.a	-	+/-	+/-	+/-	+/-
1.3.b	+	+	+	+	+
1.3.c	+	+	+/-	+	+
2.1	-	-	+/-	+	+/-
2.2	-	+/-	+/-	+	+

(-) limited; (+/-) average; (+) substantial.

(see Table 4.5)

A. user comfort: A.1.1. thermal performance; A.1.2. acoustic performance;

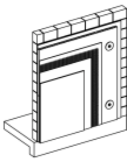
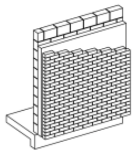
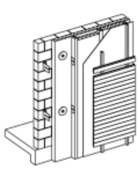
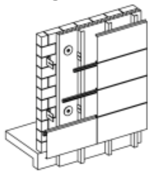
B. building life cycle: B.1.1 maintenance; B.2.1 layering; B.2.2 jointing; B.2.3 reuse potential (a. material resistance; b. Long ESLC (estimated service life of components)); B.3.1. reuse market; B.3.2. recycling; B.3.3.down-cycling;

C. (de)construction: C.1.1. clustering (a. # connections; b. preassembly); C.1.2.comprehension (a. minimum assembly skills; b. standardisation); C.1.3.comfort (a. connection simplicity; b. tolerances; c. easy to handle connections); C.2.1. accessibility; C.2.2.independence).

4.3.1.7 AGGREGATED RESULTS OF FACADE ALTERNATIVES

Table 4.16 shows the aggregated results of the selected facade categories for renovation.

Table 4.16: Aggregated results of weighting and scoring of facade category (weighting set 1)

verifiers	**facade categories**				
	category 1	**category 2**	**category 3**	**category 4a**	**category4b**
					
A	user comfort				
1.1.	19%	19%	19%	19%	19%
2.1.	8%	17%	8%	8%	8%
B	life cycle design				
1.1.	0%	6%	6%	0%	6%
2.1.	0%	1%	1%	1%	1%
2.2.	0%	0%	1%	1%	1%
2.3.a	0%	2%	1%	2%	2%
2.3.b	1%	2%	1%	2%	2%
3.1.	0%	4%	4%	4%	4%
3.2.	0%	0%	0%	0%	2%
3.3.	0%	4%	0%	4%	4%
C	(de)construction				
1.1. a	1%	0%	1%	0%	0%
1.1.b	0%	0%	0%	0%	0%
1.2.a	0%	1%	1%	2%	2%
1.2.b	0%	1%	1%	1%	1%
1.3.a	0%	1%	1%	1%	1%
1.3.b	2%	2%	2%	2%	2%
1.3.c	2%	2%	1%	2%	2%
2.1.	0%	0%	4%	8%	4%
2.2.	0%	4%	4%	8%	8%
	35%	**63%**	**58%**	**67%**	**71%**

(see Table 4.5)

A. user comfort: A.1.1. thermal performance; A.1.2. acoustic performance;

B. building life cycle: B.1.1 maintenance; B.2.1 layering; B.2.2 jointing; B.2.3 reuse potential (a. material resistance; b. Long ESLC (estimated service life of components)); B.3.1. reuse market; B.3.2. recycling; B.3.3.down-cycling;

C. (de)construction: C.1.1. clustering (a. # connections; b. preassembly); C.1.2.comprehension (a. minimum assembly skills; b. standardisation); C.1.3.comfort (a. connection simplicity; b. tolerances; c. easy to handle connections); C.2.1. accessibility; C.2.2.independence).

4.3.1.8 DISCUSSION

In today's market, a wide range of dry facade solutions are available which have a similar exterior appearance, but a quite differentiated and wide-ranging impact on the life cycle design of buildings and (de) construction potential, making a careful selection essential.

ETICS facade walls score very poor (35%) when considering more qualitative aspects than merely improving the initial thermal performance of the building facade. The high maintenance of the plaster finishing together with rigid non-layered design are responsible for the low scores of this facade category. First, future thermal upgrade of the facade was indicated as an important aspect of the facade renovation of today with a median $m \geq 7$ for each sub group. ETICS walls are difficult to upgrade due to their compositions, and therefore low performing for this matter. Also, the end-of-life options of this facade type are very limited: neither can components be dismantled, nor reused. However, in case of restricted interventions, or a limited additional depth of the facade upgrade, ETICS systems might be the most appropriate solution.

The facing brick walls generally score well for the main assessed criteria (67%). The only weak spot is in the connection between bricks: due to the type of mortars applied today little degree of freedom is left for eventual upgrade of the facade.

The facade panel wall (using sandwich panels) scores inferior to other dry facade systems (58% compared to 67% and 71%). This 'warm' facade needs a better waterproofing for the external facade leaf, meaning that the externally executed connections are more rigid than is the case for rain screen facades - in which the external leaf is only a first (non-waterproof) protection layer of the facade composition. Moreover, different functions are clustered in the sandwich panels, making upgrade of the thermal insulation difficult, and reuse and recycling of materials complicated.

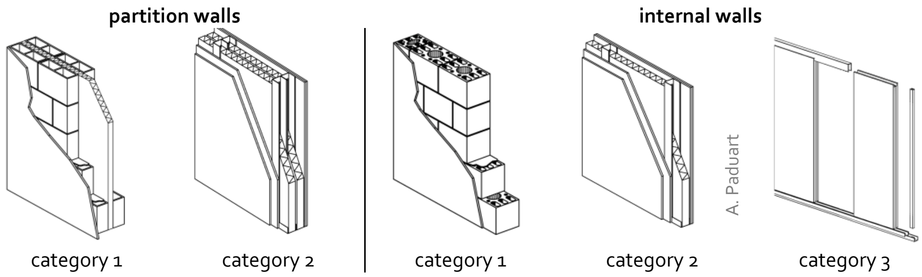
Dry facade systems that use loose panels, sheeting or rebating have a good global qualitative score. These systems are relatively fast to assemble and make a non-destructive dismantling of components possible in case reversible connections are being reused. The degree of maintenance, adaptability, the end-of-life treatment and the deconstruction strongly depend on the selected covering type (based on materialisation and dependency of the components) and their connection.
Additional measures to increase the global performance of dry facade systems would include a good execution level of the assembly works, improving the thermal and sound insulation of the facade. An important tool to enhance the execution level and increase the renovation speed - which is lacking in all existing solutions - is the incorporation of *preassembly of facade parts*. The benefits that can result from preassembly will extensively be discussed in Chapter 6.

4.3.2 PARTITION AND INTERNAL WALLS

4.3.2.1 OVERVIEW OF SPACE PARTITIONING CATEGORIES

For the repartitioning of renovated buildings two wall types are studied: partition and internal walls[7]. Two types of non load-bearing partitioning walls are analysed: *solid brickwork walls* (plastered) and *dry walls (*with gypsum boarding). For the internal partitioning a third category is added, namely *flexible* wall partitioning systems applied in offices. This last category is not applied in residential renovation, but is added to understand the differences between static en dynamic wall designs. Figure 4.11 shows an overview of the defined categories of party walls and internal partitioning for evaluation.

Figure 4.11: Representation of defined new partitioning wall categories



Category 1 consists of a single-layered or double-layered brickwork wall respectively for internal walls or partition walls[8]. The evaluated partition walls are composed by two wall leaves separated by a soft insulation layer to increase the acoustic performance. A single-layered wall composition without insulation is assumed for the internal walls, finished with gypsum plaster and paint. **Category 2** is defined as traditional dry walls – using mainly dry connection techniques – often used for new construction and renovation projects today. Partition walls are assumed to be executed using a double-layered metal stud composition (improving acoustic performance).For internal walls, the materialisation can be executed using metal studs or wooden battens.

[7] Partition walls are responsible for the separation between different living units while internal walls divide the internal space of dwellings into different rooms. The requirements for internal walls are therefore less stringent in terms of fire safety, acoustic and thermal performance.
[8] The selection of brickwork (clay bricks, sand-lime bricks or (cellular) concrete blocks) depends mostly on preferences of the designer, investment means, building standards. The materialisation of the solid wall has a great influence on physical characteristics of the walls. Cellular concrete for instance has good thermal characteristics due to its low density. The low cubic mass however has a contrary effect in acoustic terms since single-layered walls with a low mass result in poor sound insulation.

Category 3 – for internal partitioning – is defined by flexible system partitions frequently used in offices. Flexible wall systems are well-known for their capacity to repartition office space into new configurations. These wall systems however are characterised by poor acoustic, thermal and fire safety performance due to the dry detailing and materialisation, explaining their exclusion from residential projects. The evaluated wall system consists of a metal (steel) partition which is monolithic, movable and modular with mineral wool as internal filler. The junction fixing system is embedded into the panel making a vertical joint visible after installation.

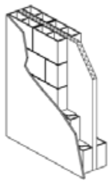
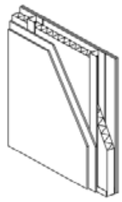
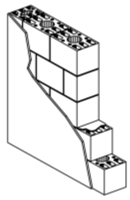
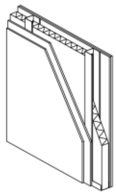
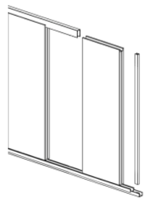
4.3.2.2 AGGREGATED RESULTS AND CONCLUSIONS

While the materialisation and assembly of current partitioning systems varies to a large extent, the ability to answer the current comfort standards is equal for al wall categories. Solid brick walls make use of the mass principle to provide sufficient acoustic insulation, whilst light-weight dry walls have been developed that provide the necessary sound performance making use of the mass-spring-mass principle. The main difference is the heat storage capacity of massive walls, which may have benefits in the context of overheating of apartment buildings. However, this aspect was not evaluated in this qualitative assessment, since it is dependent of the building design. Nevertheless, the results of the MCA analysis represented Table 4.17 in reveal fundamental differences between two wall types.

First, solid masonry walls typically cluster all functions in monolithic assemblies using wet connection methods, whilst dry walls are multi-layered and mainly apply dry connection techniques. These dry construction techniques speed up the assembly, compared to the labour and time intensive brick walls associated with small brick components and drying time of the adhesive mortar. Consequently, this results in the higher global score of dry walls (59%) compared to brick walls (49%). However, there is still room for improvement in dry walls: the reuse potential of sub components in use is small or non-existing. Indeed, gypsum plasterboards cannot be reused since any adaptation requires destructive methods. Moreover, the metal studs are not dimensioned to be reused; their assembly causes them to be damaged when walls are being demolished, making them inconvenient for further reuse. This means that both wall categories, depending on the changing sequence of the partitioning, score poorly. In case of a new required apartment layout in order to respond e.g. changing household types in social housing, walls must be completely demolished and rebuild from scratch.

In contrast, flexible office wall systems make optimal use of the opportunities of a fast (de)construction with a high capacity for change. The prefabrication and detailing of these office wall systems make this solution very fast to assemble and finish on site, and easy to remove and reuse in case of demolition.

Table 4.17: Aggregated results of the weighting and scoring for each defined internal wall category

Verifiers	Partitioning wall categories		Internal wall categories		
	category 1	***category 2***	***category 1***	***category 2***	***category 3***
					
A	user comfort				
1.1.	+	+	+	+	+
2.1.	+	+	+	+	-
B					
1.1.	-	-	-	-	+
2.1.	-	+	-	+	+/-
2.2.	-	+/-	-	+/-	+
2.3.a	-	-	-	-	+
2.3.b	+	+/-	+	+/-	+/-
3.1.	-	-	-	-	+
3.2.	-	-	-	-	-
3.3.	+	+	+	+	+/-
C					
1.1.a	-	+/-	-	+/-	+
1.1.b	-	-	-	-	+
1.2.a	-	+	-	+	+/-
1.2.b	+	+	+	+	+
1.3.a	+	+	+	+	+
1.3.b	+	+	+	+	+
1.3.c	-	+	-	-	+/-
2.1.	-	0	-	-	+
2.2.	-	0	-	+/-	+
total	**49%**	**59%**	**49%**	**59%**	**69%**

A. user comfort: A.1.1. thermal performance; A.1.2. acoustic performance;
B. building life cycle: B.1.1 maintenance; B.2.1 layering; B.2.2 jointing; B.2.3 reuse potential (a. material resistance; b. Long ESLC (estimated service life of components)); B.3.1. reuse market; B.3.2. recycling; B.3.3.down-cycling;
C. (de)construction: C.1.1. clustering (a. # connections; b. preassembly); C.1.2.comprehension (a. minimum assembly skills; b. standardisation); C.1.3.comfort (a. connection simplicity; b. tolerances; c. manageable connections); C.2.1. accessibility; C.2.2.independence).

This explains their high score compared to the other internal wall categories. However, these walls do not offer a high sound insulation neither fire safety, with harmful social effects on the living comfort of users.

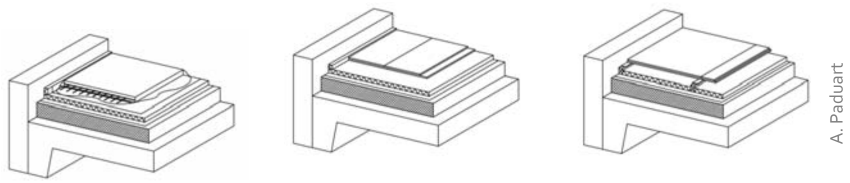
It can be concluded that to obtain wall systems with a high overall score, designers need to combine regulatory boundaries with a dynamic way of detailing. Consequently, this approach will be applied for the dynamic design of preassembled wall assemblies in Chapter 6.

4.3.3 SEPARATING FLOORS

4.3.3.1 OVERVIEW OF UPGRADE OF SEPARATING FLOORS

Construction techniques applied in post-war buildings are responsible for the poor sound characteristics in accordance with acoustic standards of today. The commonly applied light-weight reinforced concrete floor slabs (slab depth < 14 cm) combined with masonry or in-situ concrete walls typically create flanking sound transmission through the concrete skeleton - forming important acoustic leaks. One crucial aspect to improve the situation is to enhance the impact sound insulation of existing floor slabs[9]. Three floating-floor categories to upgrade the impact sound of the floor slabs are represented in Figure 4.12.

Figure 4.12: Representation of acoustic upgrade categories on top of floor slab



category 1 **category 2** **category 3**

The first category (**category 1**) consists of widely applied floating screed floor using wet in-situ construction techniques. Technical installations (electricity, heating, pipes) are typically integrated within the screed layer.

Category 2 and 3 are floor solutions which introduce *dry* floating floors. In **category 2** the decking of gypsum or wood-based panels is continuously supported by resilient materials, without fixing to the floor base[10]. **Category 3** is defined by self-supporting floating dry subfloors in which the wood-based panel overlay has support from beneath at regular intervals provided by timber battens or joists[11]. Technical services are incorporated in a flexible way under the tongue-and-groove floor panels, between the acoustic insulation.

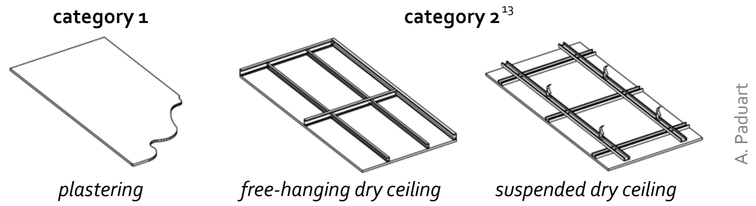
[9] One of the most effective ways to upgrade the sound insulation of these floors is by adding new dense floating-floor components. A floating floor consists of an upper floor slab separated from the structural floor slab by a resilient layer. This resilient layer usually consists of an insulation material with low dynamic stiffness – such as glass wool - resulting in a greater reduction in the impact sound level [Giebeler 2009].

[10] The insulation material used may not be highly compressible (density glass wool ≤ 150 kg/m³). Panels are usually executed in tongue-and-groove connections which are glued together on site.

[11] This system incorporates a resilient insulation material between the supports which may be more compressible (density glass wool ≤ 80 kg/m³) since the panels rest on the battens.

Floating-floor solutions may be combined with improvements on the underside of the floor slabs. Usually a compromise is sought between optimal acoustic solutions and space qualities (including the storey-height)[12]. A number of additional measures, which can be combined with the floor upgrade, are illustrated in Figure 4.13.

Figure 4.13: Representation of acoustic upgrade categories under the floor slab



4.3.3.2 AGGREGATED RESULTS AND CONCLUSIONS

The three floor upgrade categories enable a significant improvement of the impact sound possible increasing the initial user comfort. However, in terms of the overall qualitative assessment including life cycle design and (de)construction criteria, category 1 scores intermediary, i.e. 52%. This can be explained by the lack of sub layering of the floor, the selection of materials and their assembly methods. First, the time needed for screed floors (category 1) to dry is on average about one week per centimetre of screed. Since a screed floor above insulation easily mounts up to 5 cm (to reduce the risk of cracks) the total drying time of these floors can take about 5 weeks. In the context of social housing - in which dwellings need to be operational as soon as possible - this implies a significant delay of the works and thus a negative impact on renovation speed. In addition, the outcome of the survey pointed out that technical upgrade is an optional feature in floors (median for al sub groups $m \geq 7$). However, given that screed floors enclose all technical cables, wires and plumbing in poured concrete, any adaptation is difficult or even impossible without breaking up the entire screed deck. Another important observation relates to the sensitivity of screed floors for a bad execution of works; if necessary provisions are not made regarding the physical disconnection between the screed layer and adjacent walls, the sound performance may even be worse than in the initial situation. Since the acoustic performance can only be evaluated after execution of all renovation works, it is extremely difficult to make further improvements.

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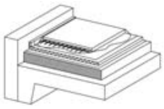
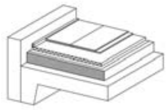
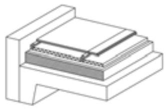
[12] Since heat loss through floors of a building is substantially lower than through the roof or the external walls, thermal upgrade of separating floors is often ignored in renovation today.

[13] Category 2 introduces dry ceilings which minimise the connection between the ceiling and the structural floor resulting in good sound insulation.

Table 4.18: Aggregated results of the weighting and scoring for the defined floor categories

Verifiers	Floor categories		
	category 1	category 2	category 3
			
A	user comfort		
1.1.	+	+	+
2.1.	+	+	+
B	life cycle design		
1.1	-	-	-
2.1.a	-	+/-	+
2.2.b	-	+/-	+
2.3.a	-	+/-	+
2.3.b	+	+/-	+/-
3.1.	-	-	+/-
3.2.	-	-	-
3.3.	+	+/-	+/-
C		(de)construction	
1.1.a	+	+/-	+/-
1.1.b	-	-	-
1.2.a	+/-	+/-	+/-
1.2.b	-	+/-	+/-
1.3.a	+	+/-	+/-
1.3.b	+	+/-	+/-
1.3.c	+	+	+
2.1.	-	+	+
2.2.	-	+/-	+
total	**52%**	**62%**	**71%**

(see Table 4.5)
A. user comfort: A.1.1. thermal performance; A.1.2. acoustic performance;
B. building life cycle: B.1.1 maintenance; B.2.1 layering; B.2.2 jointing; B.2.3 reuse potential (a. material resistance; b. Long ESLC (estimated service life of components)); B.3.1. reuse market; B.3.2. recycling; B.3.3.down-cycling;
C. (de)construction: C.1.1. clustering (a. # connections; b. preassembly); C.1.2.comprehension (a. minimum assembly skills; b. standardisation); C.1.3.comfort (a. connection simplicity; b. tolerances; c. manageable connections); C.2.1. accessibility; C.2.2.independence).

For the second category, the services incorporated in the insulation layer of continuously supported dry decks can only be adapted by breaking the upper deck floor (due to adhesives used). In addition, since new wiring requires new perforations, together with re-filling of the first perforations to ensure the support of the upper floor deck, reuse of components is limited to non-existent.

The good (de)construction properties and high reuse potential of the third category lead to a high global score (71%) compared to the two first categories. Although the removal of the upper floor deck may require destructive methods when adaptations are needed, the flexible cavity with loose-laid insulation makes technical upgrade and adjustments possible, whilst the supporting framework can be reused for new floor decking. This solution requires a higher floor depth than the continuously supported floors (category 2), but is comparable to screed floors though.

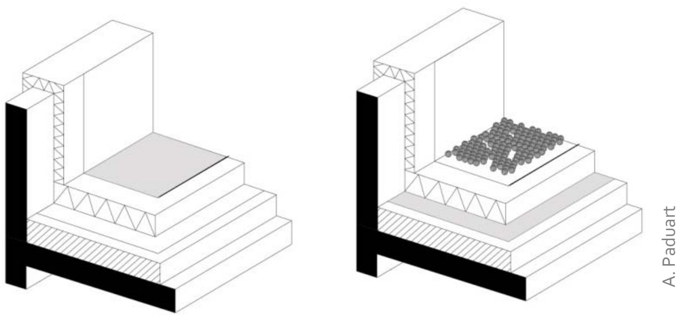
As an overall conclusion, acoustic upgrade of the separating floors through the use of dry subfloors can significantly speed up the renovation works. Additionally, dry subfloors add considerably less additional solicitation(s) to the existing load-bearing structure than screed floors, which is a considerable advantage in existing structures with a limited load-carrying capacity. However, there is still space for improvement: the current irreversible connection of the floor decks does not incorporate the possibility to reuse the subfloor component in case of required adjustments/changes.

4.3.4 ROOF SOLUTIONS

4.3.4.1 OVERVIEW OF ROOF CATEGORIES

Loss of heat through the roof of old buildings can represent up to a quarter of a building’s total heat loss [Highfield 2000]. Therefore thermal upgrade of the roof plays a key role if future heating costs are to be minimised. Concrete flat roofs can be upgraded by adding the new insulation either beneath the slab (at ceiling level) or on top of the slab. To avoid cold bridges and to minimise internal space loss preference should be given to external upgrade of the roof insulation together with external insulation of the facade [Highfield 2000, Trachte 2010]. Two types of thermal upgrade on top of the existing roof are retained - in the supposition that additional loads can be supported safely- defined by the position of the waterproofing layer.

Figure 4.14: Representation of thermal upgrade roof categories



category 1 category 2

Category 1 upgrades a roof to a warm deck roof, in which new thermal insulation is laid over the existing roof membrane (functioning as a vapour barrier) and a *new waterproof layering* is fixed over the new insulation; a waterproof felt (such as bitumen or EPDM) is typically added with adhesive techniques to prolong the longevity of the roof finishing.

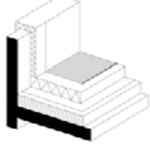
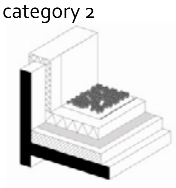
In **category 2** a warm deck roof is created, in which the thermal insulation is loose laid on top of the existing roof membrane without additional waterproof layering, while the insulation layer is finished with a movable sheeting and ballast (such as gravel) to keep the insulation in place. It is assumed that the existing waterproof layer is checked and repaired if needed, and no additional waterproofing is applied on top of the additional insulation layer. Insulation rigid boarding is selected with adequate closed-cell structure ensuring resistance to moisture absorption and providing resistance to thaw/freeze cycles.

4.3.4.2 AGGREGATED RESULTS AND CONCLUSIONS

Studies about the optimisation of the U-values in the framework of the EPBD policies indicated that the currently applied U-values in the Belgian Energy Performance Directive (EPD) are not yet sufficiently stringent and they require future revisions [Audenaert 2010]. This explains why survey groups indicate future thermal upgrade as an important aspect, and subsequently, why the second roof category results in a higher overall performance (71% versus 52%). In the first category, replacing insulation would include removal of the entire roof covering and insulation due to adhesives used, whereas in the second category the thermal insulation can be upgraded by simply adding more or better-performing insulating materials under the loose laid plastic sheeting - while reusing the flexible ballast.

However, the second roof type might experience humidity or leak problems since the covering is not executed with a waterproofing, and is depending on the initial waterproofing layer. This illustrates well how re-design decisions of today have to be balanced carefully, to make future interventions as financial and environmentally viable as possible.

Table 4.19: Aggregated results of weighting and scoring of roof categories (weight. set 1)

Verifiers	Roof categories	
	category 1	category 2
		
A	**user comfort**	
1.1.	+	+
2.1.	+	+
B	**life cycle design**	
1.1.	+/-	+/-
2.1.	-	+
2.2.	-	+/-
2.3.a	-	+/-
2.3.b.	+/-	+/-
3.1.	-	-
3.2.	-	-
3.3.	+/-	+/-
C	**(de)construction**	
1.1.a	+	+
1.1.b	-	-
1.2.a	+	+
1.2.b	+/-	+/-
1.3.a	-	+
1.3.b	-	-
1.3.c	+/-	+/-
2.1.	-	+
2.2.	-	+/-
Total	**52%**	**71%**

(see Table 4.5)
A. user comfort: A.1.1. thermal performance; A.1.2. acoustic performance;
B. building life cycle: B.1.1 maintenance; B.2.1 layering; B.2.2 jointing; B.2.3 reuse potential (a. material resistance; b. Long ESLC (estimated service life of components)); B.3.1. reuse market; B.3.2. recycling; B.3.3.down-cycling;
C. (de)construction: C.1.1. clustering (a. # connections; b. preassembly); C.1.2.comprehension (a. minimum assembly skills; b. standardisation); C.1.3.comfort (a. connection simplicity; b. tolerances; c. manageable connections); C.2.1. accessibility; C.2.2.independence).

4.4 DISCUSSION

Looking at the overall MCA results, it can be concluded that standard solutions applied in renovation today score poorly when evaluated over a larger range of qualitative criteria than merely initial user comfort and energetic upgrade of buildings. This can be explained by the contemporary use of short-term solutions, stimulated by e.g. subsidies concerning the EPBD policy today. The main goal of these current renovation strategies is to reduce excessive operational energy demand of existing buildings and to upgrade the living comfort. However, these solutions only deal to a minor degree with future use requirements, such as further upgrading, adaptations of changing the internal space, re-organising the building, maintaining technical services and reusing components. Indeed, the outcome of the survey indicated that the interviewed groups attribute a significant importance to building systems which would anticipate future adaptations in building systems. The selection of materials, sub layering and assembly methods of current solutions however are not considered in this long term perspective, and therefore miss crucial future opportunities.

A dynamic re-design approach was revealed from the survey to be an important design feature in order to repartition internal layouts of apartments, while its capacity to further upgrade the building skin and roof in the future was also perceived as a must-have feature. The main motives for change according to the outcome of the survey are represented in Table 4.21.

Table 4.20: Motivation for change of building layers over the life cycle of buildings

	Building layer	Need for change	Motivation for change
1	**internal wall** **roof**	high	*Internal flexibility / technical upgrade;* *Thermal upgrade.*
2	**partition wall** **facade**	intermediate	*New layout plan / functional upgrade;* *Thermal upgrade;*
3	**floor**	low	*Technical upgrade;*

As an answer, this PhD discussion will focus on the shortcomings revealed from qualitative assessment of existing solutions, and proposes an alternative life cycle perspective on building component design as a complement to the renovation strategies of today. The objective is to prolong the useful life of components and buildings, by incorporating a dynamic approach while re-designing buildings today. A slightly adapted way of reversible jointing, a careful choice of durable materials and a multi-layered composition of building systems are just small efforts to design sustainable building systems which in the long run create a wider range of future benefits regarding minimisation of resource consumption and waste production.

In addition, few building upgrade solutions in renovation today are able to speed up renovation works, although this was indicated by the social housing companies as a crucial renovation aspect, since it implies reduced inconvenience for the inhabitants. *Preassembly* is therefore a strategy that could offer multiple benefits since the renovation of social housing today is taking place on a low scale. Furthermore, preassembly techniques of today may incorporate diverse and reversible building solutions, which may be reused in case buildings are being demolished earlier then predicted. This is an important line of thought that will be explored in Chapter 6.

Finally, multi-criteria analysis offered a good tool to reveal lack of qualitative criteria which are often neglected in the environmental and financial assessment of buildings. Although it is a result of personal interpretations, inconsistent judgements in the survey could be easily tracked with the use of multiple weighting sets and straightforward questions - verifiers. Since the weighting sets and scores were based on literature, field research, interviews with architects, members of the VMSW, and local social housing companies the results are assumed sufficiently reliable to give a first global indication for the context of the Flemish social housing *in the scope of this research*. However, to provide an adequate and detailed overview of all social housing companies in Flanders, it is clear that a survey should be set up on a larger scale. In addition, judgements which lead to the weighting sets of the qualitative assessment are principally relevant in the renovation framework of today. The building environment is likely to evolve over the coming years, due to more stringent regulation and changing socio-economic standards. The weighting attributed to criteria today should therefore be re-assessed if more information is needed.

PART II

05

HOW FLEXIBLE IS OUR BUILDING STOCK?

The previous chapters pointed out that the contemporary renovation practice of post-war buildings is lacking an integrated long term life cycle vision. In order to apply the alternative approach proposed in this dissertation - the Re-Design for Change approach – first, an analysis is required at building level to determine the parameters which influence the present and future flexibility of the post-war building stock. Indeed, a dynamic renovation approach is not always an easy task since a wide range of parameters have already been determined in the initial construction phase.

Therefore, if one aims to introduce a dynamic approach in existing buildings, firstly, it is necessary to analyse the flexibility of existing building structures to understand inherent opportunities and barriers. This chapter explores the interference between building parameters determined by construction techniques used in the in post-war construction era, and the (future) flexibility of these buildings. An analysis of the main building typologies found in post war social housing estate is made, revealing building parameters, which therefore influence reorganisation of buildings to contemporary and future standards. The opportunities for reconversion are formulated in terms of spatial and technical flexibility, and are associated with the determined building typologies. The building typologies and their physical properties – including the load-bearing structure, organisation of the circulation and technical clustering – define if buildings have a good capacity to be re-designed today, and if a high degree for change can be incorporated for tomorrow.

Finally, four selected case studies dealing with renovation of post-war social housing estate are presented, illustrating how the originally applied construction methods and internal organisation of the building may influence the opportunities of dynamic renovation of buildings.

5.1.1 SPATIAL FLEXIBILITY

The concept of *flexibility* is an important concern in the re-design of buildings today: it refers to the idea of accommodating change over time. Therefore, flexible buildings corresponds to "buildings that can easily adapt to the changing needs of users" [Schneider and Till 2005]. To accommodate this concept, *spatial* flexibility deals with the freedom of a building to reorganise the space in new building layouts. The internal and external flexibility respectively refer to flexibility of the spatial partitioning and flexibility of the external building skin (Figure 5.2).

Figure 5.1: Internal and external flexibility of buildings

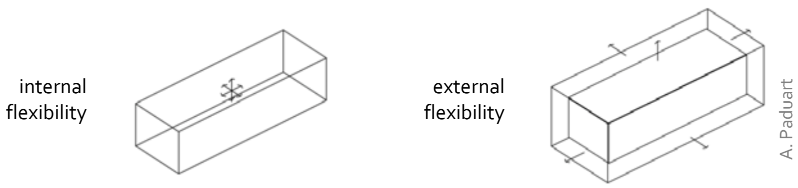
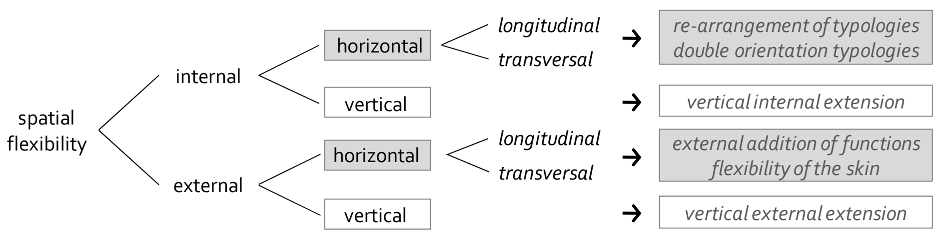


Figure 5.2: Spatial flexibility of a building



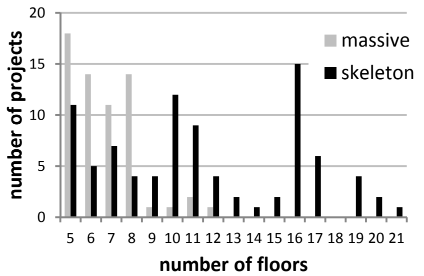
Concerning the **internal** flexibility, a high horizontal flexibility relates to the ease of repartitioning the floor space in adapted apartment typologies, whereas vertical flexibility deals with opportunities to insert qualitative duplex apartments. The **external** flexibility of buildings deals with opportunities of the building skin to integrate, upgrade or adapt external aspects of the building itself. This can include replacement of the building envelope, modification of window openings, addition of external balconies, horizontal extension of the building or even addition of a building storey - i.e. vertical flexibility.

The flexibility of existing residential buildings is closely related to the presence of permanent and variable load-bearing elements [Brand 1995, Bosma 2000, Leupen 2006, Albostan 2009, Ebbert 2010]. Determining permanent elements in the context of post-war residential apartment buildings are defined in this dissertation as the *load-bearing structure*, the organisation of the *circulation* and the *technical grouping* of functions.

5.1.1.1 LOAD-BEARING STRUCTURE

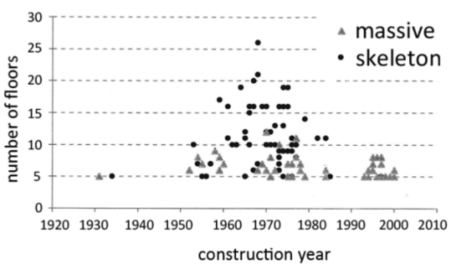
The load-bearing structure of existing buildings -being one of the most rigid and thus permanent building parts - is important in determining whether the architectural layout of existing buildings is flexible or not [Schneider and Till 2007]. The structural and dimensional characteristics of load-bearing structures therefore play a key role in the re-design of buildings. Large estate buildings from post-war construction period typically made use of industrialised construction techniques in which system building[1] with extensive prefabrication of building components was applied. The Belgian tradition of brickwork architecture was set aside during this construction period due to the limited load-bearing capacity for an overall equal thickness of load-bearing walls made of brickwork. Consequently, post-war multi-storey construction typically made use of prefabricated cross-walls, stanchions, longitudinal walls, or a combination of these elements to transfer building loads [Schmitt 1964]. Figure 5.3 and Figure 5.4 illustrate the use of system building for the load-bearing structure in social housing projects. The figures show that post-war (social) housing projects exceeding eight floors typically made use of systemised construction techniques as an alternative to brickwork construction.

Figure 5.3: Number of projects according to number of floors and load-bearing structure



Source: [Declerck 2002]

Figure 5.4: Evolution of number of floors according to the load-bearing structure



Source: [Declerck 2002]

According to their properties relating to the spatial flexibility of buildings, three main categories of load-bearing structures of post-war construction are retained: *cross wall, skeleton* and *panel wall* structures. The principal structural characteristics of each category are summarised in Table 5.1.

---

[1] System building refers to several building techniques that were different from the traditional massive masonry techniques. System building of post-war construction generally included a combination of stack work (the stacking of concrete wall elements with decreasing dimensions) and skeleton construction (construction of a load-bearing carcass with columns and beams and floors). Typically a combination was used of prefabricated or semi-prefabricated building elements (beams, slabs, walls, stairs) and in situ poured reinforced concrete work.

Table 5.1: Load-bearing structure types in post-war system building

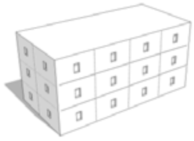
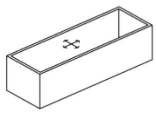
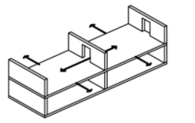
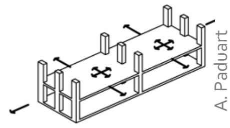
System building structure		
Cross wall structure	*Skeleton structure*	*Panel wall structure*
		
The supporting structure consists of load-bearing transversal cross walls. The structure is usually filled in with semi-prefabricated facade panels and non load-carrying internal walls.	The frame of columns, beams and floors as a whole form the load-carrying structure. The structure is usually filled in with semi-prefabricated facade panels and non load-carrying internal walls.	The structure combines load-bearing prefabricated facade panels or in situ poured reinforced concrete facades to support intermediary floors. Inner partitioning can be locally load-bearing in case of large spans.

Table 5.2: Examples of categories of post-war load-bearing structure types

Type	Examples of load-bearing type of system construction	
cross wall	 *Sint-Maartensdal, Leuven* Source: A33	 *Koning Albert building, Kessel-Lo* Source: [Sterckx 2006]
skeleton	 *Modelwijk, Brussels* Source: Foyer Laekenois	 *Sterrenveld, Wezenbeek-Oppem* Source: VMSW
panel wall	 *Silvertop, Antwerpen* Source: A. Paduart	 *Cité Galaxie, Brussels* Source: [Engels 2010]

The internal and external horizontal flexibility of post-war buildings is closely related to the presence of load-bearing elements which is determined by the load-bearing structure type. Table 5.3 summarises the degree of spatial flexibility of the three principal load-bearing structures typologies.

Table 5.3: Horizontal flexibility of load-bearing structures

		Load-bearing structure systems		
	Spatial flexibility	***panel wall structures*** 	***cross wall structures*** 	***skeleton structures***  A. Paduart
internal	horizontal flex.[2]			
	- longitudinal	-	+/- to +	+/- to +
	- transversal	+	+/ - to +	+/- to +
external	horizontal flex.			
	- longitudinal	+	-	+
	- transversal	-	-	+

(-) limited; (+/-) average; (+) substantial.

First, cross wall structures are characterised by a limited longitudinal horizontal flexibility; due to the physical presence of transversal load-carrying walls in the horizontal plan and the strong repetitive modular character, the range of interventions is restricted. The initial concept of *liberation of the plan* - one of the main objectives of modernist architects – is only applied *inside* each modular unit defined by the cross walls - i.e. transversal flexibility. Therefore, at building level it becomes difficult to make a radical layout conversion, since all adaptations are limited to modular interventions. Concerning the vertical flexibility, cross wall structures were occasionally designed as duplex apartments (e.g. King Albert Building, St. Maartensdal) offering a high degree of vertical freedom.

Building typologies based on *panel wall* facades are characterised by low *external* flexibility due to the permanent character of the facade. During renovation works only minor changes can be introduced in the facade openings, whilst thermal improvements of the building envelope can only be made by adding (external or internal) layers to this existing

[2] The vertical flexibility was not included in Table 5.3 since it is strongly dependent on the specific context of each building.

panel walls. This means that degradation or moisture problems in the structure may lead to problematic buildings since the building skin cannot be replaced by more performant solutions. Regarding the *interna*l flexibility, the longitudinal flexibility is relatively high, due to absence of permanent load-bearing elements in the space plan.

The highest degree of spatial flexibility is exhibited by *skeleton structures*; the absence of large load-bearing elements in the plan of skeleton structures results in high internal and external flexibility. Therefore, this construction system functionally liberates the plan layout – acting as a frame for generic space – while extensive external modifications are also enabled [Schneider and Till 2007]. However, the horizontal flexibility in skeleton structures can still be influenced by additional structural barriers: asymmetry of the structure, complexity of the column-beam structure, fixed circulation elements (elevators and stairs) or additional shear walls for the general stiffness of the construction. These elements may form an obstacle to provide other apartment typologies then the ones that were initially designed.

5.1.1.2 CIRCULATION

In the post-war construction time, the circulation typology played an important role in the reduction of investment costs of the industrialised building process; staircases could be designed according to the rules of prefabrication, while their position in the building could play an important role in speeding up the construction process [Schmitt 1964]. The organisation of the circulation in system building in general ran in parallel with the type of load-bearing structure. Circulation can act as an autonomous part separated from the construction or as an integrated element of the load-bearing structure. In skeleton structures, for instance, the elevator shafts and the staircases usually participate in the global stiffness of the building; in cross wall structures, on the contrary, staircases and elevators are frequently positioned externally with a minimal interference with the building structure (e.g. Block I-III at Model City).

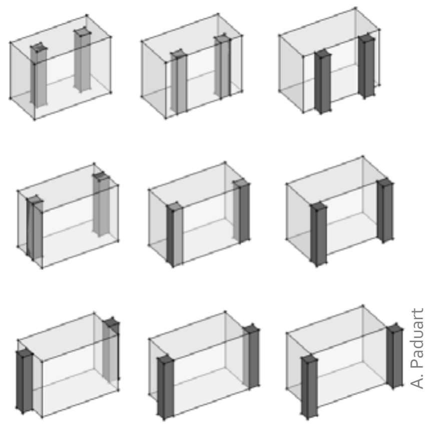
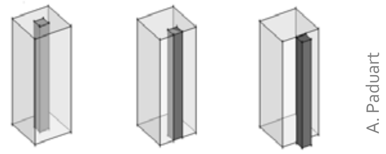
Two main aspects of circulation define the interference with the building flexibility: the plan positioning in order to offer vertical access to all floors, and subsequently, the horizontal organisation of circulation in order to reach each individual residential unit. As a result, it is the combination of vertical and horizontal circulation that influences the internal flexibility of buildings together with the type of load-bearing structure.

VERTICAL ACCESS TO EACH BUILDING FLOOR

Vertical circulation can be positioned *centrally*, *laterally* or *externally* with reference to the lateral or the longitudinal axis of the building. The main variants are represented in Table 5.4 according to the degree of interference of the circulation with the horizontal space plan. It is worthwhile noticing that highly centralised circulation may create a higher interference with the horizontal flexibility of the space plan than external building circulation.

In the case of skeleton structures, modifications are restricted normally due to their structural relevance in the global building stiffness. Consequently, radical interventions in the organisation of the vertical circulation may be labour-intensive and more material-consuming and waste-producing than simply retaining the original composition. It is therefore preferable, whenever possible, to preserve the original vertical circulation or to introduce minor modifications in order to keep the investment costs acceptable. Nevertheless, in some cases of panel facades and cross wall structures, vertical circulation can eventually be adapted more efficiently.

Table 5.4: Vertical circulation scenarios according to interference with space plan

Vertical circulation scenarios			
block	**transversal side** *central*	*lateral*	*external*
longitudinal side	**HIGH** - - - -> **LOW** *interference*		
central			
lateral			
external			
	LOW *interference*		
tower	**centralised**	**lateral**	**external**
central			
	HIGH *interference* - - - -> **LOW** *interference*		

HORIZONTAL ACCESS TO INDIVIDUAL LIVING UNITS

There is a strong relation between the positioning of the vertical circulation and the options to access each individual apartment on each building floor. Indeed, a centralised circulation will allow access to apartments with a minimum loss of horizontal circulation, while externally positioned vertical circulation will eventually demand extensive use of horizontal circulation in order to allow access to all apartments. It is important to note that the horizontal access to residential units is determinant to establish the typology of apartments. With this in mind, the access is subdivided in two principal types: *clustered* (collective hall) or *linear* (corridor). Table 5.5 shows frequently applied apartment typologies in the post-war period, as scenarios of centralised and lateral access to apartments in multi-storey buildings.

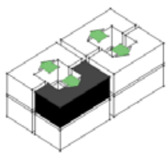
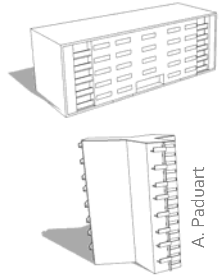
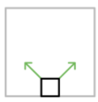
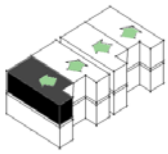
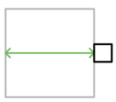
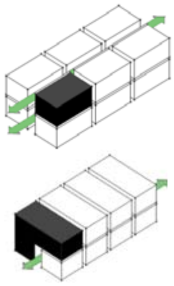
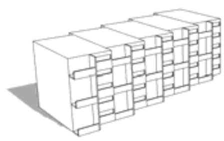
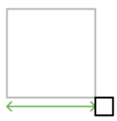
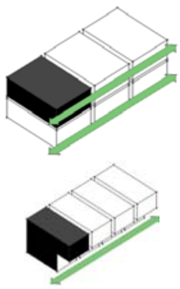
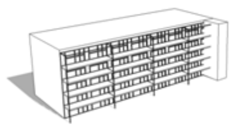
A first frequently applied apartment type, the **landing typology**, appears in skeleton structures and provides central access to clustered apartments by means of a collective hall. This typology may offer apartments with single or double orientation. Although surface loss due to circulation can be minimised, the vertical circulation may interfere with the transversal flexibility of the horizontal space of buildings: due to its central position it can obstruct longitudinal repartitioning of the building.

The **porch typology** - the most ancient type - was usually applied for buildings until four building floors. It was mainly applied before W.W.II as an attempt to maintain a low-scale multi-housing approach through limiting the amount of inhabitants using one staircase [Declerck 2002]. One of the most well-known buildings of this type is the Cité Hellemans in Brussels.

A third typology, the **internal corridor typology**, was usually a result of initial cost reducing measures: one staircase and elevator suffice to make the entire building operational. Nonetheless, this resulted in dark and long non-ventilated internal circulation together with apartments with single orientation, which do not match with contemporary living standards. A variant on this typology organises the horizontal circulation per two floors, which resulted in duplex apartments that separate day and night functions over two floor levels - increasing the acoustic, visual and indoor comfort. This provides a greater sense of individuality in apartment buildings, explaining why Braem used duplex apartments systematically in his projects [Braeken 2010]. Besides projects of Braem, Vandermeeren en Stynen, few projects of this type can be found in post-war social housing in Flanders [Declerck 2002][3].

[3] Braem at Kiel (1955-1956), Jos Van Geellaan (1955-1969), Sint-Maartensdal (1957-1961), Arenawijk (1960-1972) and Model City (1956-1969); Van der Meeren at Evere (1954-1960) and Léon Stynen at Koning Albert Building at Kessel-Lo (1956).

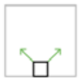
Table 5.5: Main apartment typologies based on horizontal access scenarios

	Horizontal circulation	Apartment typology: *Typology*		Apartment typology: *Example*
clustered access	central 		*landing type*	
clustered access	lateral 		*porch type*	
linear access	central 		*internal corridor*	
linear access	external 		*external gallery*	

The fourth typology, the **external gallery**, is a variant of the interior corridor. By externalising the circulation, the quality of living was enhanced: a double orientation offered improved indoor air quality. Furthermore, the position of the horizontal access does not impede subdivision of the horizontal space and allows access to apartments from every position on the linear axis. This type of circulation can be seen applied as external galleries in tower blocks I to III of the Model City in Brussels. Later down the line, a further reduction of construction costs in this large project led to clustered external circulation per two floors creating a variant on duplex apartment (buildings VI and VII of the Model City).

An overview of the spatial flexibility of the principal apartment typologies based on the positioning of the circulation in the building is proposed in Table 5.6. The ease to make a reconversion of initial typologies to these adapted to today's and tomorrow's standards is ordered in increasing rank of flexibility, from strongly centralised circulation types to lateral and external positioned circulation types.

Table 5.6: Horizontal flexibility according to the horizontal access

		Type of apartment typologies			
					
Horizontal flexibility		*corridor type*	*landing type*	*porch type*	*external gallery*
internal	horizontal flexibility				
	- *longitudinal*	+	+/-	+	+
	- *transversal*	-	+/-	+	+
external	horizontal flexibility				
	- *longitudinal*	+	+	+/-	+/-
	- *transversal*	+	+	+	+

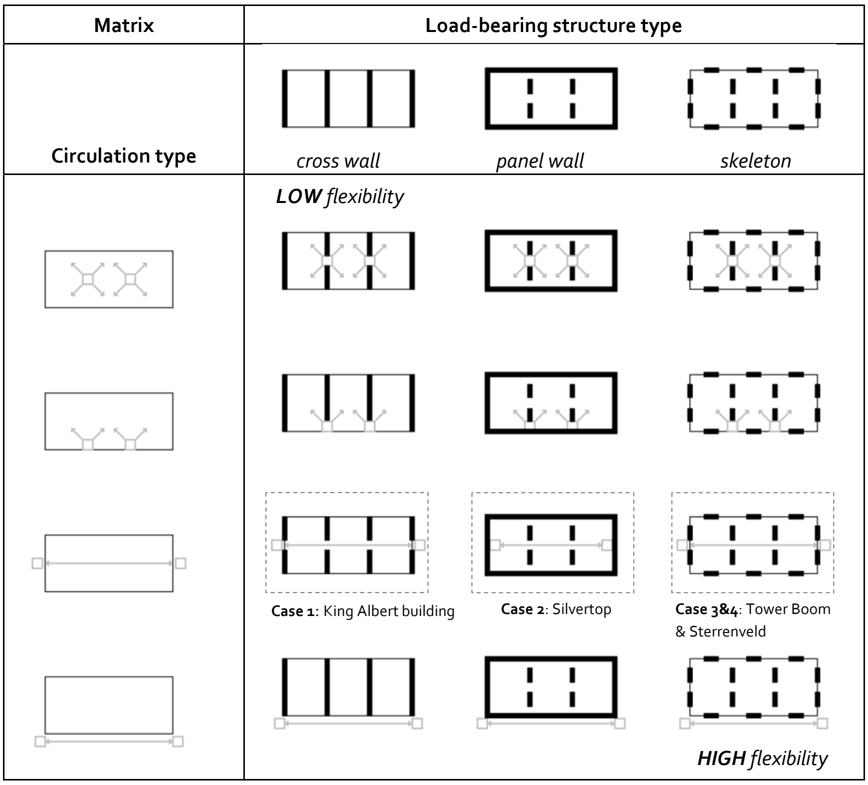
(-) limited; (+/-) average; (+) substantial.

5.1.1.3 CASE STUDIES MATRIX

In the post-war social housing stock, a wide range of combinations of the discussed load-bearing structure types combined with the circulation categories can be found. Table 5.7 shows a matrix of combinations, ordered according to the degree of spatial flexibility.

Four case studies of recently renovated social post-war buildings (marked in the table) will be discussed in §5.2 to illustrate the influence of the load-bearing structure type together with the influence of the organisation of the circulation.

Table 5.7: Matrix of theoretical combination of circulation and load-bearing building structure



5.1.2 TECHNICAL FLEXIBILITY

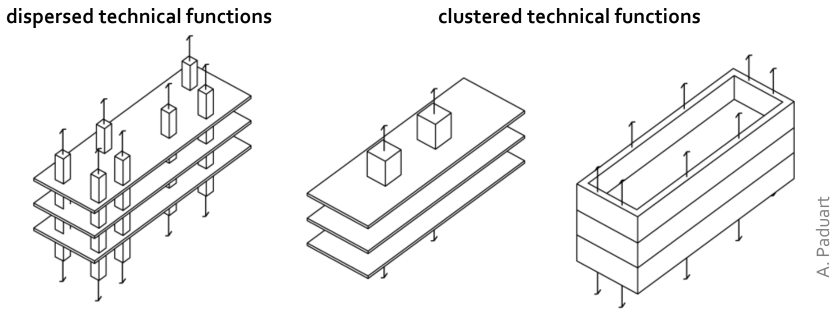
As the development of new technologies is rapidly progressing, building services find themselves out of date more quickly than the building itself. What appears to be outdated in the present-day context was -not very long ago- a progressive expression of new housing concepts. The 1960s were characterised by an enormous economic expansion side by side with increasing living standards. As a consequence, the quality of housing in this construction period witnessed drastic improvements: modern sanitary and kitchen appliances were no longer a commodity merely for high income families, whilst central heating was introduced in large estate building projects [Van Herck 2006]. As a result, the first exemplary large estate projects were characterised by their modern functional standards (e.g. Model City). Today, the estimation of these appliances as outdated and of inferior quality forms a good illustration of the consequences of fast evolving building comfort standards.

While technical accommodation is transitory, the *technical support* to distribute the building services throughout the building can be designed as a permanent structural part of the building, in order to provide technical flexibility for the future. The *technical* flexibility concerns the systematic approach used to organise the technical facilities in buildings in a flexible manner. Systematic **clustering** of technical ducts offers great benefits in the perspective of free plan partition [Albostan 2009]. A grouped vertical distribution of services which is organised across the floor section - so that the central technical element can be accessed from any plan arrangement – can introduce important additional qualities in buildings [Schneider and Till 2005]:

- *The strategic placing of service cores* allows kitchen and bathrooms to be placed within specific zones, not necessarily permanently fixed;
- A *central technical element* provides the ability to access all services so that their future update is still possible.

Two principal strategies make the vertical services highly accessible from different plan layouts. One of the practical ways is to collect all services in a single central zone so that the surrounding space is not disturbed as generic space [Albostan 2009], represented in Figure 5.5. The second approach foresees a service zone along the building skin, making them accessible from several points in the internal space.

Figure 5.5: Technical flexibility of the building structure



Clustering of technical rooms and functional zones around a central technical element in buildings has proven to surpass the test of time in many renovation projects in which Braem introduced this concept (e.g. Tower Boom, St. Maartensdal). As a result, today, these buildings exhibit a higher technical flexibility than buildings with technical shafts randomly positioned over the floor space.

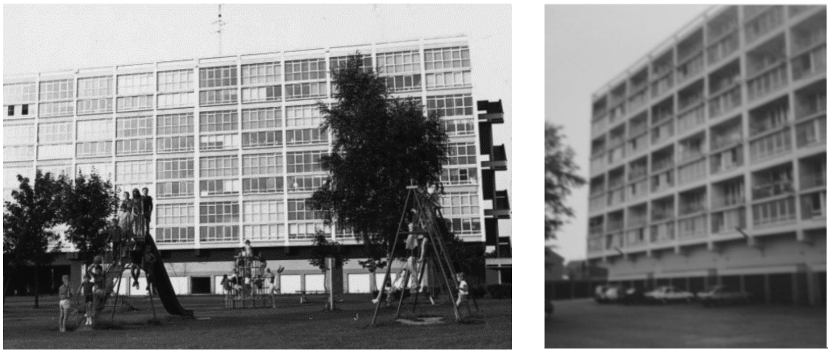
5.2 CASE STUDIES OF RENOVATION OF POST-WAR BUILDINGS

5.2.1 KING ALBERT BUILDING AT KESSEL-LO

5.2.1.1 GENERAL DESCRIPTION

The King Albert building is a constituent part of the garden city 'Casablanca' situated at Kessel-Lo and built in 1956 [Sterckx 2007]. Architect Léon Stynen designed this apartment building on pilotis in accordance with the principles of *l'Unité d'Habitation* of Le Corbusier (1952). In 1968, the space between the pilotis was used to respond the growing demand for parking space and storage room [Sterckx 2006].

Figure 5.6: King Albert building before renovation

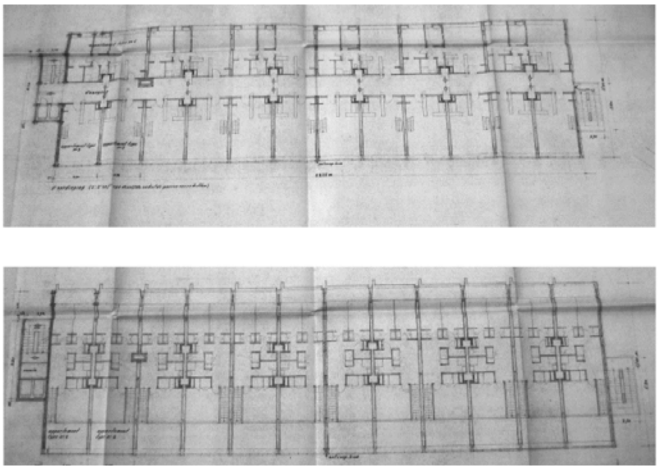


Source: Stadsarchief Leuven (SAL) Source: A33 architects

The original facade was characterised by the use of color and texture; balconies painted in red, white, blue and ochre, broke the repetitive cross wall structure and created a volumetric play in the eastern facade, revealing the structural building elements. In the western facade, monotony was avoided by emphasising the structural frame of the building. The concrete skeleton is visible in the external facade and in the internal corridor of the building [Sterckx 2006].

The central access of the building is located at the northern side of the building at street level, providing access to all uneven floors by means of a staircase and elevator. At the southern side of the building, a secondary open staircase is positioned. The connection between these two staircases results in a collective interior corridor which gives access to each individual apartment, every two floors. The cross wall building structure offers two principal types of apartments: unilevel apartments with two sleeping rooms and duplex apartments with three sleeping rooms [Sterckx 2006].

Figure 5.7: Plan view of even and uneven floors of King Albert Building



Source: Stadsarchief Leuven

5.2.1.2 RENOVATION OF CROSS WALL BUILDING STRUCTURES

In the 1990s the building started to show significant signs of degradation due to infiltrating rain water and high wind pressure. Consequently, carbonation of the building structure, instabilities of the eastern and western facade, lack of building insulation and outdated technical facilities all together led to the urgent need for renovation.

Figure 5.8: King Albert building after renovation

Source: A33 architects

Source: A33 architects

The visible cross wall structure - frequently used in post-war architecture to accentuate the building structure as an architectural expression - is often subject of significant degradation resulting in an alteration of the building structure itself. In order to ameliorate significantly hygro thermal properties of these building types in which the load-bearing structure itself works as a thermal bridge, the cross walls need to be entirely wrapped into a new thermal envelope, resulting in the loss of the original modernistic characteristics. For the renovation of the King Albert building, the architects assigned with the renovation - A33 – were also forced to propose this solution type. Enclosing the building by a glazed

shell was the only way to reduce thermal bridging and water infiltration while obtaining a higher stability of the facade [Sterckx 2006]. Inside the building, electrical appliances were renewed and sanitary rooms were updated according to contemporary comfort standards. However, the apartment layouts and the circulation remained unchanged, due to the presence of cross walls and the central positioning of the circulation, which do not facilitate an easy reconversion of the space plan. Indeed, in this building typology, adaptations of the apartment layout and size in order to give answers to changing comfort standards are difficult to make. The strong modular character defined by the presence of cross walls together with the centralised corridor, strongly determine the future use of the plan layouts - this due to the low spatial flexibility. Eventually, the addition of perforations in cross walls could enable apartments to be enlarged; however, this would imply adding an equal modular space [Elsen 2007].
Different renovation projects of these frequently applied cross wall structures (e.g. long building block and tower at St. Maartensdal) illustrate that it is complex to harmonise the strong original modernist character of cross wall facades with current energy policies and contemporary comfort standards.

5.2.2 SILVERTOP AT ANTWERP

5.2.2.1 GENERAL DESCRIPTION

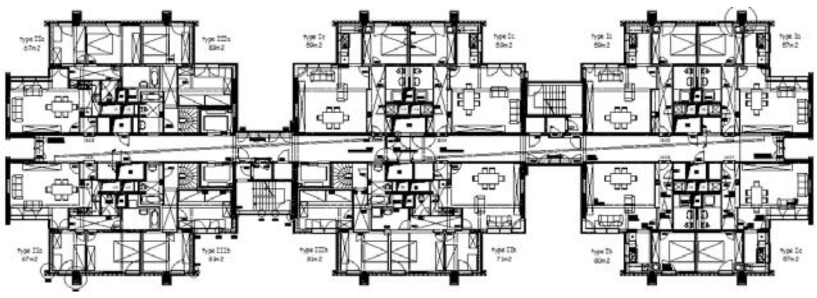
The high-rise Silvertop towers in Antwerp are prominent elements in the landscape of the Kiel district, constructed in the beginning of the 1970s according to a design of Jules De Roover. The three towers are 20 storeys high and include 608 social dwellings. The load-bearing structure consists of a skeleton concrete framework, including prefabricated facade panels [Bekker 2010]. Each tower consists of three sub towers, which on average include four identical apartment types per floor. A central interior corridor connects the three sub towers, dividing the building in an eastern and western section; two centralised staircases and elevators provide vertical access to all building floors.

Figure 5.9: Silvertop tower before renovation

Source: A. Paduart

During recent years, severe problems were experienced with moisture and water penetration throughout the jointing that was applied between the prefabricated facade panels [WTCB 2000]. These hygro thermal problems quickly resulted in vacancies of the upper floor apartments. The original internal partitioning walls made adaptations of the initial plan layout quite difficult, resulting in small apartments in the current-day context. These factors resulted in a negative connotation associated with these tower buildings. Therefore, in 2003 the Flemish minister of Housing approved a renovation of 608 subsidised flats - the most large scale renovation of social housing in Belgium until present day. The building is undergoing an extensive renovation to bring thermal and acoustic properties up to current standards, while improving the fire safety and upgrading the apartment typologies to minimum living standards [Bekker 2010].

Figure 5.10: Plan view of Silvertop tower II after renovation



Source: [Paelinck 2008]

In this building typology with load-bearing facade panels, thermal upgrade of the building skin typically results in addition of an external skin applied upon the prefabricated panels, resulting in the loss of the characteristic expressive modernist facade. This is illustrated by the renovation of the Silvertop towers in which the original facade is completely covered with contemporary cladding while all volumetric openings are streamlined, generating a homogenous monotonous building look. In addition, the external flexibility is restricted: the openings in the external walls remained identical after renovation, due to the load-bearing function of the facade.

In contrast, the internal load-bearing skeleton of this building type enables to make high-scale interventions regarding the internal fitting-out of the building. During the renovation of the Silvertop towers, the building was stripped to the load-bearing structure, meaning that the prefabricated facade panels and the concrete skeleton structure were retained, making it possible to introduce diverse apartment typologies: two apartment types with 1 and 2 sleeping rooms, and duplexes with 2 sleeping rooms. A minor enlargement of apartment resulted from reorganisation of the building plan layout, incorporation of the original external balconies and local external extension under cantilevering spaces. The new fitting-out was executed in lightweight partitioning to enhance future flexibility in the horizontal plan [Paelinck 2008].

Figure 5.11: Silvertop tower after renovation

Source: [Paelinck 2008]

Source: VMSW

Summarising, post-war skeleton buildings with a load-bearing external wall (panel wall) have an intermediate degree of flexibility to cope with periodical upgrade interventions. Although external modifications of the facade are restricted, the internal structure made high-scale reorganisation of the internal space layout possible.

5.2.3 ZONNEVELD – STERRENVELD AT BAN-EIK

5.2.3.1 GENERAL DESCRIPTION

The apartment buildings Zonneveld and Sterrenveld make part of the garden city project 'Ban Eik' situated in Wezenbeek-Oppem and developed in 1959. The garden city provided a combination of single family houses and apartment buildings amongst which these two identical multi-storey apartment blocks. The mix of residential functions, public spaces, shops, green zones, schools and a progressive district heating system for the neighbourhood made this garden city an exemplary social project in the 1960s [Passiefhuis Platform 2006].

Zonneveld and Sterrenveld are composed of a concrete skeleton structure against which non-structural prefabricated facade panels are externally added, as bracing elements. Inside the buildings, the central staircase is connected to a secondary external staircase on the northern side of the building. The resulting centralised interior corridor without sunlight or means of ventilation divides the original span plan in two lateral parts, resulting in apartments with single orientation.

Figure 5.12: Sterrenveld and Zonneveld before renovation (Ban Eik - Wezenbeek-Oppem)

Source: VMSW

Source: VMSW

5.2.3.2 RENOVATION OF SKELETON BUILDING STRUCTURES

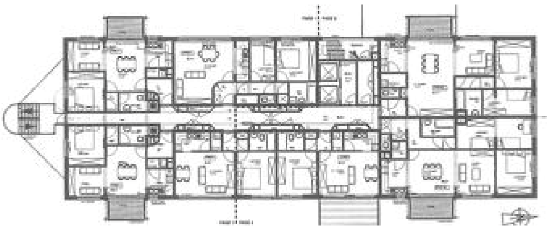
After 30 years of inhabitation the apartment blocks Zonneveld and Sterrenveld were completely outdated due to inferior quality of building materials and low construction techniques, lack of user comfort, high energy consumption and vandalism [Wallyn 2008]. The initial plans to demolish these apartment buildings - replacing them for new constructions - were cancelled due to restrictive urban planning regulations. Since new construction would be limited to building a maximum of three floors the option of renovation become more attractive.

From a conceptual point of view, the renovation of two identical buildings was used as an opportunity to make a comparison between a classical renovation approach (Zonneveld) and a sustainable renovation approach (Sterrenveld). This case study is a good demonstration of the high flexibility of skeleton building typologies, since a radical transformation was made from two identical outdated buildings towards two solutions of which the functional, spatial and technical properties after renovation are strongly diverging.

In a first stage (2001), **Zonneveld** was renovated to thermal performance standards applicable at the time of renovation with global interventions characterised by a low degree of change in the internal building fabric. Stimulated by the Flemish Government through a call for pilot projects, the renovation of the second apartment building – **Sterrenveld** – embraced a holistic view on sustainable renovation, tackling energy loss through insulation and heat recovery, minimising existing thermal bridges, installing photovoltaic panels and sun boilers, while revitalising the surrounding neighbourhood with architectural and urban planning tools [Wallyn 2008].
The renovation of Zonneveld retained the original organisation of the building around the interior corridor. Moreover, the internal structure was not changed while the building envelope was updated to a minimum and a new collective heating system was installed on the roof. The renewed additional external staircase provides the necessary measures for the building to keep up with contemporary fire safety standards.

Figure 5.13: Zonneveld and Sterrenveld after renovation

(a) Plan view of Zonneveld after renovation



Source: VMSW

Source: VMSW

(b) Plan view of Sterrenveld after renovation

Source: VMSW

Source: VMSW

On the contrary, in the Sterrenveld building, the load-bearing skeleton structure was entirely stripped, while the vertical circulation was entirely removed and reorganised. The original interior corridor made it impossible to add apartment typologies with double orientation to the existing plan. Therefore, by stripping the interior layout (non load-bearing walls) and replacing the central circulation shaft, a new flexible space plan was created at Sterrenveld that carries little or none resemblance with the initial plan layouts. The circulation was reorganised by adding three centralised circulation groups, characterised by natural daylight, each offering access to two double-orientated apartments. The new partitioning of the building was executed with dry walls to minimise the loads on the existing load-bearing structure and to maximise flexibility for future interventions.

The building services of the original construction were entirely replaced and all technical shafts were systematically replaced by six main technical shafts providing the necessary accommodation for each apartment. Supply of energy, water and electricity, drain of water and supply and extract of the ventilation system (type D) were all grouped in the centralised technical shafts, in order to organise all kitchens and sanitary rooms in the central zone of the horizontal plan.

In addition, the renovation of Sterrenveld also took benefit of the external flexibility given by the skeleton structure. At the south-west building side the envelope was entirely stripped and an external galvanised steel structure was added, giving rise to local extension of the internal spaces for bedrooms and creating winter gardens adjoining to the living spaces. These winter gardens create a thermal buffer in the apartments, which reduce the heat demand in winter and prevent overheating in summer [Wallyn 2008]. Also, the glass surface of these external terraces can be opened in summer so that the space can function as regular balconies. This additional external framework was also required to ensure the global stiffness of the building since the internal partitioning and vertical circulation was radically modified [Passiefhuis Platform 2006].

As an overall conclusion, the renovation of two identical apartment buildings, Zonneveld and Sterrenveld, according to a different level of intervention is a good illustration of the spatial flexibility offered by skeleton structures and the interference of vertical circulation on the plan layout. The renovation of Sterrenveld shows that with a holistic approach - and of course, sufficient investment means - (problematic) buildings can be re-designed to comply with current comfort standards, while anticipating challenges of the future. The originally rigid building was transformed into a flexible building - reorganising the circulation and plan layout and introducing technical clustering - creating qualitative and sustainable spaces today, whilst anticipating changes of tomorrow.

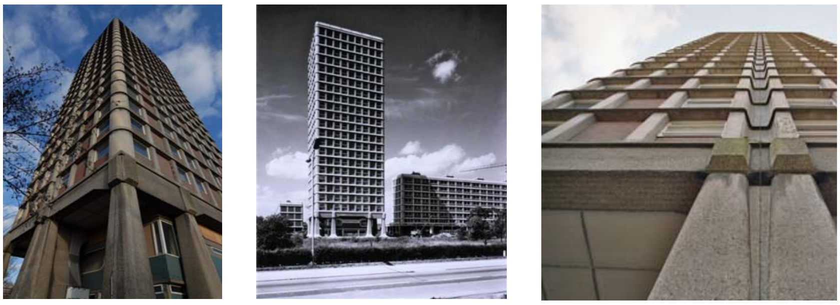
5.2.4 TOWER AT KRUISKENSLEI

5.2.4.1 GENERAL DESCRIPTION

The icon tower along the highway in Boom resulted from a collaboration between the architects Renaat Braem, Juul van Camp and Paul Van de Velde for the design of the 'Kruiskenslei', a large self-sufficient social housing estate built between 1957 and 1979 [Braeken 2010]. The tower is built up around a central concrete element including three elevators, a central staircase and an additional service shaft. The loss of circulation space is minimised by the highly clustered vertical circulation, giving access to all surrounding apartments. The original layout of the tower consisted of a repetition of one identical compact standardised living cell around the central technical shaft. The small living units (55m²) included two sleeping rooms and were strongly modularised to reduce construction costs.

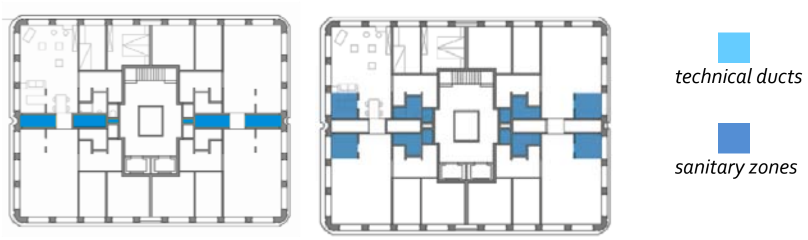
To liberate the floor plan and the external facade, Braem grouped all technical features in two technical shafts made of reinforced concrete, which perforate the entire building section. The functional zones were clustered around this technical shaft whereas living spaces and sleeping rooms were organised along the perimeter of the building, to maximise the benefits of natural daylight and of the view over the surroundings. Braem initially also proposed electrical floor heating in order to provide a rational distribution of heating but also to eliminate ducts and ventilating shafts. Nevertheless, the National Housing Society did not share his fascination for upcoming technologies and preferred individual central heating on city gas [Braeken 2010].

Figure 5.14: Tower at Boom before renovation



Source: VIOE

Figure 5.15: Clustering of sanitary functions in centralised ducts: tower at Boom



5.2.4.2 RENOVATION OF TOWER WITH CENTRAL TECHNICAL ELEMENT

After being sold to a private developer (Immoflash), in 2007, the tower was radically reconverted, including a combination of residential, office and commercial spaces. In addition, two roof storeys were placed upon the building structure, introducing penthouses and a panoramic restaurant [Braeken 2010].

Figure 5.16: Tower at Boom after renovation

Source: Immoflash

The free plan layout introduced by Braem enabled the internal layout to be drastically altered with a mix of new housing typologies: studios, apartments with 2 to 3 sleeping rooms, lofts and duplexes. With the central technical element being the only load-bearing permanent element in the plan, this skeleton structure proved to incorporate a high spatial flexibility in the longitudinal direction [Zenner 2010]. This clustering of all technical facilities with central elements enables - even today - to cluster technical appliances for apartments in a "new" organisation after renovation. Therefore, when this clustering is consequently applied, such as the tower project in Boom, it is esteemed to be a most powerful tool to deal with layout changes in order to respond the evolution of inhabitant's needs today and in the future.

However, this renovation is another example of the loss of the brutalist character after renovation, due to the applied colours and materials in the facade. The ancient prefabricated masonry panels were replaced with white sandwich panels, while the visible concrete skeleton was integrally painted in white, resulting in the loss of the initial character [Braeken 2010].

5.3 DISCUSSION

The analysis of the case studies of renovation of post-war buildings demonstrates how the spatial flexibility of post-war construction can differ to a large extent according to the load-bearing structure, the organisation of the circulation and the technical clustering of services.

The initial selection of construction technique, combined with the way buildings organised the circulation, greatly determines the flexibility to adapt plan layouts or intervene in the external building fabric today. Indeed, the case studies demonstrate in a clear way how the load-bearing structure defines the number of structural interventions possible during re-design of buildings today, in order to make buildings more responsive to change tomorrow. While the flexibility of cross wall structures is limited to transverse repartitioning freedom inside each module, panel walls and skeleton structures offer a higher overall internal flexibility to reorganise the space layout, and the circulation. In addition, the external flexibility of skeleton structures enables to make radical transformations in buildings, providing comparable opportunities as in new buildings.

When technical clustering is applied, new plan layouts are straightforward to introduce without major changes in the building structure. Moreover, the case study of Sterrenveld reveals that it is still possible to add technical clustering during renovation in order to enhance the opportunities of reorganisation of the space in the future.

Finally, buildings with a strongly centralised vertical circulation minimise the loss of horizontal floor space, while the internal circulation inside apartment is simultaneously reduced with central access. At the same time, centralised circulation optimises the access to apartments when compared to long internal corridors that subdivide the building space in two single-oriented zones.

06

FROM FIXED TO MULTI-LAYERED DYNAMIC BUILDINGS

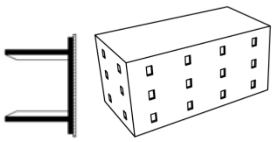
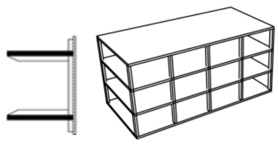
In the previous chapter the *flexibility* of post-war apartment buildings was discussed concerning the ability to upgrade these buildings to contemporary functional and spatial comfort standards. Consequently, promising flexible building typologies were identified which support a *Re-Design for Change* approach at *building level*. The aim of the following chapter is to introduce a dynamic design approach at *component level*. In this chapter, alternatively designed building solutions are proposed that anticipate and sustain building processes during the total life cycle of a building without adding to the environmental burden related to resource depletion and building waste production.

In order to renovate buildings according to a 4D approach, component design must enable reuse and/or reconfiguration of sub components and must subsequently be based on *Design for Disassembly* (DfD) principles presented in Chapter 3. To bring these design principles in accordance with current residential renovation practice, the designer needs to unite both *regulatory design* preconditions - amongst which thermal, sound and fire safety standards - and *reversible design* preconditions which ensure the adaptable nature of building systems.
The aim of this chapter is therefore to reveal any discrepancies between design principles applied in dry construction which enhance the *thermal, sound and fire resistance performance* of building solutions and principles enhancing *reversibility and reuse* of components. Subsequently, renovation solutions can be designed according to the Hendrickx-Vanwalleghem (HV) approach and detailed in analogy with dry construction techniques in order to obtain alternative solutions which maximise *reuse of components* and *ease of reconfiguration, upgrade or adaptation* of buildings whilst complying with regulatory building standards. Hence, it is illustrated how a compromise can be found between conventional renovation practice and DfD strategies in order to sustain the minimisation of resource use and waste production over the entire life cycle of buildings.

6.1.1 SCALE OF RENOVATION

The degree of interventions made during renovation of post-war buildings is usually decided based on considerations dealing with occupancy of buildings, the load-bearing structural system, required improvements of the thermal performance, or available financial budgets. Typical motives for social housing societies to restrict renovation to **low-scale** interventions are in general related to restricted investment means, the building habitation or to protection of the architectural value of buildings. Consequently, interventions during low-scale renovation are generally limited to *energy performance* upgrade including thermal upgrade of the building skin, replacement of heating installations and modernisation of sanitary provisions. In this case, the internal lay-out organisation is left unchanged while improvements of the interior climate and the thermal, acoustic and functional properties are restricted.

Table 6.1: Characteristics of renovation related to level of intervention

	Intervention strategy	
	low-scale intervention	*high-scale intervention*
load-bearing structure	 *Structures with load-bearing facade; buildings in which the existing structure is integrally being preserved.*	 *Skeleton structures, cross-walls structures and structures with load-bearing facade.*
intervention	*Addition of thermal external layer against existing building envelope. Conservation of internal functional organisation and circulation.*	*Partial or integral removal of existing building envelope. Reorganisation of the space lay-out. Addition of new internal and external fitting-out.*
interference	*Modification possible of building envelope under occupation by inhabitants.*	*Interference with building occupation due to extensive renovation works.*
degree of freedom	*Minor changes possible in external walls: window openings remain unchanged.* *Restricted update of functional organisation; apartment typologies remain unchanged. Opportunities for re-design for change in structures with high spatial & technical flexibility.*	*Major change and upgrade possible in the building envelope (thermal upgrade and new architectural statement possible) together with functional internal re-organisation. Great opportunities for re-design for change.*

Nevertheless, during low-scale interventions a long list of identified problems in the European post-war building estate amongst which monotony of building layouts, small sized flats, outdated living comfort, uniformity of dwelling typologies and low flexibility of apartments [Turkington 2004, Riccardo 2007, Power 2008, Andeweg 2007, Thomson 2009] cannot be tackled. During **high-scale** renovation, on the contrary, far-reaching measures can be introduced enhancing the overall spatial, technical, functional and structural properties of buildings. Therefore, when investors have more financial funding or subsidies at their disposal and the load-bearing structure has a long remaining service life, high-scale interventions are therefore desirable to ensure that buildings renovated today do not turn out again in problematic buildings in a short period. Therefore the focus in this chapter is on *high-scale renovation* in order to incorporate Re-Design for Change to a maximum level.

6.1.2 DESIGN BOUNDARIES

6.1.2.1 FRAME AND GENERIC SPACE

To re-design existing buildings for change a new permanent 'frame' must be selected, according to the *frame and generic space* concept of Leupen (2005) discussed in Chapter 3. This implies that all outdated building layers are removed which constrain the current performance and future opportunities for change. Depending on the specifications of buildings, the remaining permanent frame can consist of the load-bearing structure, in combination with its circulation, facade, and/or partitioning. In the context of post-war buildings, the *load-bearing structure* layer with *the circulation* layer generally acts as Leupen's permanent *frame*, whereas updated fitting-out (partitioning, floors and building skin) is usually subject to changing events and consequently act as *generic space*.

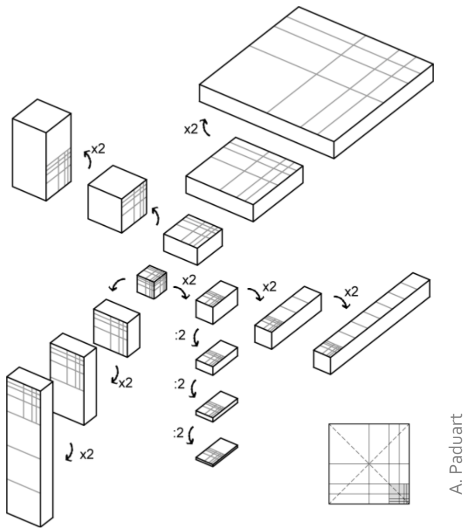
It is crucial for the future flexibility that each building layer added to the stripped load-bearing structure during renovation is physically detached from this 'frame' and designed according to Design for Disassembly (DfD) principles: all new additions embody the 'generic space' which must be able to naturally evolve over the building's life. In what follows, therefore, only the dynamic design of the new generic space is discussed - i.e. the partitioning and building skin - on the assumption that the original load-bearing remains kept and new generic space is introduced with a physical separation according to the layers of Brand (1995).

6.1.2.2 HENDRICKX – VANWALLEGHEM APPROACH

As discussed in Chapter 3 4*Dimensional Design strategies* at component level can anticipate the need for change over a building life by means of a strategic shift in the conception of building artefacts from *rigid once-off end-products* to *transitory* building products of which the configuration is continuously evolving to match with functional, technological and aesthetic alterations in society. In order to establish this shift, the proposed re-design for change approach must incorporate the principles of open building systems, for example, according to the *Hendrickx-Vanwalleghem* (HV) approach.

The goal of the HV approach is to initiate a global, collaborative data bank of building elements that allows to design, build and exchange the broadest range of building components using standardised building elements, which results in a more transparent, flexible, but still varied built environment. According to this approach all dynamic building solutions must combine simple straightforward base elements dimensioned according a generating system - namely the **fractal grid -** using **reversible connection** techniques. The approach encloses guidelines to design multiple construction systems - all compatible to each other - by which a variety of adaptable and reusable construction elements can be composed (Figure 6.1). The Hendrickx-Vanwalleghem approach was therefore selected as a suitable design strategy in the framework of this dissertation to develop building products for dynamic re-design of residential buildings.

Figure 6.1: Developments of design catalogues of basic elements using a generating fractal model



6.1.2.3 SPEEDING UP THE RENOVATION PROCESS: PREASSEMBLY

The survey with different stakeholders discussed in Chapter 4 emphasised the importance of **construction speed** for renovation. Buildings are often wrapped in plastic and scaffolding for several months due to badly scheduled renovation planning or because of slow and labour-intensive renovation techniques. For the case of social housing speeding up the renovation process of apartments is crucial since inconvenience for residents that need temporary accommodation during the works is diminished and social housing societies receive the rent for the apartments earlier which reduces the bank loans.

Research of BRE (2001) pointed out that the construction process can be considerably speeded up when partially or entirely preassembled products are used - so-called *prefabricated* or *preassembled* building components[1]. Prefabrication and preassembly are often considered for their economic benefits concerning reduced labour costs together with increased productivity, which translates into schedule compression with minimal cost impact [BRE 2001]. Moreover, they also offer environmental and social benefits. The research held by BRE [BRE 2001] indicates benefits of using prefabricated and preassembled components that are crucial in the framework and scope of this research, namely:

1. *Economic: prefabrication/preassembly of components typically results in fewer defects and speeds up the assembly process;*
2. *Environmental: prefabrication/preassembly of components can be more energy efficient, and produce less waste on site;*
3. *Social: less inconvenience for local residents during (re)construction.*

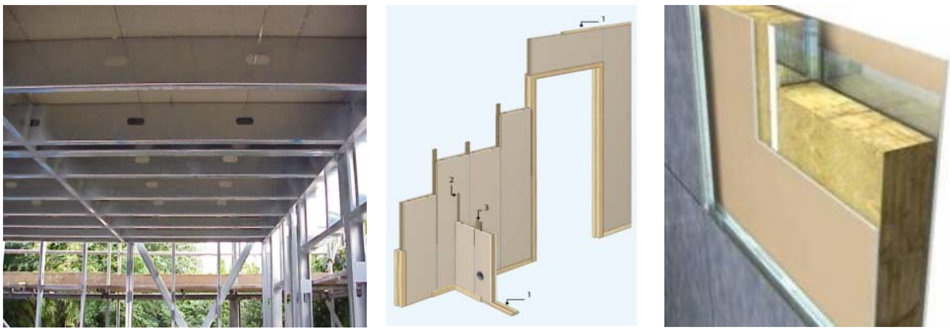
An important advantage deals with the fact that site work is traditionally vulnerable to disruption from extremes of weather. A benefit of using prefabrication/preassembly is that the site will be exposed for **shorter time** to inclement weather conditions and so the risk of delay and requirements for protection will be reduced for a given project. Prefabrication can reduce the on-site construction time by up to 50-60% and thus reduce labour costs [BRE 2001; Smith 2010]. In addition, preassembly offers opportunities of how to deal with problems arising from declining workmanship standards and skilled labour shortages on site. In factories the protected environments and usage of precise machinery make that the **quality of the finished product** is much easier to ensure than on site while factory workers do not need to be as trained as on-site construction workers. Finally, prefabrication and preassembly techniques are associated with **reduction in waste** compared to construction on site. This is a result of enhanced manufacturing processes in

[1] Prefabrication can be defined as "a manufacturing process generally taking place in a specialised facility, in which various materials are joined to form a component part of a final installation" [Tatum 1987]. Prefabrication of components often only involves the work of a single craft. On the contrary, in preassembly, work from a variety of crafts and components is typically necessary. A common used definition for preassembly is "a process by which various materials, prefabricated components, and/or equipment are joined together at a remote location for subsequent installation as a unit" [Tatum 1987]. Preassembly is generally considered to be a combination of prefabrication and modularisation: it makes use of prefabricated standardised components and it is assembled off site or near the construction site.

a controlled factory environment, enabling to reduce the material waste due to fewer inaccuracies and miscalculations in production[2].

Modern construction techniques typically include *prefabrication* of volumetric solutions and panelised solutions for new construction. Prefabricated floors, walls and facade elements are slowly becoming a steady part of the building market while three-dimensional prefabricated structures are erected much faster than labour-intensive on-site construction.

Figure 6.2: Examples of prefabricated building solutions

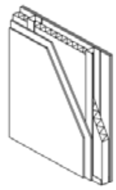
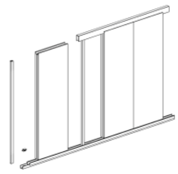


Source: Corus Source: Faay walls Source: Ruuki

Besides, more and more prefabricated building products which label themselves as *flexible* are taking over the construction market. Nevertheless, these solutions often miss their initial target due to the initial closed design as finished products. This is illustrated by two contemporary partitioning systems of which the properties are illustrated Table 6.2 namely prefabricated wall systems used for *residential* applications and flexible *office* walls.

[2] On-site construction has been estimated to waste about 40% of raw materials [Smith 2010].

Table 6.2: Characteristics of existing wall types in dry system construction

Wall properties of dry partitioning systems		Wall type: Dry wall 	Wall type: Prefabricated residential walls 	Wall type: Flexible office walls 
Building physics	*Thermal insulation*	+	+/-	+
	Acoustic insulation	+	-	+/-
	Fire resistance	+	-	+
	Resistance to moisture	+	-	+
Dynamic re-design	*Design for disassembly*	-	+	-
	Pre-assembly	-	+	+
	Layering	+	-	-
	Reuse	-	+	-
System properties	*Restricted weight*	+	+	+
	Flex. building services	-	+	+/-
	Tolerances	+	+	-
Appearance & Use	*Functional finishing*	+	-	+
	Aesthetic finishing	+	-	+

(-) poor performance; (+/-) average performance; (+) good performance.

Prefabricated residential partitioning systems enable a fast construction on site as a result of the clustering of the framework, insulation and boarding in one single modular element. For example, *Faay walls* consist of a structural core of flax with external plasterboards glued against this frame. However, the irreversible adhesive connection methods used between modules get in the way of any future adaptation or reuse of modules. The second type - prefabricated demountable partitions for offices - can be erected and repositioned with minimum effort, but nevertheless, the system flexibility is restricted to repositioning of (non-adaptable) modules. This flexible wall type scores poor in terms of sound insulation and fire safety since this type of heavily prefabricated modules results in weak jointing in terms of building physics [Tichelman 2007].

In summary, a crucial deficit in current prefabricated product design is the conception as **finished products**, gluing or pressing together all functional layers, resulting in a single-layered once-off product. Due to the strong product specificity and execution as a *mono-block* adaptations are constrained during the life cycle processes in buildings. Therefore, it is crucial to **combine** benefits of preassembly with these missing benefits offered by DfD strategies and reuse strategies. In order to achieve **dynamic preassembly**[3] sub layering of assemblies, reuse and standardisation must consequently be added.

DYNAMIC PREASSEMBLY OF BUILDING LAYERS

The survey in Chapter 3 pointed out that the desired construction speed of building systems used in renovation varies according to the considered building layer. In decreasing order of priority, the results signalised the following priorities for speeding up renovation for the following building layers, namely the *internal partitioning*, the *roof*, and finally the *facade* of buildings. A longer construction time for floors, ceilings, and partition walls was revealed to be acceptable for all questioned sub groups. In this chapter the preassembly options are incorporated in dynamic building design as an *additional design precondition* and are extensively developed for vertical partitioning and the facade solution.

6.1.2.4 PREDETERMINED DIMENSIONING SYSTEM VERSUS GENERATING SYSTEM

The context of existing buildings confronts designers with additional design challenges compared to new construction in which each design can start from scratch, without considering existing *dimensional grids* or dimensional *deviations* due to poor execution of construction works.

First, the existing building structure forms a physical set of dimensional preconditions for design and detailing of new internal and external fitting-out of buildings. The structural grid of post-war buildings is generally determined by the construction systems applied for the prefabrication of the load-bearing structure and/or facade units (e.g. Cauvet, Barets). For example, in cross wall structures the external grid is often visualised in the facade as the repetition of identical cross walls over the entire building length. Post-war skeleton structures on the contrary often applied asymmetric or mirrored horizontal grids for reasons of building stiffness making the external grid often less readable from the outside. A wide variety of dimensional systems can be perceived which makes it a difficult for current construction systems to match all dimensional variations.
Secondly, lack of experience with new construction system techniques in the early post-war construction period - an innovation at this time - in many cases led to deviations of the dimensional grid and to unevenness of structural elements. Therefore, re-design must incorporate an approach to deal with a **variety of dimensions** and construction **tolerances**.

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[3] Dynamic preassembly of buildings products is defined as the off-site preassembly of sub components combined with DfD principles. It is important to stress that the option for preassembly does not constrain for the alternative option of assembly of all sub components entirely on site if requested.

When conventional modular construction systems are used during renovation this results in high waste streams since the dimensioning of building components cannot easily be matched with the variation of scales and measurements that typically appear in existing building structures. Chapter 3 explained how open system approaches - including a **generating grid** - offer better perspectives to respond variable dimensioning systems. The generating fractal grid in the HV approach enables to set up varied design catalogues based on standardised basic elements which can be selected and customised for a specific application, while dimensions are standardised for a wider context of use. Consequently, the selection of dimensions for new components and sub components according to the generating fractal grid enables to make a better approximation of the original dimensional grid present in post-war buildings, which results in a minimisation of construction waste during renovation.

6.1.3 DFD PRINCIPLES VERSUS DRY CONSTRUCTION DESIGN

6.1.3.1 DRY CONSTRUCTION IN RENOVATION OF RESIDENTIAL BUILDINGS

The extensive use of **dry construction systems** in the renovation building sector is due to the many advantages of these systems, such as their short construction times, low weight, good economics, large availability and superiority in terms of building physics, sound insulation and fire protection compared to massive construction systems. Dry construction systems must comply with a wide set of functional, aesthetical, structural and other requirements in order to bring buildings in conformity with contemporary building standards. While detailing principles in dry construction in order to comply with current thermal, acoustic and fire protection standards are well-known, DfD design principles - which show many similarities with dry construction - are in general unheard.

Table 6.3 gives a general overview of required properties at component level for the new fitting-out of renovated post-war apartment buildings, including building physics, sound insulation, fire protection, 4D Design, system specifications and appearance. This table shows that building systems need to comply with a wide range of design boundaries. Today, as the Multi-Criteria Analysis (MCA) results indicated, building systems generally comply with all preconditions except for the design principles which ensure the reversibility of the assembly, and which enhance the reuse of sub components. In order to combine all design requirements, the DfD principles are added to the design of building systems in this chapter. The overall behaviour of building systems with dry connection detailing can be derived from the performance of dry construction systems.

Table 6.3: Required properties for building systems used for fitting-out in post-war building renovation

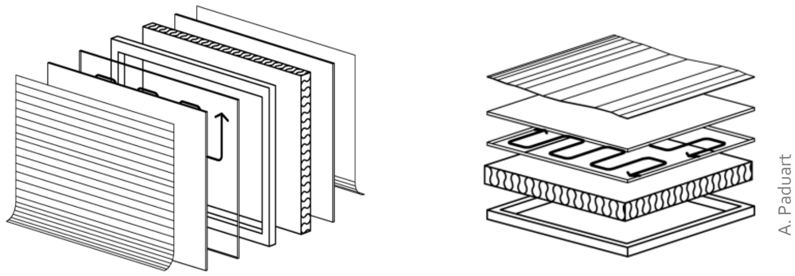
Properties		internal fitting-out			external fitting-out	
		walls	*floors*	*ceilings*	*facade*	*roof*
Building physics	*Thermal insulation*	+/-	+/-	+/-	+	+
	Resistance to moisture	+	+	+	+	+
Sound insulation	*Air tightness*	+	+	+	+	+
	Airborne sound resist.	+	+	+	+	+/-
	Impact sound insulation	+/-	+	+/-	+/-	+/-
Fire protection	*Fire resistance*	+	+	+	+	+
4D Design	*Design for Disassembly*	+	+	+	+	+
	Reuse of components	+	+	+	+	+
System properties	*Restrict. thickness/width*	+	+	+	+	+
	Restricted weight	+	+	+	+/-	+
	Integr. of technical services	+	+	+/-	-	-
	Preassembly	+	-	-	+	+/-
Appearance	*Aesthetic finishing*	+	+	-	+	-

(- = not relevant; +/- = of average relevance; + = highly relevant)

6.1.3.2 ANALOGY WITH DRY CONSTRUCTION SYSTEMS

Conventional dry construction makes use of *sub layering* to obtain comparable levels of performance - be it in terms of acoustics, thermal insulation or of fire resistance - as massive *heavyweight* building systems. In massive construction the overall performance is mainly defined by material properties of one single layer's material properties, e.g. the mass of masonry brickwork. In dry system on the contrary, each individual layer - e.g. boarding, insulation and framework - influences the overall performance. Consequently, the assembly techniques between each layer determine to a large extent which overall performance will be achieved [Hopkins 2007, Tichelmann 2007].

Figure 6.3: Layering of functions in construction systems



vertical assemblies **horizontal assemblies**

If we consider partitioning wall systems Table 6.4 shows the relevance of each layer - boarding, framework and insulation - relating to building physics, mechanical properties, ease of assembly and DfD design. The table illustrates that each individual layer is crucial for the overall wall characteristics.

Table 6.4: Relevance of boarding, framework and insulation layer in dry construction

Layer properties		boarding	framework	insulation
Building physics	*Fire protection*	+	+/-	+
	Moisture resistance	+	+/-	+
	Dimensional stability	+	+	-
	Diffusion permeability	+	+/-	+
	Thermal insulation	+/-	+/-	+
	Airborne sound insulation	+	+	+
	Impact sound insulation	+	+	+
Mechanical prop.	*Strength*	+	+	-
	Stiffness	+	+	+
	Surface hardness	+	-	-
Assembly	*Workability*	+	+	+
	Weight (transport& assembly)	+	+	+
	Handleable dimensions	+	+	+
DfD	*Dry connections*	+	+	+
	Material reuse	+	+	+

(-) not relevant; (+/-) of average relevance; (+) highly relevant.

The main difference between dynamic wall assemblies and conventional dry wall systems lies upon the **reversibility** of connections techniques and **material selection** of components which can - if appropriately selected - enhance component reuse. Together, these two aspects may form a crucial design barrier when dynamic building assemblies must comply with stringent building standards.

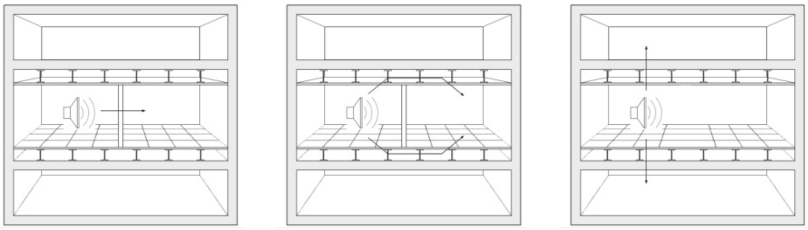
6.1.3.3 CHALLENGE FOR DFD DESIGN IN RESIDENTIAL CONTEXT

In residential buildings each *building layer* needs to comply with particular requirements, depending on its specific function. For instance, the main concern for wall partitioning beside its space-dividing function is *sound insulation* and *fire protection*. Dry construction systems are able to achieve stringent insulation levels and high fire resistance classes when appropriate materials are selected for the boarding, insulation and structural framework. In addition, vertical and horizontal joints between sub components are avoided - e.g. by rendering of walls - in order to reach high performance levels [Hopkins 2007, ASFP 2003].

This way of detailing does not match with the reversible detailing directly linked with dynamic design. The sealed and fixed enclosure of all joints, junctions and connections prohibits reuse of sub elements. Clearly, a compromise needs to be sought between the design principles which maximise component reuse and the detailing which enables to reach high performances which are requested in residential construction. Consequently, the thermal, sound and fire behaviour of dry construction systems are analysed to expose discrepancies between DfD design principles and conventional dry construction detailing. In the next paragraph, this is discussed for the example of wall partitioning in residential buildings.

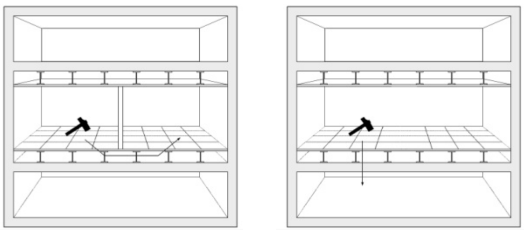
When considering interventions in post-war apartment buildings in order to enhance the sound performance we find that improvements are restricted due to limitations related to the building structure. Most of the encountered acoustic problems are directly linked with the building methods which were customary at the time of construction, the availability of materials and the sound control requirements valid at the time [Giebeler 2009].

Figure 6.4: Paths for airborne sound transmission



1a **b** **c**

Figure 6.5: Paths for impact sound transmission



A. Paduart

1a **b**

Given the construction techniques used in post-war multi-storey buildings it is normally found that the industrial techniques used gave rise to poor sound insulation according to acoustic standards of today. These buildings typically used lightweight reinforced concrete floor slabs (slab depth <14cm) combined with masonry or in-situ built concrete walls with *flanking sound transmission* through the concrete skeleton causing acoustic leaks. Dependent on the context of the building, it is not always an easy task to reach the required airborne sound and impact sound insulation levels.

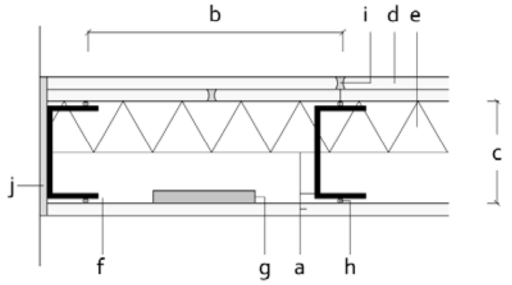
A simple strategy to reduce airborne sound transmission is to increase the *mass* of the building components [Kutruff 2006, Hopkins 2007]. The object is made as heavy as possible and thus given a high inertia that, due to the fact that it consists of a material with a high density, the airborne sound waves cause it to vibrate only to a limited extend.

In assemblies, this mass principle is replaced by using double-leaf assemblies with an insulated cavity in between - the so-called “mass-spring-mass” principle. This principle combines two leafs separated by a cavity and filled with air or a flexible material that acts as a spring in between. The sound attenuating properties of lightweight stud walls systems are superior to those of solid walls with a self-weight up to 10 times lower [Kutruff 2006, Hopkins 2007]. However, properties of individual components and their connections, quality of workmanship on site and constructional boundary conditions all may influence the final sound insulation characteristics. In this particular issue it is crucial that **rigid connections** are minimised to avoid sound bridges which reduce the desired sound improvement [Kutruff 2006, Hopkins 2007]. Table 6.5 and Figure 6.6 show the factors that influence the sound insulation of lightweight dry systems representing both horizontal and vertical sections.

Table 6.5: Factors influencing the sound insulation of dry systems: mass-spring-mass principle (adapted from [Tichelmann 2007])

System component	Physical influencing factor	Positive effect on sound insulation
Boarding	*Mass per unit area*	- High density of boarding material - Number of layers - Adding ballast to the boarding
	Rigidity	- Limiting boarding thickness - Boarding material with low rigidity
	Air tightness	- Ensuring adequate air tightness at joints
Framework	*Decoupling of the leaves*	- Large cavity width - Large stud spacing - Decoupled supporting framework - Acousticly optimised profiles -Metal studs exhibit better acoustic properties than wooden studs;
Connections	*Decoupling of the leaves*	- Intermediate elements (e.g. transverse battens, insulating strips, resilient elements) - Non rigid fixing of boarding (e.g. spacing, type of fixing) -Minimise direct fixing of boarding, via intermediary elements, or spring elements
Insulation	*Sound absorption*	- 80% of the voids filled -Acoustic properties of insulating material (e.g. sound impedance)

Figure 6.6: System components that influence the acoustic behaviour of dry systems [Tichelmann 2007]



a material type
b space between studs
c space between leaves
d number of layers and thickness
e thickness insulation
f type of framework
g additional weight
h connections
i,j joints

Subsequently, design of *dynamic building assemblies* for residential buildings can be restricted by specifications for high sound insulation levels regarding the boarding, framework and the connection techniques.
First, the required finishing of boarding to ensure that air leakages and open joints are minimised may form an important barrier for DfD and reuse strategies. Secondly, the section correspondent to the framework and the boarding needs to be sufficiently resistant to ensure possible reuse after deconstruction. In contrast, the problem remains that in order to maximise the acoustic performance of assemblies rigid components are normally avoided. Table 6.6 summarises the discrepancies between priorities in a DfD approach and dry construction measures to improve sound insulation.

Table 6.6: Conflicts between dry construction measures enhancing sound insulation and DfD principles

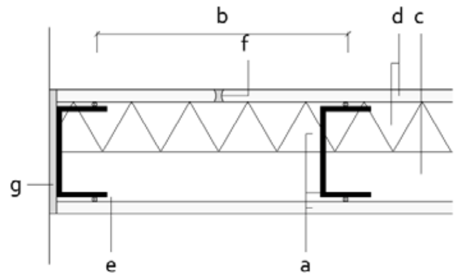
DfD properties			Acoustic performance
framework	resistant framework for reuse	↔	resilient framework (spring)
boarding	resistant boarding for reuse	↔	resilient boarding (mass)
connections	reversible dry connections	↔	avoid rigid connections
	reversible joints	↔	avoid air leaks

FIRE PROTECTION

Similar design conflicts arise from fire safety requirements at component level. The fire protection of partitioning systems is dependent on several system properties: the facing boards (material, thickness and number of layers), the framework material, insulation materials in the void and also presence of horizontal and vertical joints [ASFP 2003].

The selection of an appropriate boarding material and use of mineral insulation materials is a first crucial factor to improve the fire resistance. Boarding materials that eventually enable reuse do not necessarily correspond to the materials with the best fire resistance characteristics. Figure 6.8 therefore shows the fire resistance of boarding depending on the thickness and the material of the boarding itself. Literature points out that reusable wood-based boards show to have inferior fire resistance compared to gypsum based boards or calcium silicate boards which for their part have inferior reuse potential.

Figure 6.7: System components that influence the fire resistance of dry construction systems



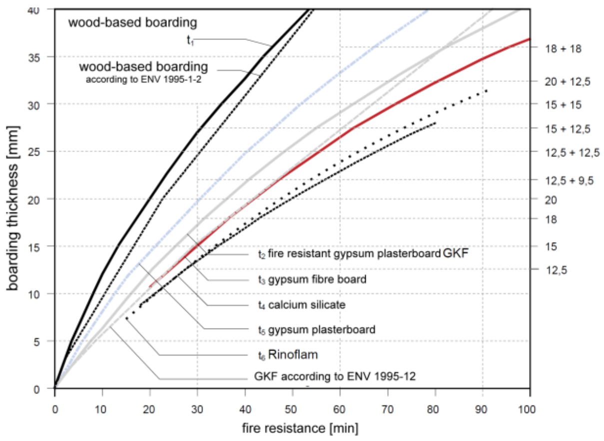
a material type
b space between studs
c air layer
d thickness layers
e type of framework
f,g joints

Table 6.7: Factors influencing the fire resistance of dry systems

System component	Physical influencing factor	Positive effect on fire resistance
Boarding	*Mass per unit area* *Combustibility*	- High density of boarding material - Non-combustible materials - Able to maintain integrity and stability
Framework	*Integrity*	- Limit loss of strength - Limit movement and expansion (e.g. wood expands less than steel keeping the framework more in place)
Connections	*Air tightness* *Thermal inertia*	- Use fixings that prohibit the development of gaps - include a thermal break, or timber or plaster inserts to increase the thermal inertia
Insulation material	*Melting point* *Mass per unit area* *Combustibility*	- High melting point of materials (e.g. rock wool) - High density of insulation material - Non-combustible materials

Secondly, the connection of dry boarding is vital: connections must avoid development of gaps between the boarding - although deflection, expansion, contraction or change in material properties will tend to promote cracking [ASFP 2003]. Once gaps start to occur integrity failure is imminent because the positive pressure on the fire side will force hot gases through the partition gaps. Furthermore, the head and base track of wall partitioning have to be carefully designed, including a thermal break or local increase of the thermal inertia. Similarly, where there are large gaps between the joints in the boards problems can be created associated with heat transfer through the partition can occur which could lead to a loss of insulation and ultimately of the integrity [ASFP 2003].

Figure 6.8: Fire resistance of boarding materials



Source:[BMS 2004]

High fire safety requirements can thus only be matched with dynamic dry construction systems if the selected facing boards are non-combustible, and horizontal and vertical gaps are eliminated. Again, this means that restrictions are set up for dynamic design and that a compromise is needed between regulatory design and design for deconstruction principles.

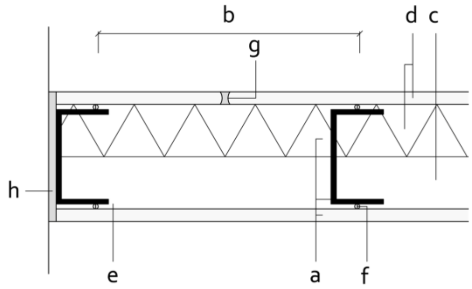
Table 6.8: Conflicts between fire protection measures and DfD properties in partitioning

	DfD properties		Fire resistance measures
boarding	Resistant boarding for reuse	↔	Fire resistant boarding material
connections	Reversible connections	↔	Avoid horizontal & vertical gaps and air leaks

THERMAL INSULATION & INTERIOR CLIMATE

Thermal insulation is to a large extent dependant on the thermal conductivity and the thickness of the materials and presence of thermal bridging, and has been indicated to be a secondary concern in dry wall partitioning since the requirements are easy to reach with the insulation present for acoustic purposes [Tichelman 2007, EPB 2010]. In addition, a good air and wind tightness of the roof and the building facade has a positive influence on the interior climate and on the energy consumption of buildings. Consequently, the factors that influence the thermal performance of building systems are summarised in Table 6.9.

Figure 6.9: System components that influence the thermal insulation of dry systems



a	material type
b	space between studs
c	air layer
d	thickness
e	type of framework
f	connections
g, h	joints

Table 6.9: Factors influencing the thermal insulation of dry systems

System component	Physical influencing factor	Positive effect on thermal insulation
Boarding	*Heat transfer* *Air tightness*	-Low thermal conductivity of boarding material - Increased thickness of the boarding - Adequate air tightness at joints
Framework	*Thermal bridging* *Heat transfer*	-Decoupled supporting framework - Large stud spacing - Thermally optimised profiles - Materialisation of studs with low thermal conductivity
Connections	*Thermal bridging*	- Decoupled fixings - Minimise number of connections - Fixings with thermal breaks
Insulation material	*Heat transfer*	- Low thermal conductivity of boarding material - Increased thickness of insulation layer

As a result, the problems that may occur when a DfD approach is applied for building layers with a thermal function are represented in Table 6.10.

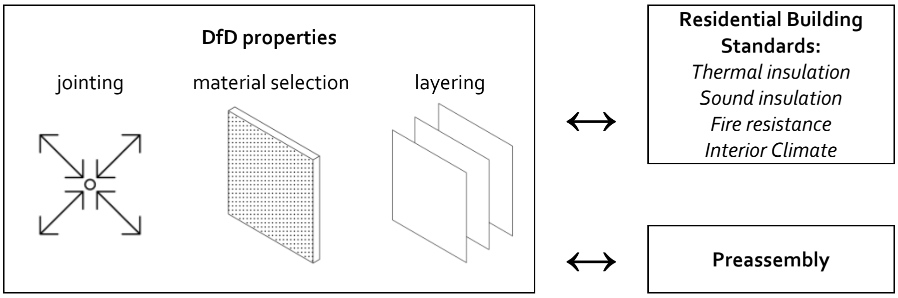
Table 6.10: Conflicts between thermal insulation measures and DfD properties in dry systems

	DfD properties		Thermal performance
framework	durable framework for reuse	↔	low thermal conductivity of framework
connections	reversible dry connections	↔	avoid thermal bridging
	reversible jointing	↔	avoid air leaks

In summary, important discrepansies are revealed between DfD principles and general detailing practise in order to enhance the sound, thermal and fire resistance properties.

As represented in Figure 6.10 physical separation of reusable layers using *reversible connection techniques* are crucial principles to intervene in sub layers without using destructive methods and ensure adaptability.

Figure 6.10: Preconditions for the design of DfD assemblies



These reversible connection techniques may be incompatible with design principles of common building practice. This chapter therefore aims to shed light over this complex issue, thereby discussing contradictions between DfD principles and thermal, acoustic and fire safety requirements and dynamic detailing to deal with this issue. Challenges in the materialisation of sub layers in DfD assemblies will be explored, balancing design for change against compulsory criteria in residential buildings.

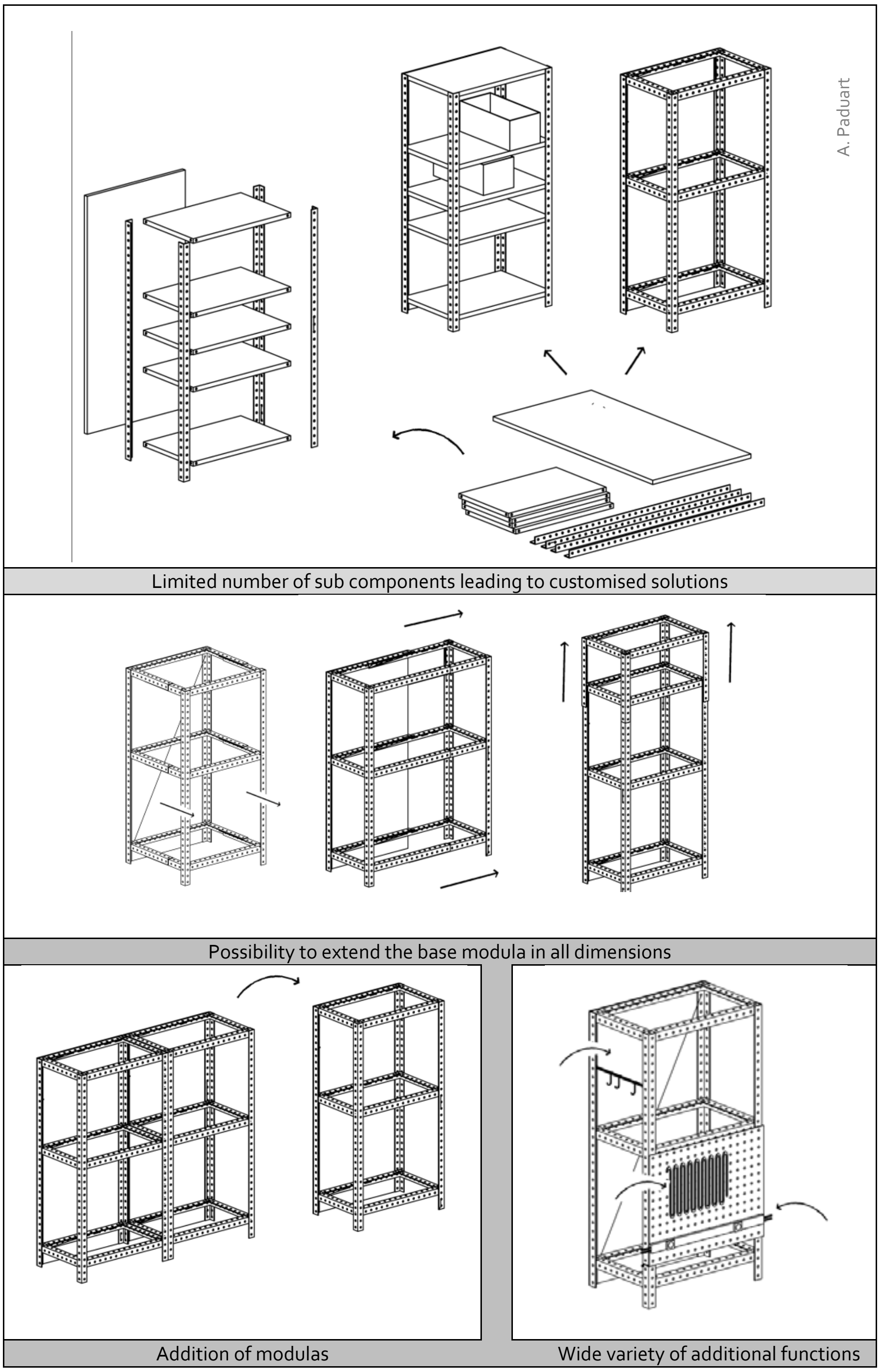
6.2 DYNAMIC DESIGN OF VERTICAL PARTITIONING

6.2.1 DESIGN CONCEPT

If we take a closer look the manner of composing wall assemblies has a lot in common with the use of industrial shelving systems. Both make principally use of structural members forming the support to add supplementary functions while the infill of this framework can be customised and adapted according to specifications depending on the context of use. These similarities led to the conceptual starting point for the design of dynamic partitioning from the design of shelving systems. Industrialised modular shelf systems are widely available systems which allow simplicity for adaption in order to solve any storage need in housing, warehouses, offices or retail establishments. These systems enable accurate and fast assembly of a wide range of components using simple and standardised connections techniques ensuring that people without specialised skills are able to constitute their own personalised shelving. The physical properties result from the combined action of all individual members. Depending on the specification functional layers can be added such as storage functions for shelving systems, whereas for walls additional functions can relate features to enhance thermal, acoustic, functional and technical properties. For instance, the boarding type can be selected to comply with sound insulation, fire protection of thermal insulation standards while the voids between the members of the supporting framework can be filled with insulation or technical appliances can be incorporated. Similar to a piece of furniture walls may need to be relocated in order to give customised answers to increasing individuality, altering of residents with characteristic spatial needs, or adapted use of the space.

Therefore, in this chapter the design proposal of dynamic wall partitioning aims to conceive multi-layered and multi-functional, customised but ever transformable vertical assemblies. The internal fitting-out of buildings designed as dynamic assemblies which are composed by a number of linear and planar base elements introduces more variety within modularity like in a Meccano® kit-of-part system. Like in these timeless 'toys' base elements can be combined to transitory building components which can be adjusted/updated/upgraded in case of altering needs, repositioned to create new plan lay-outs and of which the composing elements can be reused for similar or alternative applications if needed (Figure 6.11).

Figure 6.11: Design concept of dynamic assemblies based on flexible storage systems



6.2.2 PREASSEMBLY PRECONDITIONS

To determine relevant preconditions of preassembly for *wall partitioning*[4] meetings were organised with a company representative specialised in flexible office walls commercialised over Europe. These meetings - including interviews about product specifications of flexible wall categories, surveys about (dis)assembly of flexible wall products and visits to the building yard during adjustments of office spaces - enabled to gain more insights about obstacles related to design of preassembled wall units. Relevant additional design preconditions for preassembly of wall partitioning were determined:

1. *Assembly and finishing on site by 1 or 2 persons;*
2. *Maximum panel weight up to 40-50kg;*
3. *Use of simple connection techniques* [5]*;*
4. *Use of dimensional tolerances to enable vertical assembly;*
5. *Use of technical panel to deal with horizontal tolerances.*

6.2.3 SELECTION OF GENERATING SYSTEM

An important issue when applying a generating system is the selection of the fractal grid and its dimensions. Once this grid has been selected all base elements can be generated according to the same dimensioning rules which will enhance the overall compatibility. In Chapter 3 it was discussed that the **fractal grid** of Hendrickx-Vanwalleghem approach offers the advantage that geometrical properties of all basic element are standardised and can be interchanged [Debacker 2009]. The use of these basic elements allows the conversion of each building component to a different configuration, by means of adding, removing or transforming the basic elements it is made of. This means that when we consider recycling and direct or indirect reuse of one given artefact, one finds that they enclose a extremely high potential for these purposes.
In this chapter consequently, each point, linear or planar element together with the connection points applies the same standardisation based on this fractal grid in order to stimulate interchangeable parts while offering a wide range of building solutions.

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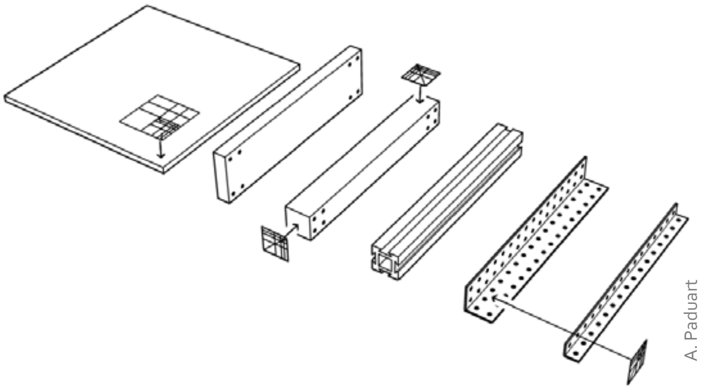
[4] For the facade layer, the preconditions for preassembly will be further discussed during the design proposal of the facade.
[5] Interestingly, connection techniques were identified crucial to speed up assembly and to ensure quality of execution: labour workers preferred simple, well-known, standardised and accessible connection techniques over high-tech connections associated with increased complexity of the assembly requiring more skills and thus more training.

Figure 6.12: Use of a generating system for the form and dimensioning of compatible building sub components

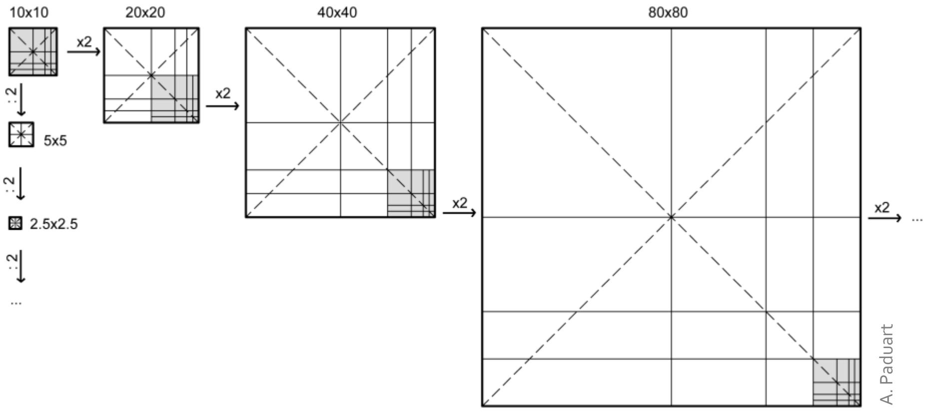


Next, the selection of the *basic dimensional unit* is a crucial aspect of design of compatible and building systems with interchangeable parts [Henrotay 2008, Debacker 2009]. In the most ideal scenario a consensus would already exist between manufacturers of building materials about the overall standardisation of form and dimensioning of building elements. In this case design of building elements could simply apply a globally accepted dimensioning system ensuring the compatibility with existing building products. Unfortunately, and for several reasons, most fabricants of building materials produce diverse incompatible dimensioning systems.

In this research, the *metric* dimensioning system was selected based on the use of metrical units in Belgian building practice and surrounding EU countries. The metric dimensioning system is decimal-based, and therefore simple and fast to use, compared to the imperial units (using feet and inch). Multiplying, for instance, 29 feet and 8-5/8 inches by 37 feet and 6-7/16 inches, to obtain a surface area, is a good demonstration of the complexity of the imperial system. The Canadian Construction Association reported that when commercial construction in Canada switched to the metric system several years ago this resulted in direct benefits: design costs reduced, efficiency in construction operations increased, and material and component dimensioning techniques improved [PBS 1995].

Subsequently, the next step to select an appropriate dimensional generating grid consists in choosing a base unit. The base unit is selected with the objective to generate dimensions that closely match with existing dimensions used in current building practice. As a base unit for the generating grid, the unit of ***10x10 mm*** is chosen in this research, since analysis of existing building products shows to have multiple similarities with this base unit. The dimension series resulting from duplication are the following: 10mm, 20mm, 40mm, 160mm, etc. The dimensions series resulting from halving then become 10mm, 5mm, 2.5mm, 1.25mm, etc.

Figure 6.13: Generating grid of 10x10 mm



As an example, Table 6.11 shows the similarities between dimensions of buildings used in current dry wall applications and the proposed generating grid based on *10 x 10mm*.

Table 6.11: Similarities between generating grid based on 10x10 mm and dimensioning of existing building products

Generating grid					
… - 1.25 mm – 2.5 mm – 5 mm **– 10 mm –** 20mm – 40 mm – 80 mm – 160 mm - …					
Dry walls with metal studs					
metal stud section (width)			**boarding - gypsum plasterboard (thickness)**		
40 mm =	40	mm	12.5 mm =	(10 + 2.5)	mm
45 mm =	(40 + 5)	mm	15 mm =	(10 + 5)	mm
50 mm =	(40 + 10)	mm			
70 mm =	(40 + 20 + 10)	mm	**insulation layer**		
75 mm =	(40 + 20 + 10 + 5)	mm	30 mm =	(20 + 10)	mm
100 mm =	(80 + 20)	mm	40 mm =	40	mm
125 mm =	(80 +40 + 5)	mm	60 mm =	(40 + 20)	mm
Brick walls					
clay bricks			**cellular concrete blocks**		
90 mm =	(80 + 10)	mm	70 mm =	(40 + 20 + 10)	mm
140 mm =	(80 + 40 + 20)	mm	100 mm =	(80 + 20)	mm
190 mm =	(160 + 20 + 10)	mm	150 mm =	(80 + 40 + 20 + 10)	mm

Design catalogues based on this generating grid can now be set up for base elements that compose the wall assemblies.

6.2.4 DESIGN CATALOGUES

First, material characteristics need to be analysed in order to determine suitable materialisation of each sub layer featuring in wall assemblies based on structural, acoustic, thermal and other material properties. The material characteristics determine the ability to process or shape certain materials into element forms [Debacker 2009]. The section shapes of, for instance, structural members in dry partitioning materialised in steel or solid wood differ to a great extent due to different material manufacturing processes. Then, once suitable building materials are selected according to each physical layer, the morphology of the basic elements can be determined according to geometrical standardisation rules of the HV design approach in order to develop design catalogues for the selection of solutions according to required properties. The material selection and dimensioning are illustrated in the next paragraphs, for dynamic design of walls. Thereafter, selection of elements from the developed design catalogues illustrates how wall design can deal with the contradictions between dynamic design and a selected performance according to building physics standards.

6.2.4.1 STRUCTURAL FRAMEWORK

For reasons of stability planar boarding elements – like gypsum plasterboards – require a stiffening supporting framework. Based on literature on dry construction systems [Tichelmann 2007] the selection of materials for the structural framework of dry systems is limited in this study to *steel, wood* and *aluminium*. Each of these materials enables reuse to a certain extent. Steel and wooden members are the most frequently applied materials in dry wall partitioning whereas in demountable partitioning aluminium is also frequently applied. Table 6.12 shows properties of these materials for dry construction systems.

Table 6.12: Characteristics of materials for structural application for framework for dry construction

			Structural material	
		Galvanised steel	Solid softwood	Aluminium
Properties[6]	ρ (kg/m³)	7800	500	2700
	E (GPa]	200	10	70
	σ_t (MPa)	400	2,1[7]	470
	σ_c (MPa)	400	26[8]	470
	λ (W/m²K)	45	0,15	203
Applications	Thermal	-	+	-
	Acoustic	+	-	+/-
	Fire	+	+	-
	Reuse	+	+/-	+

(-) generally unsuitable ; (+/-) suitable application ; (+) very suitable;

[6] With (ρ) density; (E) Young's modulus; (σt) ultimate tensile strength; (σc) ultimate compression strength; ; (λ) thermal conductivity.
[7] Perpendicular on fiber direction.
[8] Parallel on fiber direction.

Steel, wood and aluminium are materials with diverging material characteristics. Upon selection of the materials used for the structural framework one has to consider concurrently the assembly techniques, the reuse potential, but also the eventual sound insulation, fire resistance and thermal performance.

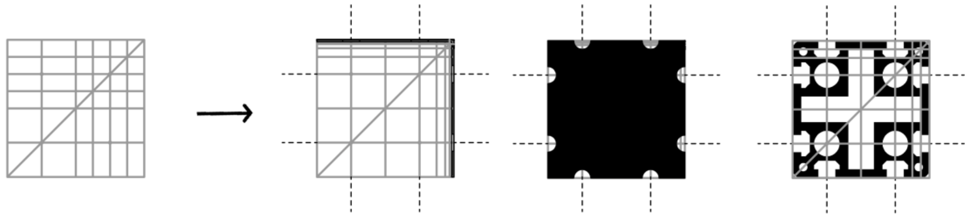
Solid timber is frequently used in dry system constructions for its wide availability, ease of processing and reasonably pricing. However, wooden members may not be desirable when abundant moisture is present in residential buildings [Tichelman 2007]. In addition, use of wooden battens in dry walls may result in significant acoustic leaks making them non-appropriate for wall partitioning. The potential of wood for reuse strongly depends on the connection techniques and the deformation of wood during occupation of buildings. The properties of wood together with the relatively small sections used in dry walls make wooden components more vulnerable for actions during transport, use and after dismantling, and therefore less suitable for design for multiple reuse.

Steel and aluminium profiles can be connected with highly reversible connections, whereas solid wood needs additional interventions to make bolt connections possible. This makes steel and aluminium more desirable for component reuse. An interview with a sales representative of movable office wall partitioning argued that although partitioning based on aluminium sub frames may be the most economically viable one, the reuse potential is significantly lower than when using a steel framework. The reuse of aluminium components after demounting strongly depends on the skills of the labour workers: if components have been deformed due to reckless dismantling, the components fail for a next use. Consequently, steel sections show to be most appropriate for assemblies with a high need turnover rate as (internal) wall assemblies. In addition, use of *reversible connections* is *crucial* to maximise the opportunities of adaptation of building systems with reuse of compatible standardised elements.

It is preferable to work with base elements which have a *simple form and straight-forward design*, instead of complex base elements which are only applicable in a limited number of building solutions. The more symmetric and non-specific the building elements, the wider the future use application field [Debacker 2009]. Designers tend to ignore temporal aspects of building products they design. Instead, they fixate on the aesthetic aspect and functional performance in pursuit of a static object of perfection, freezing out the time parameter [Schmidt 2010].
As an example, the generating grid is applied for the section shape of steel, wood and aluminium as structural members taking into account their materialistic characteristics for processing. Steel sections are typically processed in thin L- or U-cross sections but cold-worked techniques such as bending and rolling of steel coils or sheets offer many more profiling possibilities [BWS 2007]. Solid wood is principally used in its monolithic form, whereas aluminium offers a high degree of form freedom because of the extrusion process. Figure 6.14 shows some example of sections with geometrical form and

dimensions according to the selected generating grid. Sub components dimensioned according to the same generating grid can be interchanged in similar applications.

Figure 6.14: Sections of structural members for dry wall construction using the generating grid for materialisation in steel, wood and aluminium



An important remark must be made when designing sub components for multiple reuse: selected sub components do not necessarily correspond to the most optimised design for the application in which they feature. For instance, the majority of dry construction systems - i.e. studs walls, independent wall linings, suspended ceilings - use *metal* sections as a supporting framework for the boarding elements. The standards thickness of these thin-wall sections is between 0.6 mm and 1.0 mm. Reduced thickness of the flanges can be selected since it is the *combination* of boarding and studs that provides the rigidity of the partitioning. Steel profiles with such thin sections are optimised for assembly and use, but are not suitable for reuse after deconstruction. When preassembly and reuse are integrated in dry wall design, sections for the structural framework are selected to meet higher structural requirement than needed in conventional dry walls.

6.2.4.2 BOARDING LAYER

The boarding sub layer is crucial in dry construction systems since it strongly influences the interior space of buildings, is a vital element for the bracing and plays an significant role in the mass-spring-mass acoustic principle in lightweight constructions. The external boarding materials have a direct effect on the interior space meaning that they are also directly influenced by the room conditions (moisture in humid rooms, mechanical loads, exposure to fire, etc.). Therefore, Table 6.13 gives an overview of available boarding materials and their suitability for residential applications while considering their potential for reuse. Design catalogues for sub components of boarding in dry construction are shown in Figure 6.16.

Figure 6.15: Design catalogues of the sections of sub components for the structural framework of dry assemblies using the generating grid

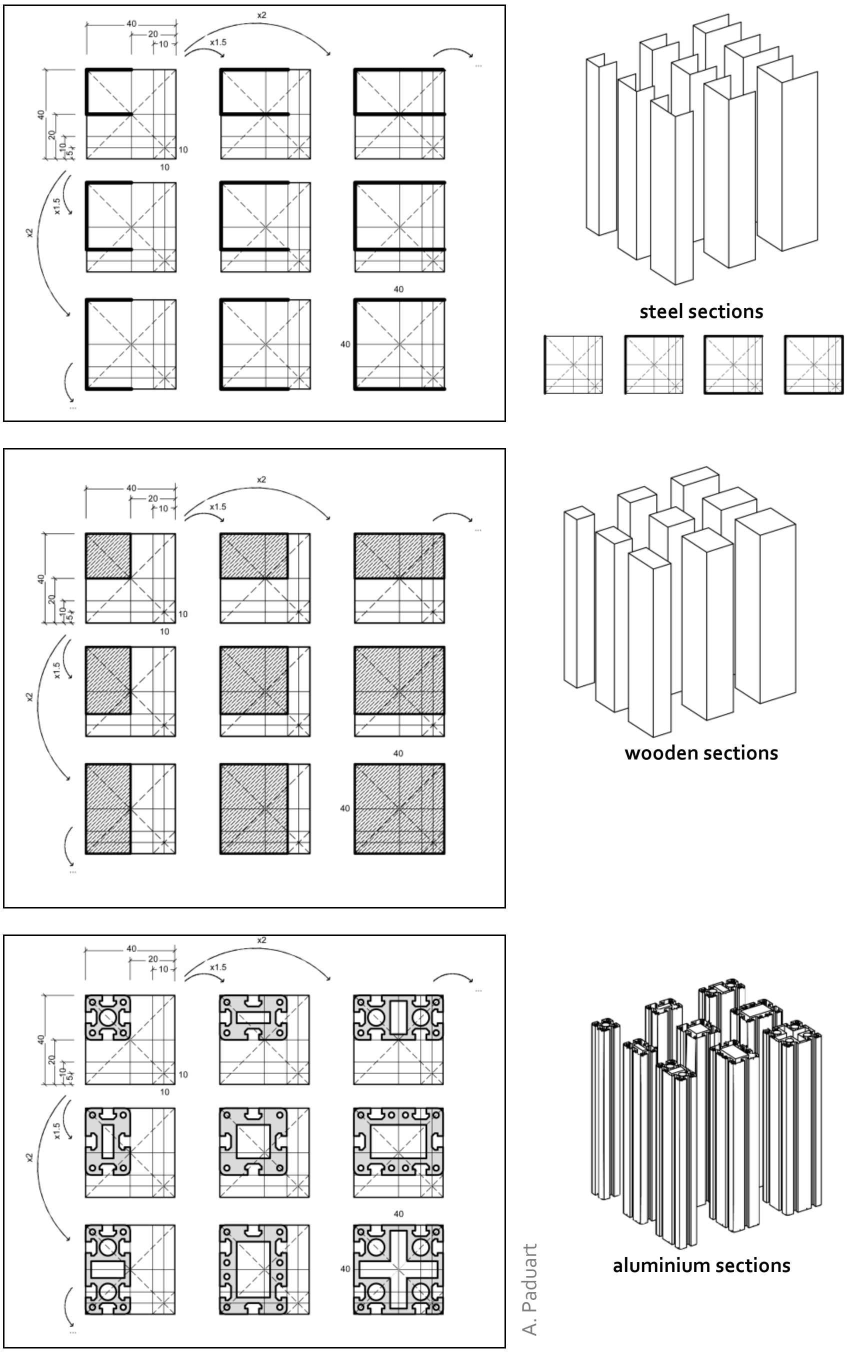


Table 6.13 explains why gypsum based boards are so frequently used in dry walls, namely for their good characteristics for sound insulation and fire resistance in case neither reuse neither structural requirements are needed. In addition, gypsum based boards are widely available, cheap and easy to work with during assembly. However, when interventions are required gypsum plasterboards will cause integral removal and replacement of boarding due to the limited material resistance for reuse. Gypsum fibreboards create more perspectives in this matter: these boards combine good characteristics for fire safety and acoustic sound insulation while higher rigidity and surface resistance make it more appropriate for structural applications and eventually reuse.
Wooden based boards, such as OSB, particle board and MDF show to have good structural characteristics and can be reused if attention is given to reversible connection methods and the use conditions. However, due to their higher price, their combustibility, sensitivity for moisture and more labour-intensive assembly than gypsum boards they are not common for facing boards in conventional dry construction. This leads to a first conclusion that the selection of boarding materials is a sensitive aspect when designing for change while complying with the current building standards. With building materials for boarding available today a compromise needs to be made between the degree of adaptability and stringent requirements of building physics.

6.2.4.3 INSULATION LAYER

The primary objective of insulation materials in dry construction is to improve the sound insulation and the fire resistance [Tichelmann 2007]. The thermal properties of insulation materials are only crucial for applications in external walls, ground floors or roof applications. Table 6.14 gives an overview of thermal, acoustic and fire properties of insulation materials suitable for dry construction together with their reuse potential.

Open cell insulation materials are suitable for sound insulation application since they have a high sound absorption coefficient and sound impedance [Tichelmann 2007]. These requirements are satisfied by all customary fibrous insulating materials (mineral wools and organic fibrous materials). Ti improve the impact sound insulation materials must have a low dynamic stiffness in order to absorb the impact energy from the subfloor to the underlying structural floor. Mineral wools (glass wool, rock wool) combine these characteristics, together with a low thermal conductivity and good fire resistance. In addition, compared to other insulation materials mineral wools have a high potential for reuse. Design catalogues for the sub components of the insulation layer in dry construction are shown in Figure 6.16.

Table 6.13: Characteristics of boarding materials for application in dry construction (adapted from [Tichelman 2007])

Boarding material	Properties			Applications							
	ρ [kg/m³]	Fire class.[9]	λ [W/m²K]	*n°*	*Fire protec.*	*Sound insul.*	*Room acoustics*	*Humid condit.*	*Dry subfloor*	*Struct. applic.*	*Reuse*
Gypsum bonded boards											
Gypsum plasterboard (GKB)	680-750	A2- s1, do		++	+/-	+	- -	+/-	+/-	+/-	--
Gypsum fire-resistant board (GKF)	800-950	A1	0,25	++	+	+	- -	+/-	+/-	+/-	--
Gyps. sound insulation board	800-900	A2- s1, do		++	+	++	- -	+/-	+/-	+/-	--
Gypsum fibreboard	950-1250	A2- s1, do	0,2-0,38	++	+	++	- -	+/-	+	++	+
Highly compressed gypsum fibre bd.	1350-1500	A2- s1, do	0,44	+	+	++	- -	+/-	++	++	+
Gypsum special fire-resistant board	800-900	A1	/	++	++	+	- -	+/-	+/-	-	-
Mineral bounded boards											
Calcium silicate board	450-900	A1	0,01-0,3	+	++	+	- -	+	+/-	-	-
Cement-bonded mineral board	1000-1150	A1	0,17-0,4	+	+/-	+/-	- -	++	++	-	-
Wood based board products											
MDF (dry process fibreboard)	750	D-s2,do	0,23	++	- -	+/-	- -	+/-	+/-	+	+
OSB (oriented strand board)	680	D-s2,do	0,17	++	- -	+/-	- -	+/-	++	++	++
Particle board (chipboard)	600	D-s2,do	0,18	++	- -	+/-	- -	+/-	++	+	+
Multiplex (whitewood)	450	D-s2,do	0,15	++	- -	+/-	- -	+/-	+/-	+	+
Hardboard	900	D-s2,do	0,29	++	- -	+/-	- -	+/-	+/-	+	+

(--) absolutely unsuitable ; (-) generally unsuitable ; (+/-) suitable, atypical application ; (+) very suitable; (++) ideal, specific application.

[9] According to EN 13501-1.

Figure 6.16: Design catalogues for the thickness of the boarding and insulation layer of dry assemblies using the generating grid

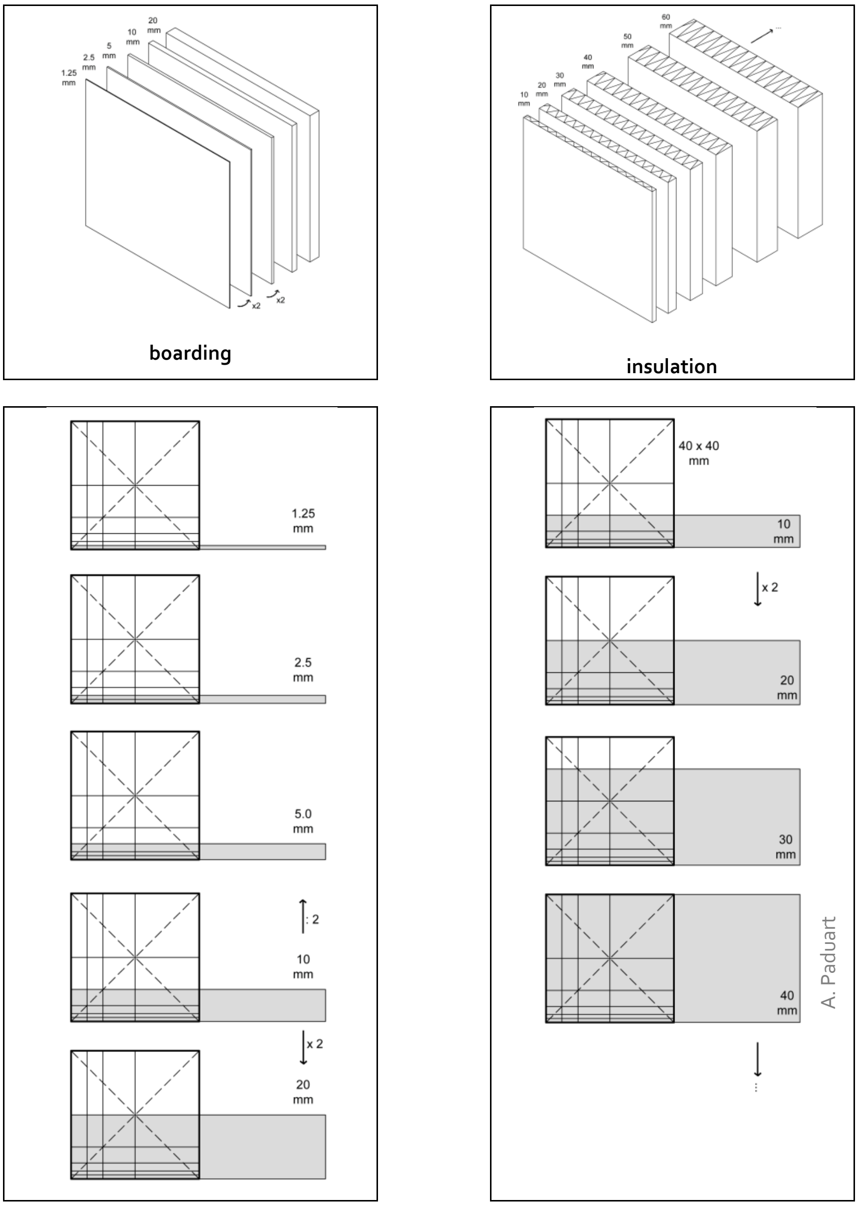


Table 6.14: Characteristics of insulation materials for application in dry construction adapted from (adapted from [Tichelman 2007])

Insulation material	Properties			Applications					
	ρ [kg/m³]	Fire Class.	λ [W/m²K]	*Fire protection*	*Sound insulation*	*Room acoustics*	*Impact sound*	*Thermal insulation*	*Reuse*
Based on mineral resources									
Glass wool	30	A1	0,035	+	++	++	++	+	++
Rock wool	50	A1	0,035	++	++	++	++	+	++
Cellular glass (CG)	110	A1	0,04	+	-	- -	- -	+	+/-
Expanded perlite (EPB)	135	C-s1, do, F	0,05	++	+/-	+/-	+	-	+/-
Perlite, vermiculite, expanded clay	100	/	0,05-0,09	++	+/-	+/-	+	-	+/-
Based on petrochemical resources									
Polystyrene, expanded (EPS)	15	E-F	0,04	- -	- -	- -	+	++	+
Polystyrene foam, extruded (XPS)	30	E	0,033	- -	- -	- -	- -	++	+
Polyurethane rigid foam (PUR)	33	E-F	0,025	- -	- -	- -	- -	++	+
Phenolic foam (PF)	41	C-s1/ C-s2, do	0,04	- -	- -	- -	- -	+	+
Based on renewable resources									
Wood fibres (WF)	45-100	/	0,045	+/-	++	+	++	+	+/-
Cellulose fibres	65	E	0,045	+/-	++	+	+/-	+	+/-
Cotton, sheep's wool, hemp	30-35	/	0.04	+/-	++	+	+/-	+	+/-
Insulation cork board (ICB)	110	/	0,04	+/-	- -	- -	+/-	+	+

(--) absolutely unsuitable ; (-) generally unsuitable ; (+/-) suitable, atypical application ; (+) very suitable; (++) ideal application.

6.2.5 TWO SCENARIOS: INTERNAL AND PARTITION WALLS

Depending on the required level of thermal and acoustic performances the configuration and materialisation of the structural steel frame and its added functions can be selected from a set of design catalogues based on the HV strategy, each one based on combinations of selected parametric rules. Hence, wall partitioning can be tailored to the demands of the designer like in a Meccano® kit-of-parts system. Two principal scenarios were set up for the design of dynamic preassembled partitioning each characterised by the degree of adaptability/reuse, thermal and sound insulation, and fire resistance.

Walls with a **high turnover**, i.e. the internal wall partitioning, correspond to walls for which no stringent requirements are established in building standards. Design of walls according this **scenario A** therefore includes a higher degree of freedom for the detailing and the material selection. **Scenario B** represents walls with a **lower turnover**, i.e. residential partition walls, separating different living units. In this scenario a compromise is required to harmonise both dynamic design and regulatory design for wall assemblies according to this scenario.The conception of the framework like storage shelving allows the application of alternative boarding, variable dimensions, or modification of material layers (e.g. insulation, boarding), each with particular thermal and acoustic behavior, fire resistance, environmental impacts and financial costs. The two scenarios are detailed and analysed in order to match the physical and functional criteria set up by current building standards and dynamic design. These walls are designed as preassembled panelised solutions which can be handled by one or two persons.

6.2.5.1 SCENARIO A: INTERNAL WALLS

The objective of scenario A is to provide highly transformable internal wall partitioning, enhanced by the use of reversible connections and selection of reusable sub components.
Figure 6.17 shows the selection of sub components from design catalogues and the reversible connection techniques. The reusable steel sections - multifunctional L-sections which enable a wide range of applications - are comparable with the frame used for industrial storage systems as illustrated in §6.2.1. The preassembled unit is composed of a structural framework - decoupled using two L-sections of 40x40 mm - including insulation, against which enclosing rigid OSB boarding is mounted. All connections are reversible to ensure disconnection of all basic elements in order to enable any transformation and stimulate component reuse. This also means that the sub components can still be assembled to wall assemblies integrally on site if needed.

Figure 6.17: Selection of sub components from design catalogues for scenario A

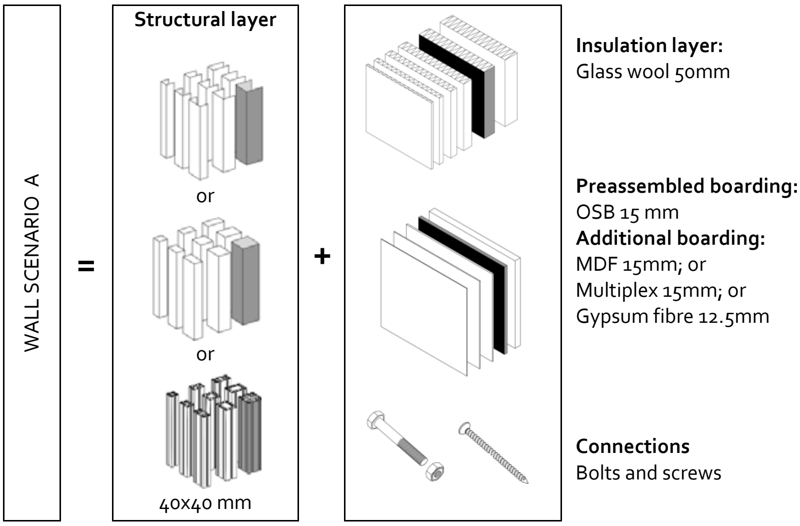


Figure 6.18 shows the assembly steps on site of two partially preassembled units for scenario A connected and finished on site. First, two preassembled base panels are interconnected by adding additional vertical connection elements of wood-based materials. Rubbers are being inserted between these vertical elements in analogy with the car industry in order to limit contact between the steel frame and the boarding, thereby enhancing the sound insulation. Following, the two planar vertical elements - placed on both sides of the projecting steel frame - are in such manner connected with bolts that tightening them up results in narrowing of the intermediary space and in order to compress interbedded rubbers. Consequently, these rubbers disconnect principal assembly parts thus reducing presence of acoustic leaks. Thereafter, the steel profiles of the second preassembled panel can be interlocked between the created crevices. To provide the final finishing layer an additional layer of (demountable) facing boards is mounted externally of which the seams are eventually covered with clipped on finishing profiles. Wood-based boarding and gypsum fibre board are selected in this scenario for respectively the boarding of the preassembled panel, and the facing boards added on site. The properties of wall scenario A (and B) are represented in Table 6.15.

Figure 6.18: Assembly of preassembled panels finished on site: scenario A

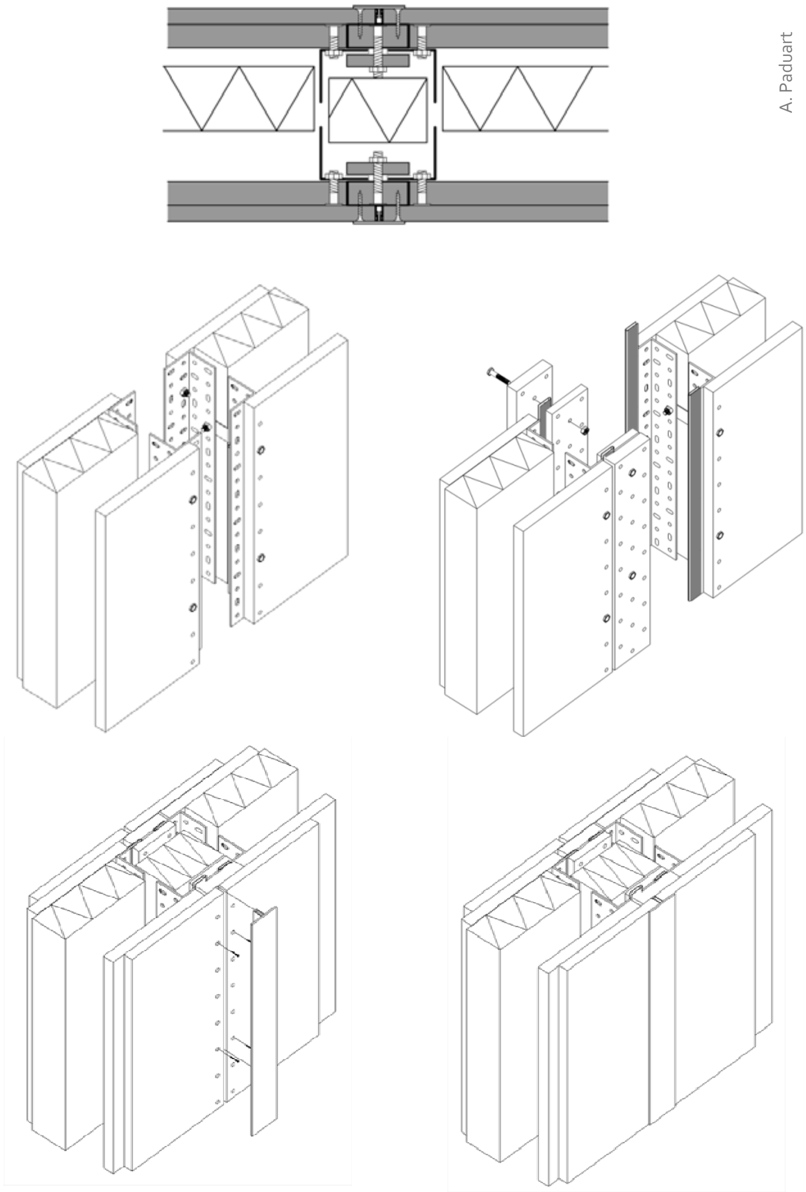
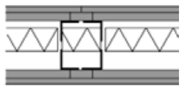
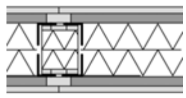


Illustration: A.Paduart

Connection of two preassembled panels: adding of vertical connection elements that compress rubbers, embracing the steel profiles. The steel profiles of the second preassembled panels can then be blocked between these vertical connection elements. Adding of secondary demountable boarding and finishing of the seams using vertical strips that can be clipped using dry connections. The wall finishing shows vertical lines.

Table 6.15: Scenarios of dynamic wall assemblies

	Scenarios of wall assemblies	
	A	**B**
Properties	*DfD ++* *acoustics +* *fire resistance +*	*DfD +* *acoustics ++* *fire resistance ++*
Wall composition		
Reuse of comp.	++	+/-
Ease of change	++	+/-
R_w [10]	≈ 50 dB	≈ 60-62 (-4, -10) dB
Fire resist. [11]	½ h-1h	1 ½ -2h
U -value	**steel** : 0,55 W/m^2K	0,60 W/m^2K
Applications	internal wall	partition wall

6.2.5.2 SCENARIO B: PARTITION WALLS

In case of partition walls - characterised by a slower rate of turnover - a compromise is sought to comply with compulsory acoustic, thermal and fire resistance standards while maximising design for change with reuse of sub components (scenario B).Therefore, the preassembled base unit is retained as the base (dynamic) support for additional boarding, including a higher degree of insulation and an adapted selection of materials for the facing boarding and the finishing. First, the facing board is adapted to meet the higher functional requirements. The use of gypsum fibreboards for the external boarding incorporates the main functional characteristics of gypsum plasterboards while it exhibits a better fire resistance in order to balance the lower fire resistance of the primary wood-based boarding.[12] In this scenario the *external finishing* plays a key role to achieve the current building standards. Therefore, the strategy in this case consists in *sacrificing the external layer* in order to maximise the reuse of the remaining sub components. Whilst all sub components of the preassembled units are reusable, the external layer is not materialised and assembled according to DfD and reuse strategies. To avoid all air leakage and open joints all seams are closed using irreversible finishing as in standards gypsum plaster board finishing. Consequently, if changes are required in the partition walls the external layer

[10] Weighted sound reduction index according to EN ISO 717-1. The estimated values are approximations, and have been derived from the tested values of existing flexible wall partitioning (solution A) and decoupled dry wall solutions. However, to have the correct value, the only way is to test prototypes.

[11] Estimated based on information about fire resistance of the boarding materials and results on fire tests on traditional dry walls.

[12] If reversible connections would not be applied, gypsum fibreboards could eventually be reused, for instance, for the subfloor of dry floors

must be removed (and disposed) but the base support can still be reused. Figure 6.19 shows the assembly on site of partially preassembled units for scenario B connected and finished on site. Again, two preassembled base panels are interconnected adding two wood-based vertical connection components. The finishing however is equal to the finishing of tradition gypsum plasterboards, making fast adaptations more complex.

Figure 6.19: Selection of sub components from design catalogues for scenario B

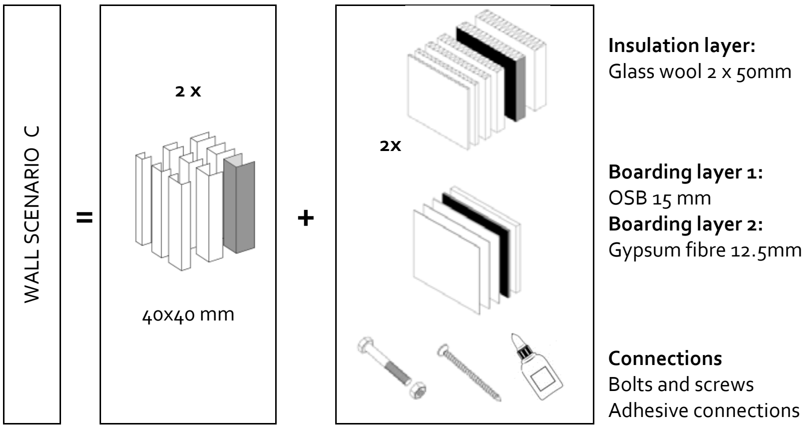
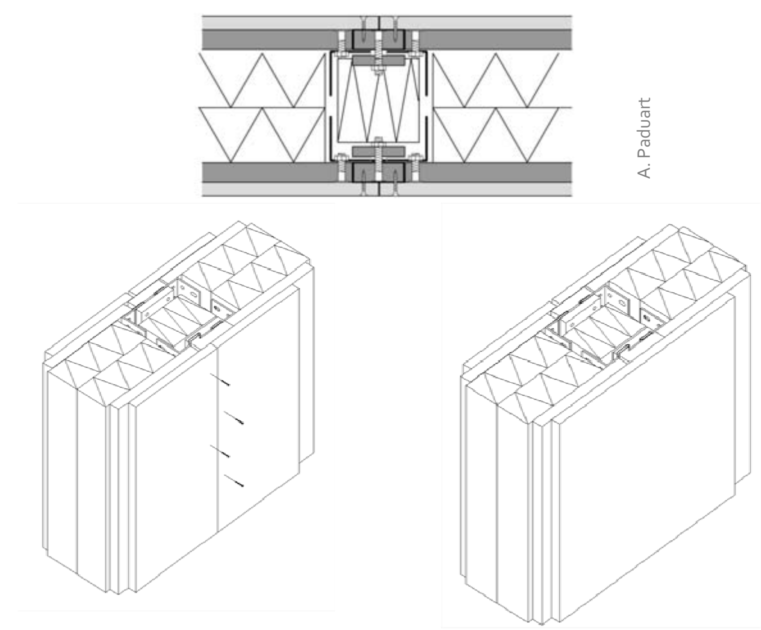


Figure 6.20: Assembly of preassembled wall panels: scenario B



The first steps are similar to scenario A. The additional boarding is gypsum-based and is screwed against the supporting OSB boarding. All seams are closed to avoid leaks using adhesive connections. The wall finishing is seamless.

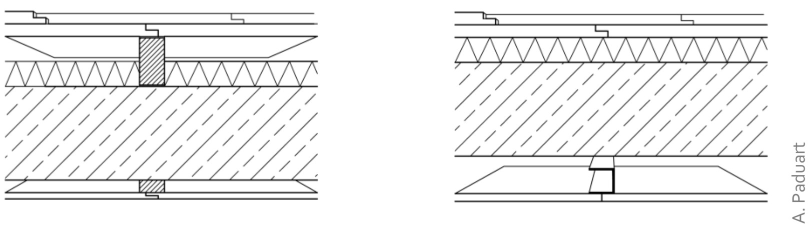
All by all, alternative detailing may exist offering future perspectives to deal with the oppositions between DfD design and the regulatory residential building requirements. Open linear joints, enhancing the reversibility of the assembly, may be filled with removable strips, foams or tape which enhance the fire resistance and prevent air leakage. However, to evaluate the performance of such solutions prototype testing is recommended on real-scale assemblies in a realistic setting. This was unfortunately out of the scope of this research.

6.2.5.3 ASSEMBLY AND DETAILING

Figure 6.22 shows the different required steps of assembly on site of the preassembled wall units finished on site. The semi-finished panels are erected on mounted channels on floors and ceilings in order to level any unevenness of the existing floor slabs. Next, the panels are connected with each other using additional linear structural elements (Step 4). To deal with tolerances in the horizontal plane a technical panel is introduced (Step 6 and 7). Additional finishing is required for residential partitioning and consequently, supplementary facing boards can be mounted against zones foreseen on the primary supporting boarding (Step 8).

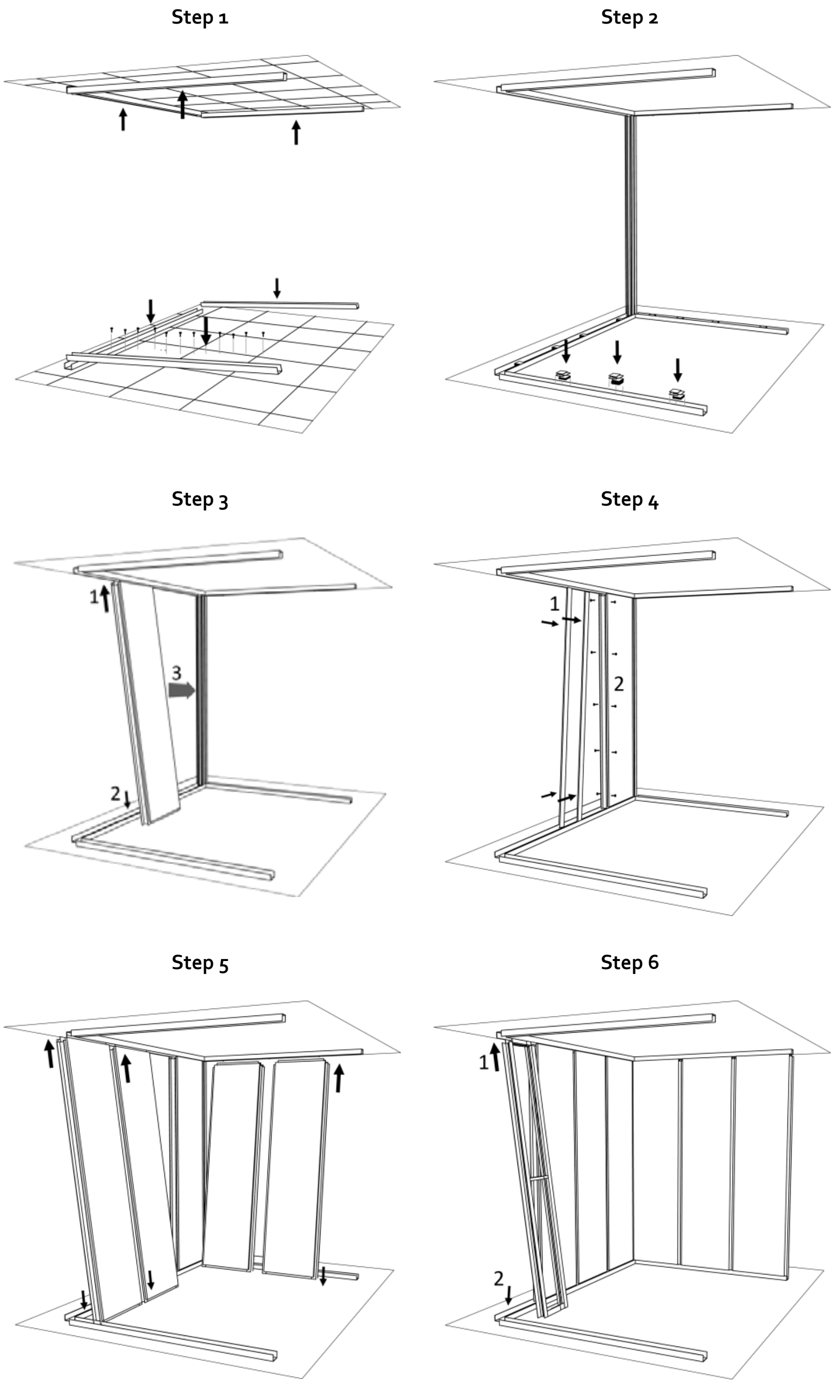
Dynamic floors and ceiling solutions could thereafter be established according to specific contextual requirements. Indeed, floors and ceilings can be considered as a variation of the same set and variants of base elements used in the kit-of-part system developed for wall assemblies. However, in the specific context of post-war building renovation the restricted storey-height makes flexible floor systems inappropriate since they introduce raised floors are suspended ceiling solutions. Therefore, for the separating floor of these apartment buildings dry floating deck floors are more suitable, as presented in Chapter 4.

Figure 6.21: Flexible solutions for the floor and ceiling assemblies



Finally, as illustrated in Figure 6.22, the selection of base elements for the structural framework, the boarding and the insulation used in the fitting-out of buildings, is dependent on the application and the contextual requirements. Combinations for the *internal wall partitioning* are detailed in Figure 6.23.

Figure 6.22: Required steps in assembly of preassembled wall partitioning



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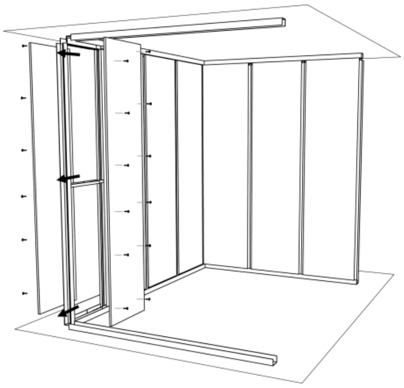
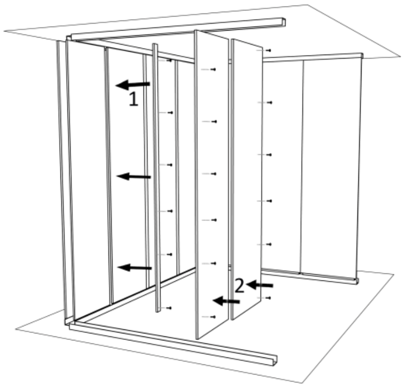
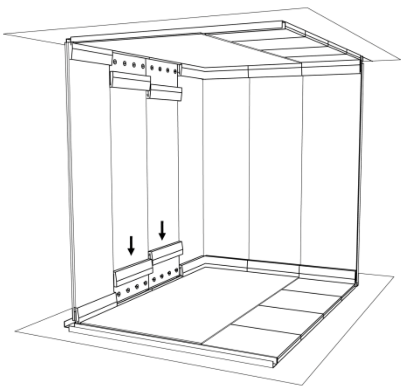
Step 7



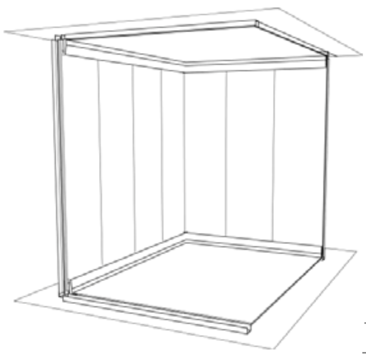
Step 8



Step 9



Step 10



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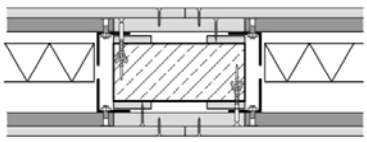
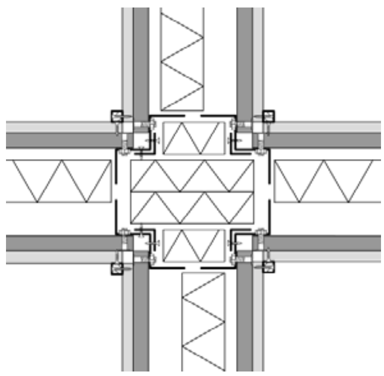
Step 1	Connect support profiles to floor slabs on selected grid
Step 2	Provide elements that incorporate vertical tolerances to eliminate any floor unevenness
Step 3	Tilt preassembled wall units into support profiles
Step 4	Provide vertical connection elements between two wall units
Step 5	Continue to place all wall panels
Step 6	Provide a technical panel that incorporates horizontal tolerances
Step 7 & 8	Provide finishing against the preassembled wall units according to the required performance level and finishing
Step 9	Assemble the floor/ceiling to the required performance level and finishing
Step 10	Close up the (insulated) technical void

Figure 6.23: Details of finished preassembled internal walls (horizontal and vertical section) including measures to enhance acoustic and thermal insulation, and fire resistance

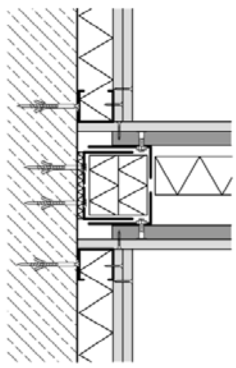
Horizontal section



Linear connection with existing column

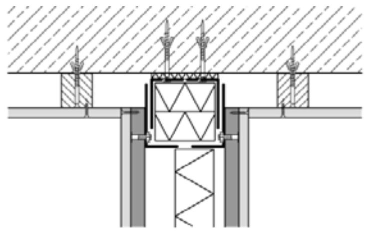


Connection in 3 directions

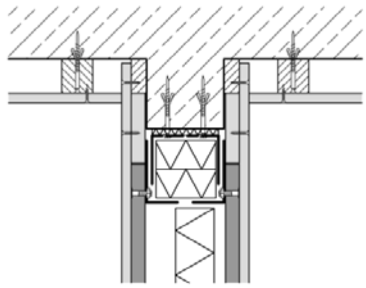


Connection with existing wall

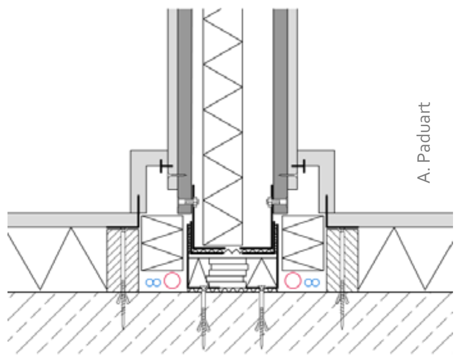
Vertical sections



Connection with ceiling



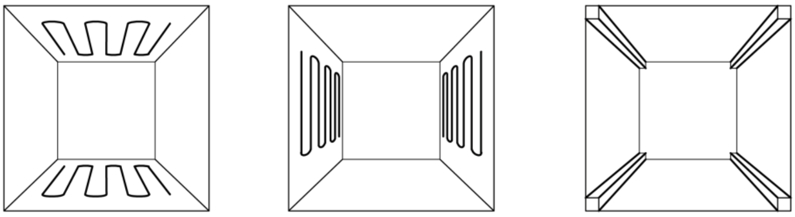
Connection with existing floor beam



Connection with floor

Different flexible systems are currently present on the building market in order to incorporate of technical systems in floors, walls and ceilings. For the horizontal layers flexible systems are generally associated with loss of storey-height, e.g. raised access floors and suspended ceilings. This means that flexibility in the horizontal plane is difficult to apply in post-war buildings characterised by low storey heights, as mentioned before. Therefore, flexible integration of technical systems was oriented towards wall solutions.

Figure 6.24: Distribution of technical cabling through ceilings, floors, walls and plints.



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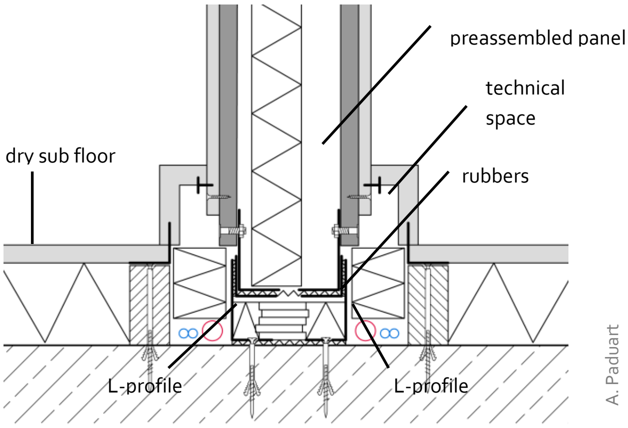
Existing solutions for flexible integration of technical distribution of walls systems typically creates acoustic leaks. Indeed for a floating subfloor, the junction of the subfloor with the partition is critical for the sound transmission between two adjoining rooms. If the subfloor continues below the partition the flanking transmissions are expected to be very high [Tichelmann 2007].

Figure 6.25: Examples of existing flexible distribution of technical wiring and cables

Source: Knauf, Gyproc Cable stud

In the case of partitions with high sound insulation requirement therefore, the dry subfloor needs to be interrupted at the partition in order to ensure good acoustic qualities. The wall partitioning may be optimised but if the junctions are badly designed, all efforts serve for nothing.Therefore, an assembly detailing is proposed when using preassembled wall panels in which the walls are positioned on top of the concrete floor slabs, mounted in supporting profiles which consist of two separated L-sections - connected to the floor slab. These L-sections enable to deal with tolerances due to unevenness of the floors while they also provide the support for the preassembled panels. Consequently, the preassembled panels are mounted in these L-profiles with an acoustic disconnection with rubbers between the floors - executed with dry subfloors - as can be seen in Figure 6.26. The created void can be used for flexible technical distribution and filled with flexible insulation.

Figure 6.26: Flexible incorporating of technical distribution in wall partitioning



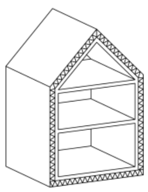
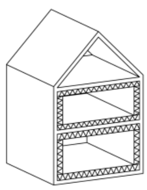
Hence, the proposal incorporates a flexible organisation of the technical distribution of wires and cabling in an insulated technical zone which can be closed off using technical plug-and-play skirting board. Like this, acoustic and thermal bridging is minimised while complying with fire protection requirements.

6.3.1 DFD PRINCIPLES VERSUS RESIDENTIAL BUILDING STANDARDS

6.3.1.1 THERMAL UPGRADE OF FACADE

Thermal upgrade of the building envelope is one of the main motivations for renovation of post-war buildings today, including upgrade of the *facade* and the *roof* [Giebeler 2009, EPB 2010]. Two main alternative strategies exist to improve the thermal performance of existing post-war buildings, i.e. by internal or external insulation. Since cavity walls were mainly introduced from the 1970s on, insulation of the cavity - a third possible strategy - is not possible. An adequate selection between both strategies relates to the building context and to thermal and acoustic targets, economic criteria, and architectural boundaries. Advantages and disadvantages of these three main methods[13] are summarised in Table 6.16.

Table 6.16: Advantages and disadvantages of insulation placement for post-war buildings (based on [Trachte and De Herde 2010])

Insulation type		Description of (dis)advantages
external 	**advantages**	-risks of local thermal bridges suppressed; -simple detailing; -wall protection against rain, frost and cracking; -improvement of the external coating; -conservation of thermal inertia;
	disadvantages	-modification of the external appearance; -high costs (new coating); -possible encroachment on public space;
internal  A. Paduart	**advantages**	-the appearance is preserved; -the cost is generally lower than outside insulation; -thermal bridges sometimes unsolved;
	disadvantages	-loss of thermal inertia; -lower summer comfort; -continuity of the vapour barrier difficult to ensure -possible degradation of the external wall (humidity and cooling); -risk of cracking (temperature variations); -new interior finishing and interior volumes decreased;

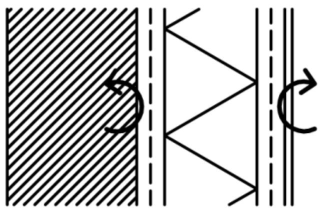
[13] A fourth method - a combination of internal and external insulation - combines the advantages and disadvantages of these two insulation methods.

The external insulation of existing buildings in general avoids problems of the building fabric in the future use. Since this research does not focus on buildings of which the facade is listed, this external approach is selected as the most appropriate to establish a sustainable renovation intervention.

6.3.1.2 DYNAMIC RAIN SCREEN FACADES VERSUS BUILDING REGULATION

Rain screen facades are well-known solutions for thermal upgrade in which a cladding is applied over an existing building structure. Rain screen cladding consists of an outer weather-resistant decorative skin fixed to an underlying structure by means of a supporting grid which maintains a ventilated and drained cavity between the facade and the structure. In these rain screen facades as well dry reversible connections can be used as fixed adhesive assembly techniques. When reversible connection techniques are used rain screen facades have been evaluated in Chapter 4 to have high adaptation and reuse opportunities. An overview of typical layers in rain screen facades is given in Figure 6.27 including - from outside to inside - the cladding, ventilation layer, wind tight layer, insulation layer, supporting grid, air tight layer and the structural shell.

Figure 6.27: Composition of layers in rain screen facades



Although these rain screen facade solutions are well-established dry construction systems the following problems can arise. The connections in order to assemble the rain screen facades against the structural shell may perforate the insulation layer which typically results in formation of **thermal bridges**. As metallic elements exhibit a much higher thermal conductivity than insulation materials significant heat losses in the building envelope make be created [Tichelmann 2007]. Given the increasingly stringent thermal demands placed on the facade of residential buildings today attention must be given to dry connection detailing techniques for external cladding. The same is true for acoustic performance: dry anchoring also result in acoustic leaks reducing the final sound insulation of the facade.

In addition, the *supporting grid* may cause reduction of the thermal performance due to non-homogeneous insulation, while also for the sound insulation of the building envelope the rigidity of this grid plays a negative role.

What is more, *open joints* in these facades may contradict the principles of fire safety and sound insulation. Therefore, in analogy with dynamic wall assemblies Figure 6.17 represents discrepancies between DfD principles in relation to residential building regulation.

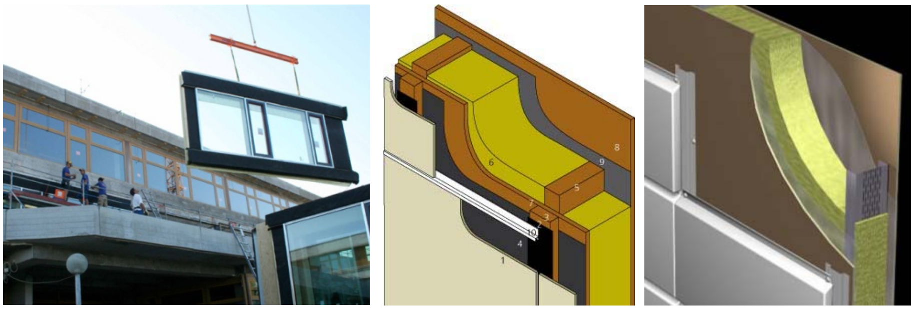
Table 6.17: Conflicts between thermal and sound insulation , and fire resistance measures and DfD properties for dynamic rain screen facades

	DfD properties		**Acoustic performance**		**Thermal insulation**		**Fire resistance**
framework	reusable framework	↔	resilient framework	↔	avoid thermal bridging		
cladding	reusable cladding	↔	resilient cladding	↔		↔	fire resistant covering material
connections	reversible connections	↔	avoid rigid connections	↔	avoid thermal bridging	↔	
jointing	reversible joints	↔	avoid air leaks	↔		↔	avoid horiz.& vertic. gaps and air leaks

6.3.2 DESIGN CONCEPT

As the qualitative assessment in Chapter 4 revealed there is still room for improvement in dry rain screen facades regarding the speed of upgrade of the building skin (Chapter 4). Increased construction speed decreases the costs and inconveniences associated with long renovation interventions, and more crucially, reduces long waiting lists for candidate-renters of social housing. The thermal upgrade of building facades can be considerably speeded up with the use of preassembled units which can easily be mounted against the existing building fabric [BRE 2001, Smith 2010, TES 2009]. Current trends show that there is a market for prefabricated external wall elements in renovation made from timber-based elements as well as steel sections.

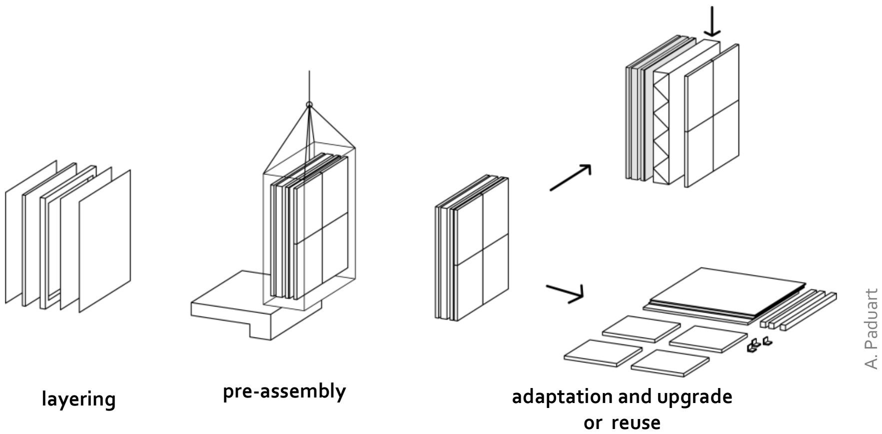
Figure 6.28: Examples of prefabricated facade panels



Source: [RUUKI 2005, TES 2009]

For instance, the TES (Timber based Element System) element developed in a joint project between northern European countries aimed to develop energy-efficient and sustainable renovation methods based on prefabrication using wooden elements [TES 2009]. Another example, the Nordicon Facade Element System [RUUKKI 2005], exists of extensively prefabricated facade solutions using steel profiles to speed up on-site upgrade of the building facade. However, these solutions of prefabricated facade modules are again executed as permanently fixed end-products. Lack of dynamic design in these facade modules may hinder thermal upgrade in the future and reuse of sub component in the end-of-life phase. Therefore, a *preassembled* but *dynamic* facade panel is proposed as an alternative incorporating the DfD and reuse principles.

Figure 6.29: Design concept of the preassembled facade unit



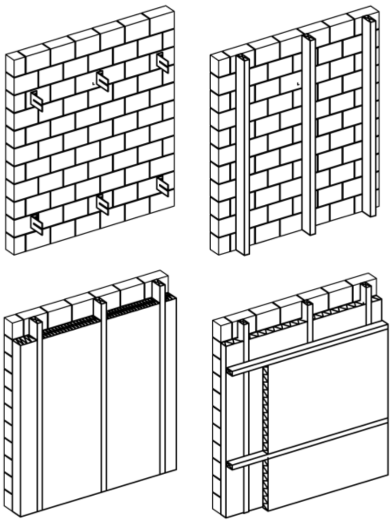
6.3.3.1 OPEN SYSTEM APPROACH

In analogy with the methodology used to design dynamic wall assemblies standardised basic element for the sub layers of a preassembled facade panel can be materialised, dimensioned and selected according to the specification of the renovation context. Similar to wall partitioning a set of sub layers is analysed, materialised and dimensioned, i.e. the carrier framework, insulation layer, carrier grid for cladding, wind and air tight layer and cladding. For most sub layers the morphology of the sub components can be derived from the design catalogues set up for the wall partitioning since simple and non-specific elements were selected using the fractal model. The sections however will differ since loads in facades are of another range than in non load-bearing wall partitioning.

6.3.3.2 REVERSIBLE CONNECTIONS VERSUS THERMAL BRIDGING

In dry rain screens the use of wooden battens, aluminium brackets or steel components – forming thermal bridging in order to attach the front covering – all contribute to negative reductions of the thermal performance of the building skin. To calculate the impact of thermal bridging on the thermal performance of the building skin the crucial factors to be included are: the *number of anchoring* used to connect the cladding to the building shell, the *cross-sectional area* of these fixings and the presence of *thermal breaks*.

Figure 6.30: Parameters influencing thermal bridging



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Presence of point bridging / line bridging
Number of anchoring
Material of anchoring
Cross section area of the anchoring
Thermal breaks in the anchoring
Layering of the insulation

From there on, the calculation of the thermal transmittance of the facade must include all point and linear thermal bridging caused when anchoring or wooden battens disrupt the insulation layer.

The overall thermal insulation level of the facade is then given by the thermal transmittance coefficient - i.e. the U-value - which is the rate of heat transfer through one square meter of a wall divided by the Kelvin difference in temperature between to wall sides. This value can be determined according to the following formula [CSTB 2008]:

$$U_p = U_c + \Delta U$$ **Equation 6.1**

$$U_c = \frac{1}{R_T}$$ **Equation 6.2**

$$R_T = R_{se} + R_{wall} + R_{si}$$ **Equation 6.3**

$$R_{wall} = \sum_{i=1}^{n} R_i$$ **Equation 6.4**

With:

U_p	Thermal transmittance coefficient of the wall [W/(m².K)]
U_c	Thermal transmittance coefficient of the central part of the wall without thermal bridging [W/(m².K)]
ΔU	Transmittance due to thermal bridging in the wall [W/(m².K)]
R_T	Thermal resistance of the total external wall [(m².K)/ W]
R_{se}	External thermal surface resistance [(m².K)/ W]
R_{si}	Internal thermal surface resistance [(m².K)/ W]
R_{wall}	Thermal resistance of the external wall [(m².K)/ W]
R_i	Thermal resistance of the layer i, featuring in the external wall [(m².K)/ W]

Furthermore, to take the point and linear thermal bridging into account two calculation methods were used. First, in case the insulation layer is perforated through punctual mechanical fixings - like brackets supporting the facade covering - the correction of the thermal transmission coefficient of the external wall can be calculated with the following formula [CSTB 2008]:

$$\Delta U_p = 0{,}8\ \frac{\lambda_f\, A_f\, n_f}{d_i} \left(\frac{R_I}{R_T}\right)^2$$ **Equation 6.5**

With:

ΔU_p	Transmittance due to point thermal bridging in the wall [W/(m²K)]
λ_f	Thermal conductivity of the material of the fixing [W/ (m.K)]
A_f	Area of section of the fixing [m²]
n_f	Number of fixings (per m²) [m^{-2}]
d_i	Length of the fixing that perforated the insulation layer [m]
R_I	Thermal resistance of the insulation layer perforated by the fixings [(m².K)/ W]
R_T	Thermal resistance of the total external wall [(m².K)/W]

For non-homogeneous layers, such as an insulation layer in which wooden battens are present (line bridging) an equivalent thermal conductivity λ_{EQ} can be calculated for the entire layer based on present fractions of the different materials in the non-homogeneous layer. The thermal resistance of non-homogenous layers can then be calculated with the following formula [EPB 2010]:

$$R_{NH} = \frac{t_{NH}}{\lambda_{EQ}}$$ **Equation 6.6**

$$\lambda_{EQ} = \sum_{i1}^{n} \lambda_i \cdot f_i$$ **Equation 6.7**

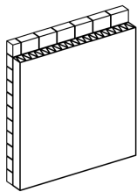
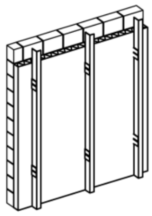
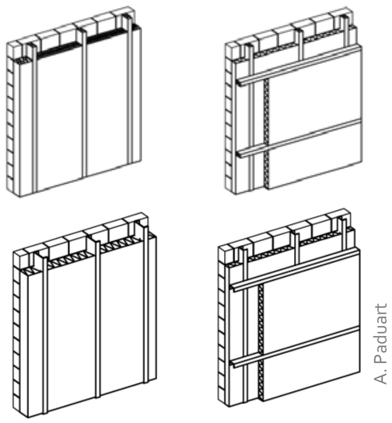
With:

R_{NH}	Thermal resistance of the non homogeneous layer [(m².K)/ W]
t_{NH}	Thickness of the non homogeneous layer [m]
λ_{EQ}	Equivalent thermal conductivity of the non-homogeneous layer [W/ (m.K)]
λ_i	Thermal conductivity of the material layer i in the non-homogeneous layer [W/ (m.K)]
f_i	Fraction of material i in the non-homogeneous layer [%]

Table 6.18 shows some examples of the influence of linear and punctual thermal bridging on the overall calculation of the U-value of facades.

First, the U-value for a homogeneous insulation layer placed against the structural shell (without supporting structure) was calculated to be equal to 0,22 W/m²K. The U-value calculated for point bridging caused by anchoring of brackets resulted in an augmentation of 40% (low number of brackets) and 110% (high number of brackets) of the initial value. Wooden battens also cause an augmentation of around 40% for a single layering, whereas steel sub frames cause a significant augmentation of 110%. It can therefore be concluded that the assembly techniques used in the facade have a crucial influence on the overall thermal performance of facades, and attention should be given to the reduction of thermal bridging due to dry connections used in relation to DfD practise in the building skin.

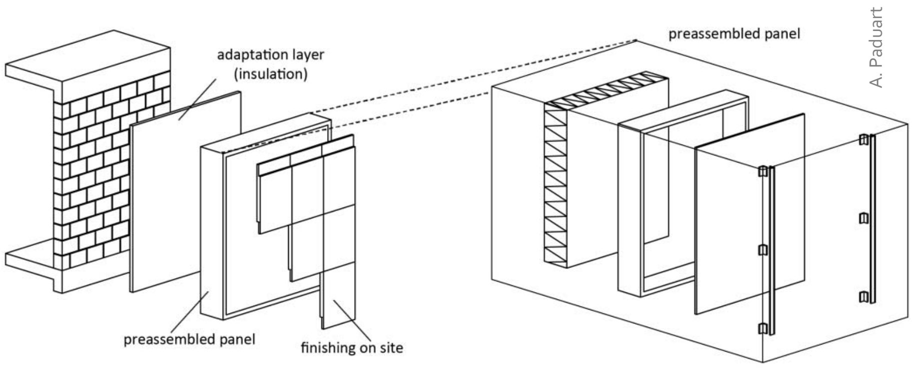
Table 6.18: Impact of anchoring and substructure against the building shell on the U-value

	Insulation layer type		U-value [W/m²K]	
homo-geneous		expanded clay bricks (14 cm) + glass wool (14 cm)	*0,22*	
with anchorings		*aluminium brackets*	# brackets = 2	# brackets = 4
			0,31	*0,47*
layered			single	double
		wooden battens	*0,31*	*0,27*
		steel profiles	*0,48*	*0,44*

6.3.3.3 CLUSTERED PREASSEMBLED PANEL

Clustering in preassembled units adds a supplementary sub layer to conventional rain screen facades, i.e. a carrying frame that clusters several main sub layers. It is the objective to preassemble the insulation layer, the carrier grid and the wind tight layer so that the only steps needed on site are connection of the clustering frame to existing structure and finishing of the facade by means of cladding.

Figure 6.31: Dynamic preassembly concept with clustering frame



As was illustrated in the previous paragraph the material selection and the assembly techniques used for this clustering frame is crucial. Based on the calculations made for materialisation of sub frames in wood or steel (Table 6.18) wood was selected as the most suitable material for the dynamic sub frame

Figure 6.32 shows how design catalogues could be developed for the sections of wooden battens. Subsequently the morphology of the wooden carrier frame was analysed to diminish the thermal bridging due to the presence of wooden battens.

Figure 6.33 shows how different selected elements of the design catalogue can be combined to a variety of scenarios for the carrier framework, and the composition can reduce the presence of thermal bridging.

Figure 6.32: Example of design catalogues for wooden battens

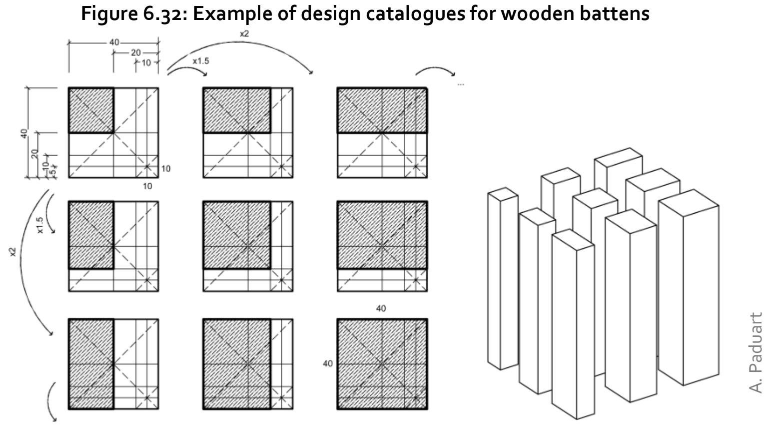
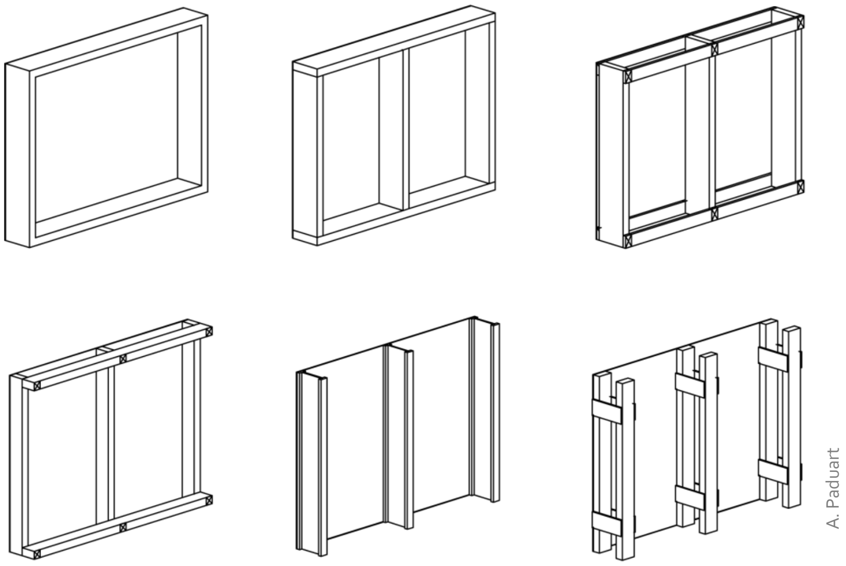


Figure 6.33: Combinations of elements from the design catalogue leading to different compositions of the wooden carrier framework for the preassembled facade unit



The first composition in Figure 6.33 illustrates significant thermal bridging due to linear battens that create multiple linear thermal bridges in the facade. The last composition shows how layering of the carrier frame can reduce the overall thermal bridging in the facade.

Then, wood-based boarding is added as outer panelling to make of the facade element a warm wall construction which is wind tight and protected from the external climate. Panelling fulfils multiple requirements as enclosure for the insulated element, protection against mechanical impact during assembly as well as building physics requirements [TES 2009]. For instance, moisture and wind resistance is offered from outside and vapour tightness from the inside, while fire resistance and sound insulation is increased (mass and absorption) [Tichelmann 2009, TES 2009]. The boarding can be consequently selected from design catalogues, in analogy to the wood-based boarding selected for dynamic wall assemblies.

INSULATION LAYER

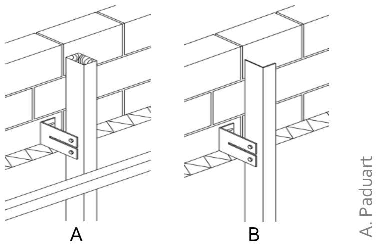
In the preassembled facade sub layering, insulation can be found in two applications; as thermal insulation in the preassembled wall unit and as an adapting insulation layer placed between the existing structural shell and the added modular facade unit (see

Figure 6.31). The latter enables to deal with tolerances and provides thermal integrity over the overall structural shell. The selection of insulation materials is based on fire resistance together with the thermal and sound insulation properties represented in Table 6.14 in analogy with dry wall assemblies. The insulation can again be selected from the design catalogues for insulation in analogy with dynamic walls.

CARRIER GRID FOR CLADDING

The supporting framework of rain screen facade covering generally consists of aluminium profiles or wooden battens because of the associated low weight[14]. Substructures materialised in wood exist of layered crossed wooden battens (vertical and horizontal). Aluminium substructures mount the main vertical aluminium profiles (L- or T-profiles) to aluminium connection plates, fixed to the structural shell

Figure 6.34: Typical wooden (A) or metallic (B) substructure for rain screen facades



Since wooden substructures are interconnected with screws, disassembly for multiple reuse and adaptation in the case of wooden battens is more difficult than is the case for aluminium or steel substructures. For this specific application aluminium is evaluated as an adequate option when a limited facade cladding weight is applied. Galvanised steel profiles have a higher initial environmental cost but their capacity to carry higher loads makes them suitable as a substructure for the heavier sandwich panels for non-ventilated facades. The sections can be developed based on the fractal model as for partitioning walls, and can include tolerance such as the steel sections of industrialised shelving systems.

14 Galvanised steel profiles have a higher weight, but can also carry higher weights, and are therefore used for sandwich panels (non-ventilated facades).

The connection techniques used for the rain screen cladding are crucial to enhance the ease of adaptation and the reuse of components. Therefore, preference is given to flexible connection techniques between the carrier grid and the dry cladding as represented in Figure 6.35. Examples of the connection types are shown in Table 6.19.

Table 6.19: Examples of rain screen cladding types

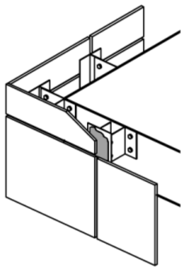
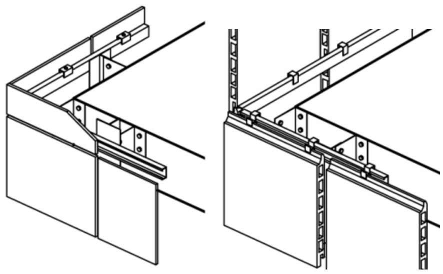
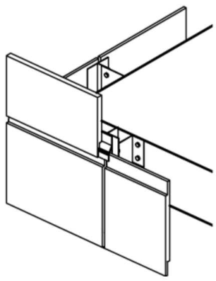
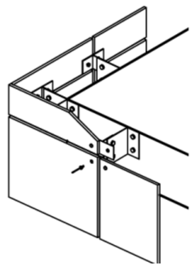
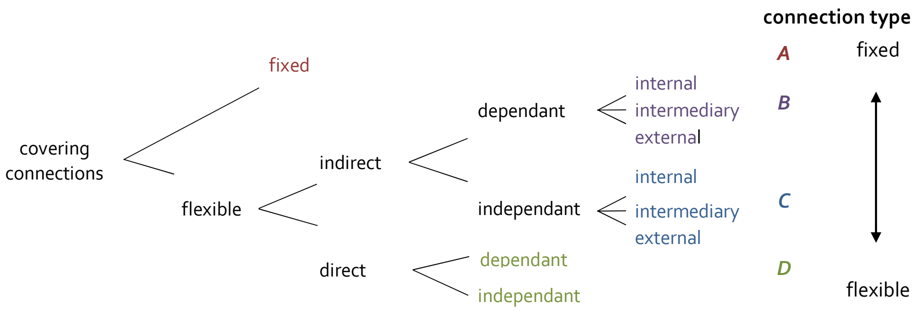
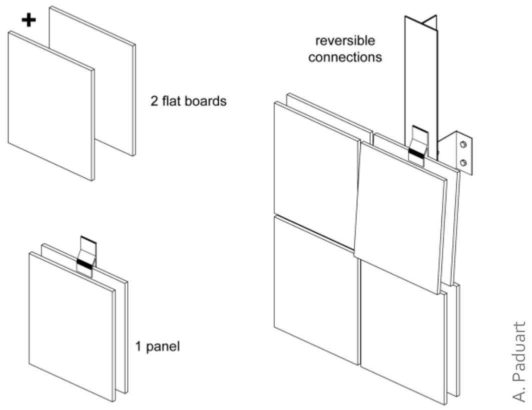
Cladding type & description			
 A		 B	
 C		 D	A. Paduart
A	The cladding is connected directly to the substructure using adhesives. Reuse of cladding is difficult or impossible.	**B**	The panels are hung to an additional horizontal profile by means of brackets connected to the back side of the panel. Profiled edges of panels are placed in additional rails by means of brackets, and are overlapping.
C	Profiled boards are inserted into a clip connected to the substructure that enabling that each panel can be removed separately.	**D**	The cladding is directly connected to the substructure with rivets.

Figure 6.35: Rain screen cladding types in function of reversibility



Connection D is determined to have the highest degree of flexibility. However, materials that enable this dry connection t directly to the carrier grid are rare (see Chapter 4). An example of the design of cladding is shown in the next figure based on a simple geometry that enables reversibility, ease of assembly and a wider reuse market due to its non-specific design. The free zones at the sides enable overlapping of different panels, while tolerance can be dealt with.

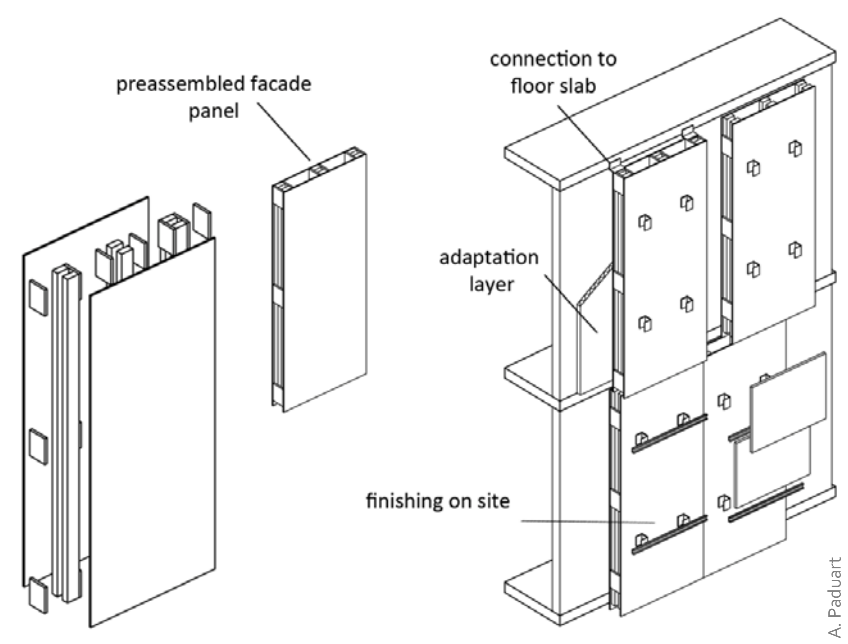
Figure 6.36: Dynamic cladding of rain screen facades



6.3.3.4 FINAL COMPOSITION AND DETAILING

As an example, the use of a wooden preassembled dynamic facade unit is illustrated in Figure 6.37. It illustrates how a great deal of assembly work is moved away from the construction site in order to increase the speed of works. The panels are composed of sub components selected form the design catalogues and assembled using reversible connection techniques. To restrict thermal bridging the wooden panelling is selected according to Figure 6.33 so that the direct thermal bridging is avoided.

Figure 6.37: Preassembled dynamic facade unit finished on site



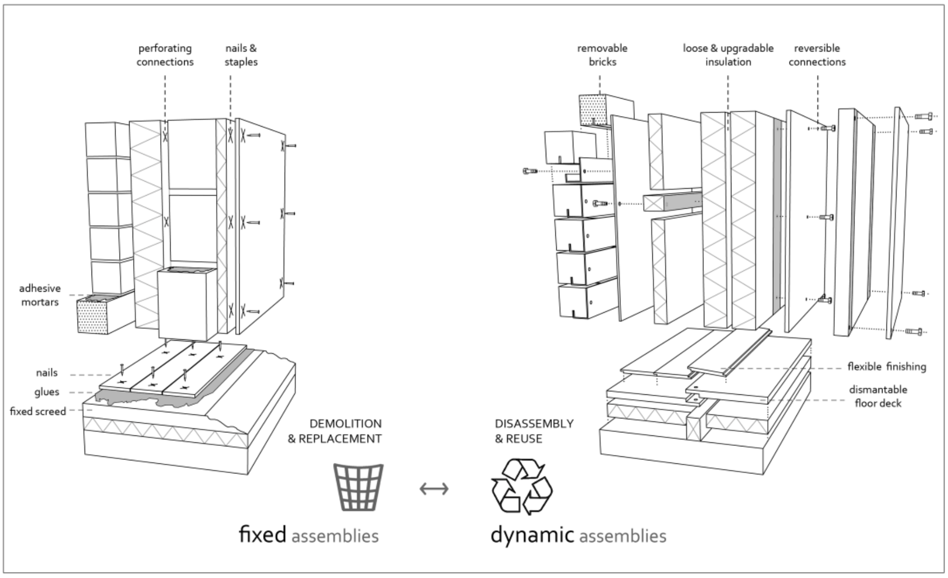
An insulation layer is provided between the structural shell and the preassembled panels as an adaptation layer while inside the panels the required insulation is provided, ensuring the thermal and acoustic insulation level. The OSB boarding provides the vapour barrier and the airtight barrier for the facade composition. Cladding can be added on site.

As was the case for the partitioning, these facade units can be customised to the current building standards, while they incorporate dynamic features that enable them to easily adapt or upgrade according to new standards. In addition, these panels can be easily removed at the end-of-life of the building life cycle, as an integral unit. This will increase the opportunities for a ‘deconstruction’ site instead of a ‘demolition’ site.

6.4 DISCUSSION

In this chapter, the technical challenges for dynamic re-design of existing buildings were revealed in the compulsory context of residential housing. The wide range of physical and functional requirements for building solutions in residential buildings, make sort that the opportunities of dynamic building layers cannot always be maximised. Several acoustic, thermal and fire resistance design principles clash with DfD principles that enhance the opportunities for adaptation and component reuse. Amongst them, the need for rigid sub components, presence of open joints (air leakage), thermal/acoustic bridging and the need for material selection with sufficient fire resistance were revealed as typical preconditions to enhance dynamic design, contradicting with the standards building requirements.

Figure 6.38: Conceptual representation of the shift from fixed towards dynamic assemblies



Nevertheless, in this chapter it is illustrated how a dynamic approach can be matched with the building regulation of today by means of compromising. The conflicts between DfD design and thermal insulation, sound insulation and fire resistance were analysed, leading to the detailing of some scenarios with a varying degree of change. Hence, it was illustrated how can be complied with building standards, while still, a high degree of reuse of the sub components can be incorporated.

In addition to solely conformity with building standards, the HV approach of the building artefacts enables to anticipate for future change, e.g. further upgrade. Thermal upgrade of facade will be a crucial matter for the future due to development of more stringent Energy

Performance of Buildings Directives. Buildings renovated according to current thermal policy may fail in the future, requiring an upgrade to more stringent building performances. In this case, this proposal may convince social housing societies to start renovation works instead of postponing renovation of their building stock until the revisions of the energy directives are stabilised.

The design of dynamic wall assemblies in analogy with shelving systems provides multiple options for the future. The standardised sub components enable to customise walls to a specific need today, while leaving future scenarios open through deconstruction and reassembly for other purposes. Hence, wall portioning can be further upgraded, for example from internal to partition walls, using the same sub elements. It clearly offers benefits compared to the demolition and replacement of building components that is typical for the throw-away culture in the built environmental nowadays.

In addition, the approach also offers a dynamic view on sound insulation of buildings. To improve the sound insulation of buildings during renovation, the plans and detailing can be only be adapted in the initial design stage. However, it is only after the execution of the renovation that in situ measurements can evaluate the overall sound performance. When acoustic solutions are applied in renovation, there is little margin for deficiencies. If the acoustic performance of the solution does not perform as expected, the combination of restricted storey-height and conventional static result in buildings that are difficult or impossible to be reversed to better performances. Adaptable solutions can offer important solutions in this matter. When the final result does not meet the targets, the solutions are still reversible and upgradable to achieve satisfactory properties. The weak points can be evaluated and ameliorated in a second phase without need for entire demolition of the created building solutions.

PART III

07

ASSESSMENT METHODOLOGY

In the previous chapter, dynamic design of building layers was discussed for re-design of existing buildings, as a complementary renovation strategy to contemporary energetic renovation. Re-design for change approach offers a long term design vision which incorporates the life cycle of building materials.
To compare the effect of such dynamic design approach with traditional design, environmental benefits and drawbacks must be evaluated over an entire building life cycle - in which replacement of building layers regularly takes place.

To achieve more sustainable production and consumption patterns in our built environment we must consider the environmental implications of the whole supply-chain of building products, their assembly, use and waste management, i.e. their entire life cycle from cradle to grave [European Commission 2010a]. In this chapter the methodology applied to perform this environmental life cycle assessment (LCA) is communicated in a transparent manner, to enable a correct comparison between different building solutions.

However, in today's context, a financial life cycle evaluation of consequences related to this dynamic approach may not be disregarded. Consequently, life cycle costing (LCC) is put forward. The combination of environmental and financial life cycle assessment is carried out in one single software, using the same functional unit for each research object. The methodology is discussed in this chapter.

In addition, an assessment matrix is developed, to give designers a first indication of the need for a dynamic design approach of building components based on their initial environmental impact.

7.1 INTEGRATED LIFE CYCLE ASSESSMENT OF BUILDINGS

7.1.1 LIFE CYCLE PERFORMANCE ASSESSMENT OF BUILDINGS

In the age of skilled craftsmen, habitation of buildings often spanned several generations and subsequently, buildings were traditionally well-maintained on the assumption that their service lives could be extended without limit [Kohler 2010]. When buildings eventually needed to be demolished, most inherent materials were dismantled and reused for use in construction of similar buildings. In this context, there was no consciousness about the *end* of a building *life cycle*. As buildings were built to resist for life, and maintenance took place continuously, there was no need to carry out periodic renovation or demolition in the manner we are familiar with in regard to today's building environment. Buildings were only demolished as an ultimate option.

This form of building development changed only since the 20th century. During the post-war building boom new construction materials and techniques were introduced with very little knowledge of their behaviour in the long term [Kohler 2010]. The energy crisis of the 1970s initiated increased awareness of the environment and a change of direction towards sustainable development. This brought forward the need to consider products and buildings from the point of view of their entire life cycles. Today, life cycle assessment of buildings is steadily becoming common practice to achieve sustainability, throughout the assessment of environmental impacts - life cycle assessment (LCA) - and financial life cycle aspects -life cycle costing (LCC)[1].

The integration of both life cycle assessment and life cycle costing of buildings and their components is not an easy task, due to the complex nature of buildings. It requires a combination of various methodological principles and procedures, which are described in this chapter for this research study.

Life cycle assessment is a method to assess the environmental impacts throughout the life cycle of products, from raw material acquisition through production, use and end-of-life [ISO 14040 2006]. It is a widely acknowledged quantitative assessment method and is therefore selected for this research. The well-established Life Cycle Costing (LCC) technique is incorporated in the assessment methodology to evaluate related financial costs of building components over the entire life cycle of buildings. LCC of buildings is defined in ISO 15686 as the total cost of a building or its parts throughout its life, including

[1] Social performance assessment is not incorporated in this research, since the methodology and impact indicators are still under development.

the costs of planning, design, acquisition, operations, maintenance and disposal, less any residual value' [ISO 15686-1 2006].

7.1.2 OBJECTIVES OF THE ASSESSMENT

The aim is to evaluate the environmental impacts and the financial costs of building products over the entire *life cycle* of the buildings which are being re-designed for change, meaning that not only the *initial* renovation context is evaluated, but also the *maintenance phase* and at the *end- of- life phase* over the remaining service life of the buildings renovated today. The environmental assessment is expressed in environmental *impacts*, whereas the financial assessment expressed in financial *costs*.
The building phases taken into account in these financial and environmental life cycle assessment are the **extraction** and **production** phase, **construction** phase, **maintenance/replacement/alteration** phase and **end-of-life** phase.

The aim of this chapter is to form the basis for comparison of *conventional* versus *dynamic* design of building components in renovation, over the entire building life cycle. The focus is therefore not on expressing absolute values of environmental impacts and financial costs, but on making a comprehensible and transparent relative comparison for different design strategies in buildings in which changing events take place over the years.

The focus is on the life cycle of building components which form the main building layers subject to renovation, i.e. the facade, the partitioning, the floors and the roof of a building. Optimisation of energy performance of buildings, including the selection of technical services is not included in the evaluation, since this is not included in the scope of this research. Technical services and thermal resistance of the building skin are assumed to be equal in all evaluated scenarios, and can therefore be discarded in the evaluation.

7.2 LIFE CYCLE ASSESSMENT

7.2.1 GENERAL DESCRIPTION

The building sector started to recognise the impact of their activities on the environment in the 1990s, with the release of several environmental reports [Club of Rome 1972; RIVM 1987; World Commission on Environment and Development 1990; Meadows 1990]. From that moment on, the building sector started to reflect on how buildings were designed, built and how they operated. One of the drivers was public policy, and another was the growing market demand for environmentally sound products and services [Haaipo 2008]. Building performance started to be a concern of professionals in the building industry and environmental building performance assessment emerged as one of the major issues to make buildings more sustainable [Crawley and Aho, 1999].

In 1989, SETAC (Society of Environmental Toxicology and Chemistry) organised a workshop on the issue how to indicate the effects of materials on the environment. In 1996, they formed a working group that concentrated on Life Cycle assessment (LCA), and established the acceptance of the name (and framework) for life cycle assessment. The original organisation of LCA supplied by SETAC (1990) represented the first attempt to establish guide lines to develop a complete study of LCA.

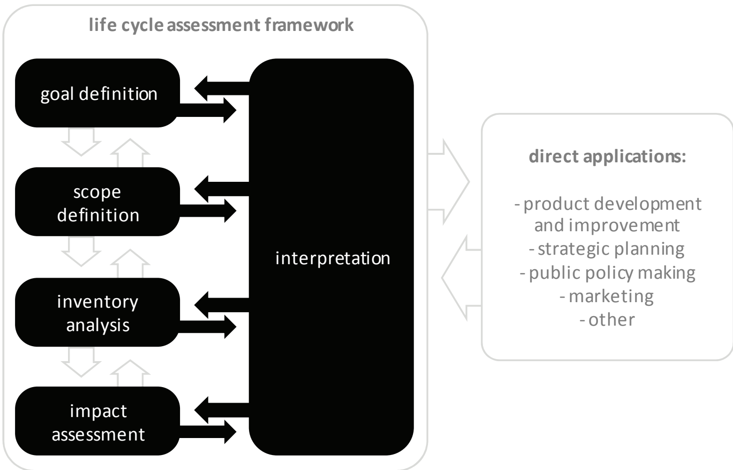
As is extensively discussed in literature, the complexity of buildings requires a separate approach within the LCA practice [SETAC 2003]. Programs needed to be developed with the building sector in mind. BREEAM, the first commercially available environmental assessment tool for buildings, was established in 1990 (UK), and ever since, many other tools have been developed around the world, aiming to assess the environmental impacts from building materials to entire buildings.

Today, life cycle assessment has been widely standardised in international standards such as ISO 14040, in which Life cycle assessment (LCA) is described as a systematic analysis of the resources drawn from nature and the environmental effects of a product over its entire life cycle (from cradle to grave). The ISO 14040 describes the principles and framework for LCA. Since the steps to be executed are widely discussed in literature, they are shortly summarised in the next paragraphs.

7.2.2 STEPS IN LIFE CYCLE ASSESSMENT

According to ISO 14040, an LCA study must be performed in four iterative steps [ISO 14040 2006]:

Figure 7.1: Framework for life cycle assessment (adapted from [ISO 14040 2006])



1. **Goal and scope definition:** Description of the aims of the study, system boundaries, functional unit, required data quality and impact assessment methodology.

2. **Life Cycle Inventory** (LCI): In a life cycle assessment, the consumed emissions and resources, the waste treatment, and eventual co-products that can be attributed to the life cycle of a product are compiled and documented in a Life Cycle Inventory. The LCI involves the collection of data and definition of procedures to quantify the inputs and outputs of the studied product system for all stages of the life cycle. Typically, the LCI phase requires the highest efforts and resources for data collection, acquisition, and modelling.
   Input data cover all natural resources, while the output data include products, co-products, waste, emissions to air, discharges to water and soil and other environmental exchanges (e.g. losses of heat). The LCI results are the input to the subsequent LCIA phase.
   Allocation procedures must be considered when dealing with systems involving multiple sub products and recycling systems.

3. **Life Cycle Impact Assessment** (LCIA): the purpose of LCIA is to provide additional information to help assess the LCI results of a product system to understand their environmental significance. In the LCIA, the results of the LCI

are linked to specific environmental impact categories. The LCIA is divided into five steps of which the first three are mandatory, the last two optional:

a. **impact category definition**: definition of the impact categories that are addressed, e.g. global warming, acidification, depletion of resources;
b. **classification**: the impact assessment at midpoint and/or endpoint level is performed by first assigning the elementary flows to one or more relevant categories of impact., e.g. CO_2 emissions are related to global warming, SO_2 emissions are related to acidification and respiratory effects;
c. **characterisation**: the inventory results for the individual elementary flows are usually linearly multiplied with the relevant impact factors from the applied LCIA methods, thus determining the extent to which inventory data contribute to an environmental impact;
d. **normalisation**: In this step, the relation is established between the environmental impact of a product system and the impact of a reference system, by dividing the indicator results by the respective reference value. The average yearly impact of a European citizen is often used as reference basis [Allacker 2010]. By doing so the contributions to the different environmental impact categories are expressed as a percentage of the impacts of the reference system, e.g. yearly average impact of a European citizen to *Human Health* damage equals 0,0154 DALYs[2] according to Eco-Indicator 99 for the Hierarchist profile [Goedkoop & Spriensma, 1999];
e. **weighting:** the normalised indicator results for the different impact categories or damages are each multiplied by a specific weighting factor, that is intended to reflect the relative relevance of the different impact categories/category endpoints among each other. Weighting sets involve subjective value judgments. In EcoIndicator 99, and ReCiPe for example, e.g. *Human Health* is equally important as *Quality of Ecosystems* according to the average profile [Goedkoop & Spriensma 1999, Goedkoop 2009].

4. **Interpretation of the results**: Results obtained from previous phases are analysed, conclusions are drawn, limitations of the LCA are described and recommendations are formulated. If needed sensitivity analyses are performed.

[2] DALY= Disability Adjusted Life Years

7.2.3 LCA OPTIONS

7.2.3.1 SOFTWARE

The last decade an overflow of software packages have been developed, which make it possible to calculate environmental impacts at building level, product level and material level. To categorise this large offer of sustainability assessment tools, the ATHENA institute, has developed a basic, three-level classification system that provides a uniform framework for discussing, assessing and comparing tools [Trusty 2000]:

- *Level 1*: Product comparison tools and information sources, e.g. BEES [Lippiatt 1999, BEES 2009], SimaPro [Pré Consultants 2009], TEAM [Osset & Cortijo 1997] (quantitative assessment);

- *Level 2*: Whole building decision support tool, e.g. EcoQuantum [W/E Adviseurs 1999], GreenCalc [Reijndersand & Huijbregts 2000], ATHENA [Trusty 2000], typically focusing on a specific area of concern, such as life cycle costs, life cycle environmental effects, operating energy;

- *Level 3:* Whole building assessment frameworks or systems, e.g. BREEAM [BRE 2009,], LEED [USGBC 2008], which provide a broad coverage of environmental, economic, social and other issues deemed to be relevant to sustainability (qualitative assessment).

Several assessment tools of Level 2 and Level 3, strive to take a holistic and integrated design approach into account which assesses how different building components, assemblies, and subsystems interact with each other and lead to an overall building performance. Therefore, a fixed assessment method, standard components, and predicted service lives of buildings and components are used. Further analysis of the impact of the assessment methods, variable service lives of components, or the life span of buildings are not possible to assess, while variety of components is limited to building solutions we known today.

On the contrary, assessment tools of Level 1 gives users more control over the life cycle inventory data, service life scenarios, underlying assumptions and parameterisation, model development, and impact assessment. These LCA software packages often include extensive generic LCI databases not restricted to standardised building products, while providing an interface for modelling alternative products with specific service lives, specific assembly techniques, specific materials, of which the environmental impact can be analysed. Such LCA software can be used to generate a detailed model of a specific building, assess its overall environmental impact, and evaluate an almost infinite number of material and component substitutions and design alternatives[3]. In addition, for example, SimaPro [Pré Consultants 2009] enables to incorporate other assessment methods, like LCC (Life Cycle Costing). Since non-standardised modelling of building products is required in this research, SimaPro software, issued by Pré Consultants is used, which enables to model and analyse complex life cycles in a transparent way, according to ISO 14040 principles. The software includes a database with generic inventory data for the most common materials and processes, and contains several impact assessment methods amongst which the Eco-indicator 99 method, CML 2002, EDIP and ReCiPe 2008.

7.2.3.2 LIFE CYCLE INVENTORY

Databases for life cycle inventory data contain the results of an environmental impact balance for products. Recognised databases in Europe include Envest 2 (UK), GaBi (Germany), Ökobau.dat (Germany), ecoinvent (Switzerland). Ecoinvent and GaBi are applied internationally in numerous life cycle assessment programmes for modelling building products, e.g. in SimaPro and Umberto.

For this research, a database was needed that includes building materials, for the West-European -Belgian - context. The ecoinvent database contains Swiss data, valid for the European context, and is available in SimaPro software. Ecoinvent version 2.0 is not only one of the most complete databases (3500 processes) for the European context, but it is also widely accepted as one of the most reliable ones and is updated frequently [Allacker 2010]. In this research ecoinvent version 2.2 is applied, containing more than 4000 industrial datasets.

To make the dataset more representative for the Belgian context, the electricity mix (originally for Swiss/German mix) and transport processes in the data records were adapted to the Belgian situation. To replace those processes, European corresponding processes were chosen since most building materials used in the Belgian context are produced all over Europe [Allacker 2010]. To adapt all building materials and their import adapted to the Belgian situation, would imply that specific information would be required about the differences between the Swiss and Belgian imported building materials. Collection of these specific data was esteemed to be out of the scope of this research, and the availability of data was assumed to be sufficiently adequate based on literature.

---

[3] It is clear that this type of software requires a level of expertise that usually exceeds that of most building professionals. Collecting original life cycle inventory data will clearly be more time-consuming, but will be more accurate for this research.

When information of building products is lacking within the inventories used in ecoinvent, availability of EPD (Environmental Product Declaration) is checked, and modelled according to the given data. The characteristics of Environmental Product Declarations are currently under revision through the European standardisation program "Sustainability of constructions works (CEN TC 350). EPD's are based on ISO standards and are therefore in accordance with international practice, providing comparable data on the environmental and health-related properties of products, concerning the production processes, energy and resources usage.

7.2.3.3 SYSTEM BOUNDARIES

In the ideal case, LCA studies include the entire life cycle of the product system and all unit processes that are linked to it. In practice, lack of data results in studies that focus on a part of the life cycle. Therefore, the system boundaries need to be clearly communicated and documented, explaining which life cycle stages and unit processes from the product system are included. Also, the allocation procedures must be communicated. The key is to achieve the best compromise between practicability of the study and validity of the results [CMHC 2004].

The life cycle phases taken into account for both the environmental and financial life cycle assessment are:

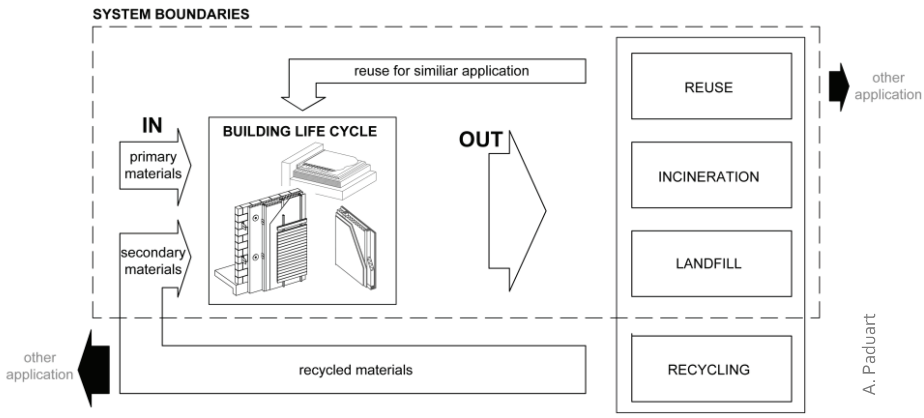
- **Production phase**: extraction and production of the building materials, including transport;
- **Construction phase**: transport to the building site, assembly of the (re)construction;
- **Use phase**: maintenance, repair and replacement of building products during the reference study period and production phase of the new components including transport;
- **End of life phase**: removal (separation, reuse, deconstruction, demolition) and end-of-life treatment of building materials (incineration and landfill), including transport.

The initial demolition phase of building parts, to upgrade the building today is not considered, since the analysis of building components in this research is comparative. It is assumed that equal impacts derived from initial demolition are related to each building solution, and therefore they can be left out of the assessment.

7.2.3.4 ALLOCATION

The purpose of allocation is to distribute the inputs and the outputs of a process to the products in order to be able to quantify the environmental (and financial) burdens and resource consumption for each single product. The end-of-life treatment of building materials needs a clearly stated allocation procedure [Goedkoop 2004]. In the case of recycling and reuse, environmental benefits (avoided raw materials extraction and avoidance of waste treatment) and burdens (collection of waste, energy use during the recycling/reuse process) need to be divided amongst the process that generates the waste (primary product system) and the process that will use the recycled fraction (secondary product) [Vrijders & Delem 2009]. Allocation methods for recycling vary from cut-off at the recycling processes to a full subtraction of avoided impacts. In this research, it is assumed that the system boundary cuts off the recycling process itself. The impacts related to the products are included until the sorting plant (including the transport until the sorting plant), while the transport to the recycling facility and the recycling process itself are allocated to the next system. This approach implies that the benefits of recycling are partially allocated to the first system and the second system. In the first system, the benefits go to materials that can be recycled - since they are alleviated of the disposal impacts-, and for the second system, to the recycled materials - through reduced impact from raw materials extraction. The impacts of the production processes for new materials based on recycled materials are subsequently allocated to the second system.

Figure 7.2: System boundaries: EOL treatment processes



Ecoinvent follows the same cut-off allocation procedure (recycled content method) for recycling. Using this cut-off approach in the built environment can be argued with different arguments.

First, due to the long service life of buildings compared to other daily life products, recycling may have negligible effect in the future on the environmental impacts which are

esteemed of significance today [Vrijders & Delem 2009]. Secondly, benefits of recycling in the future are generally calculated based on the current state-of-the art, while it is expected that scarcity, ecological carrying capacity, energy mixes and other factors may change radically in the future [CMHC 2004, Kotaji 2003]. Also, the recycling processes are currently being developed, and are expected to be more efficient than current recycling practice.
On the other hand, the effect of recycling buildings constructed today only result in benefits in the future. Therefore, the benefits cannot be credited against consumption today as this would imply that current environmental impact is allocated to future generations, which would favour the consumption of primary materials today [CMHC 2004, Kotaji 2003].

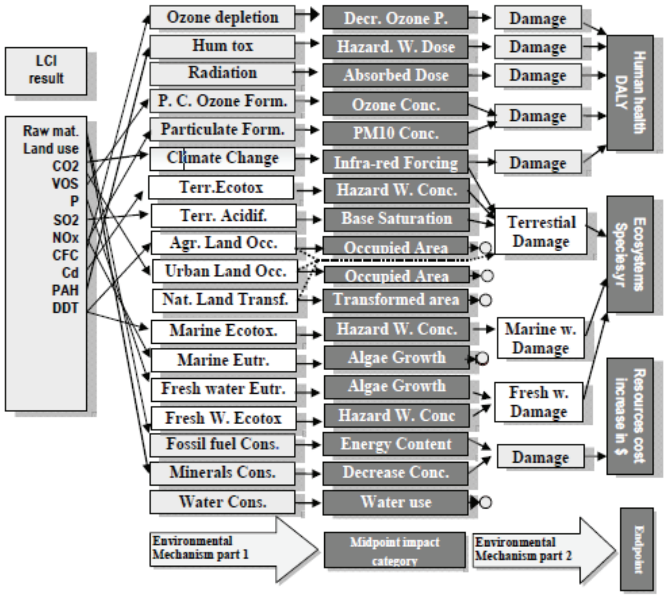
7.2.3.5 LIFE CYCLE IMPACT ASSESSMENT: RECIPE

Literature review reveals that a wide range of impact assessment methods is currently in use in Europe [Pré Consultants 2009a, European Commission 2011]. Main existing LCIA methodologies in Europe today are CML 2002 (Netherlands), Eco-indicator 99 (Netherlands), EDIP (Denmark), Impact 2002+ (Switzerland), ReCiPe (Switzerland), EPS 2000 (Sweden). The most appropriate life cycle impact categories are still being under discussion in various forums [European Commission 2011].

Although an LCIA framework of 'default' impact categories does not exist [Bare & Gloria 2008, Allacker 2010], the general categories to be considered include *resource use*, *human health* and *ecological consequences* [Jönsson 2000]. Each of these categories can be subdivided into different sub aspects, of which the most broadly recognised and of importance within the building sector include *climate change*, *ozone depletion*, *eutrophication*, *acidification*, *human toxicity (cancer and non-cancer related) respiratory inorganics*, *ionising radiation*, *ecotoxicity*, *photochemical ozone formation*, *land use*, and *resource depletion (*Figure 7.3*)*. The emissions and resources are assigned to each of these impact categories, which are subsequently converted into indicators using the *impact assessment models*.

A differentiation is made between *midpoint* and *endpoint* approaches. The most important distinction is whether the results will provide a profile of the environmental burden, or whether a single value is communicated.
Midpoint indicators are located on an intermediate position on the cause-effect chain between the LCI data and the damage (or endpoint). Midpoint impact category - or problem-oriented approach - translates impacts into environmental themes such as climate change, acidification, human toxicity, and is useful to provide information to the stakeholders that do not want to base decisions on the more uncertain endpoint indicator results.

Figure 7.3: Impact categories and pathways covered by the ReCiPe methodology [Goedkoop 2009]



Endpoint impact category -also known as the damage-oriented approach- translates environmental impacts into issues of concern, i.e. human health, natural environment, and natural resources, and is characterised by a higher rate of uncertainty. While midpoint indicators are more certain, they have a lower relevance for decision support than endpoint indicators [Bare et al. 2000]. An endpoint approach is therefore chosen since the aim is to provide a global picture of the environmental impacts related to products, which can be expressed into a single value, so that the results are comprehensible for all stakeholders and can be easily compared.

The developers of the Eco-indicator 99 method -PRé Consultants- initiated a joint project effort called 'ReCiPe' in 2008 with Leiden University Institute of Environmental Sciences, the developers of the Dutch CML approach [Goedkoop 2009]. ReCiPe 2008 is a follow up of the well-established Eco-indicator 99 and CML 2002 methods. It integrates and harmonises midpoint and endpoint approach in a consistent framework, since there are calculated on the basis of a consistent environmental cause-effect chain (except for land use and resources) [European Commission 2010a]. Since the method built further on the experience of well-established methods (CML and Eco-Indicator 99), and ongoing research initiated by the European Commission [European Commission 2011] recommends ReCiPe as a suitable impact assessment method for life cycle assessment in Western-Europe, it was selected as the impact assessment method in this research.

ReCiPe 2008 comprises two sets of impact categories with associated sets of characterisation factors. Eighteen impact categories are addressed at the midpoint level, of which a general description is given of each environmental impact categories and what they entail in Appendix II:

1. climate change (CC)	*2. ozone depletion (OD)*
3. terrestrial acidification (TA)	*4. freshwater eutrophication (FE)*
5. marine eutrophication (ME)	*6. human toxicity (HT)*
7. photochemical oxidant formation (POF)	*8. particulate matter formation (PMF)*
9. terrestrial ecotoxicity (TET)	*10. freshwater ecotoxicity (FET)*
11. marine ecotoxicity (MET)	*12. ionising radiation (IR)*
13. agricultural land occupation (ALO)	*14. urban land occupation (ULO)*
15. natural land transformation (NLT)	*16. water depletion (WD)*
17. mineral resource depletion (MRD)	*18. fossil fuel depletion (FD)*

At endpoint level, most of these indicators are further converted and aggregated into three endpoint categories: damage to human health (DALY), damage to ecosystem quality (biodiversity, PDF.m2.yr) and damage to resource availability (surplus cost).

Similar to the Eco-indicator 99 method three versions exist according to the cultural perspectives theory of Thompson (1990). According to this theory, consistent sets of subjective choices on time horizon and assumed manageability can be grouped around three perspectives:

- **Individualist**: Short time perspective (20 years); optimism that technology can avoid many problems in future;
- **Hierarchist**: Consensus model, as often encountered in scientific models, this is often considered to be the default model. The time perspective is medium (100 years);
- **Egalitarian**: Long term based perspective (500 years); the scientific proof does not always have to be at the maximum level.

In this research, the *hierarchist perspective* was selected as the default model, since it is the most recommended one [Goedkoop 2004]. Sensitivity analysis was done on the overall results, using the three perspectives.

Also for weighting of normalised scores, each version has its own weighting sets. The three damages models can be either combined with a particular weighting set corresponding to their own perspective (H,E or I), or an average weighting set (A) can be applied. The default ReCiPe method is the *hierarchist* version with European normalisation and an *average* weighting set (H/A).

7.2.4 MODELLING OF BUILDING COMPONENTS

7.2.4.1 FUNCTIONAL UNIT

For a viable comparison of alternative building assemblies that serve a certain function, a general base of comparison needs to be defined. This basis is called the *functional unit* [ISO 2006a]. In this research, when building assemblies need to respond a number of functional requirements, the most stringent (compulsory) requirement is set as the base of comparison. The most critical requirement for each building layer (e.g. facade, partition walls, and separation walls) is selected based on literature and the outcome of the survey.
For instance, in the case of facades, the thermal performance, i.e. the U-value of the facade composition, is set as the base of comparison for a functional unit of 1m² of facade. For secondary requirements, e.g. fire resistance, acoustic performance, a minimum must be reached by the concerning solutions. In Chapter 8 all assessed solutions are consequently expressed for a functional unit of 1m² of the concerned building layer.

7.2.4.2 END-OF-LIFE SCENARIOS

DEMOLITION VERSUS DECONSTRUCTION

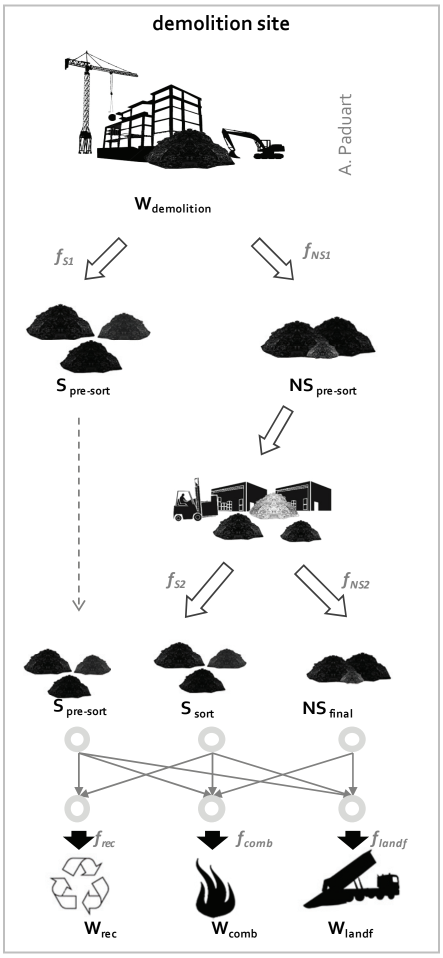
Current end-of-life practice is to complete demolition as quickly and efficient as possible [CIRIA 2004]. Materials and components of significant value are generally removed for reuse and recycling, but low-value materials for recycling or reuse is usually a secondary concern. This can be explained by two following reasons.

First, a key factor is the ease with which materials can be removed from the building. Conventional building design creates demolition waste which often cannot easily be separated to its initial material streams, due to fixed connections between building materials. Where more effort is required to separate or remove them from other materials, materials are more likely to be left in-situ and demolished during the physical removal of the structures [Addis 2004].
A second practical objection is the inconvenience of separating materials on site: sorting is presumed to be time and labour-consuming, and moreover, the large number of containers required to sort materials is perceived as a problem. However, firms that are practising sorting to a very high degree consider that these objections are often due to lack of knowledge and experience [Thormark 2001].

When components have been assembled in a reversible way, and when the remaining estimated service life span of components is still significant, the components may still exhibit *residual value*. One could estimate the residual value of components at the end of the life span of the building as the environmental gain or as the selling value, associated with the reuse of the component for the remaining service life [ISO 14040 2006]. Although there is a high uncertainty about the end-of-life scenarios of components in a far long future, the inherent environmental value of building components may not be overlooked. Design methods like DfD, which take this value into account, potentially improve both the economic and environmental efficiency of the entire life cycle.

In addition, when building materials can be entirely separated from other materials, it becomes possible to subdivide the entire waste stream of a building product entirely into flows for recycling, combustion and landfill. In reality, only a fraction (f_{S1}) of a building product A is pre-sorted at the demolition site. The remaining mixed fraction is transported to a sorting centre, where a fraction (f_{S2}) of the building product is further separated, and a fraction of mixed waste remains. The typical demolition scenario which uses destructive is represented in Figure 7.4.

Figure 7.4: End-of-life treatment of material end-of-life streams wit destructive techniques at demolition site



demolition site

$W_{demolition}$	*total EoL stream*
f_{S1}	*fraction of EoL stream at demolition site that is being pre-sorted*
f_{NS1}	*fraction of EoL stream at demolition site that cannot be pre-sorted*
$S_{pre\text{-}sort}$	*sorted EoL fraction on demolition site*
$NS_{pre\text{-}sort}$	*non-sorted EoL fraction on demolition site*

sorting site

f_{S2}	*fraction of EoL stream at sorting site that is being sorted*
f_{NS2}	*fraction of EoL stream at sorting site that cannot be sorted*
S_{sort}	*sorted EoL fraction on sorting site*
NS_{final}	*non-sorted EoL fraction on sorting site*

eol treatment

f_{rec}	*fraction of EoL stream for recycling*
f_{comb}	*fraction of waste stream for combustion*
f_{land}	*fraction of waste stream for landfill*
W_{rec}	*EoL stream for recycling*
W_{comb}	*waste stream for combustion*
W_{landf}	*waste stream for landfill*

In this end-of-life scenario, the total material EoL stream of product A, for respectively *recycling*, *combustion* and *landfill* processes, is therefore the sum of all sorted EoL streams multiplied by the fraction for respectively *recycling*, *combustion* and *landfill*, represented in Equation 7.5, Equation 7.6 and Equation 7.7.

$$W_{dem,A,} = W_{rec,\,A} + W_{comb,\,A} + W_{landf,\,A}$$ **Equation 7.1**

$$f_{rec,\,A} = f_{rec,\,pre\text{-}sort,\,A} + f_{rec,sort,\,A}$$ **Equation 7.2**

$$f_{inc,\,A} = f_{inc,\,pre\text{-}sort,\,A} + f_{inc,sort,\,A} + f_{inc,\,NS\,final,\,A}$$ **Equation 7.3**

$$f_{landf,\,A} = f_{landf,\,pre\text{-}sort,\,A} + f_{landf,sort,\,A} + f_{landf,\,NS\,final,\,A}$$ **Equation 7.4**

$$W_{rec,A} = (S_{pre\text{-}sort,A} + S_{sort,A}) \times f_{rec,A} = [(W_{dem,A} \times f_{S1,A}) + (W_{dem,A} \times f_{NS1,A} \times f_{S2,A})] \times f_{rec,A} \quad \textbf{Equation 7.5}$$

$$W_{comb,A} = (S_{pre\text{-}sort,A} + S_{sort,A}) \times f_{comb,A} = [(W_{dem,A} \times f_{S1,A}) + (W_{dem,A} \times f_{NS1,A} \times f_{S2,A})] \times f_{comb,A} \quad \textbf{Equation 7.6}$$

$$W_{land,A} = (S_{pre\text{-}sort,A} + S_{sort,A}) \times f_{land,A} = [(W_{dem,A} \times f_{S1,A}) + (W_{dem,A} \times f_{NS1,A} \times f_{S2,A})] \times f_{land,A} \quad \textbf{Equation 7.7}$$

With:

$W_{dem,A}$ *total EoL stream of product A in demolition scenario (kg or m³)*
$W_{rec,A}$ *material EoL stream for recycling of product A (kg or m³)*
$W_{comb,A}$ *material waste stream for incineration of product A (kg or m³)*
$W_{land,A}$ *material waste stream for landfill of product A (kg or m³)*
$f_{rec,A}$ *fraction of the total EoL stream of product A for recycling(%)*
$f_{comb,A}$ *fraction of the total waste stream of product A for incineration(%)*
$f_{land,A}$ *fraction of the total waste stream of product A for landfill(%)*
$S_{pre\text{-}sort,A}$ *sorted EoL fraction on demolition siteof product A (kg or m³)*
$S_{sort,A}$ *sorted EoL fraction on sorting site of product A (kg or m³)*

The sorted fractions can be increased introducing DfD strategies in the design of building products, which have a double function: increasing the level of separation of building materials to augment the potential for recycling, and increasing the level of direct reuse. In this case, one talks about a *deconstruction site*, instead of a *demolition site*. This scenario is represented in

Figure 7.5

In this EoL scenario, the total material EoL stream of product A, for respectively reuse, *recycling*, *combustion* and *landfill* processes, is therefore the sum of all sorted EoL streams multiplied by the fraction for respectively *reuse*, *recycling*, *combustion* and *landfill*, represented in Equation 7.10, Equation 7.11, Equation 7.12 and Equation 7.13.

$$W_{dec,A,} = W_{reuse,A} + W_{rec,A} + W_{comb,A} + W_{landf,A} \quad \textbf{Equation 7.8}$$

$$f_{reuse,A} = f_{reuse,\,pre\text{-}sort,A} + f_{reuse,\,sort,A} \quad \textbf{Equation 7.9}$$

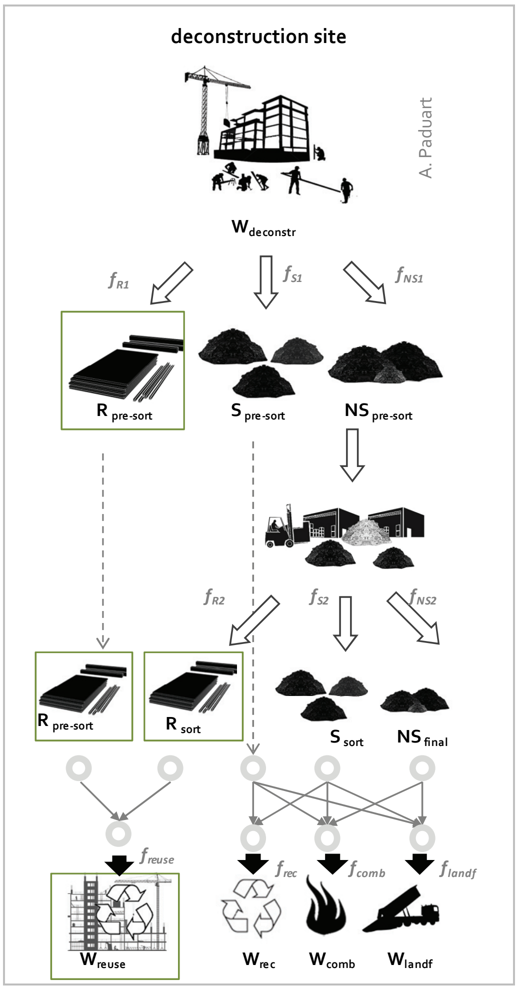
$$W_{reuse,A} = (R_{pre\text{-}sort,A} + R_{sort,A}) \times f_{reuse,A} = [(W_A \times f_{R1}, A) + (W_A \times f_{S1,A} \times f_{R2,A})] \times f_{reuse,A} \quad \textbf{Equation 7.10}$$

$$W_{rec,A} = (S_{pre\text{-}sort,A} + S_{sort,A}) \times f_{rec,A} = [(W_A \times f_{S1}, A) + (W_A \times f_{NS1,A} \times f_{S2,A})] \times f_{rec,A} \quad \textbf{Equation 7.11}$$

$$W_{comb,A} = (S_{pre\text{-}sort,A} + S_{sort,A}) \times f_{comb,A} = [(W_A \times f_{S1}, A) + (W_A \times f_{NS1,A} \times f_{S2,A})] \times f_{comb,A} \quad \textbf{Equation 7.12}$$

$$W_{land,A} = (S_{pre\text{-}sort,A} + S_{sort,A}) \times f_{land,A} = [(W_A \times f_{S1}, A) + (W_A \times f_{NS1,A} \times f_{S2,A})] \times f_{land,A} \quad \textbf{Equation 7.13}$$

Figure 7.5: End-of-life treatment of material end-of-life stream on deconstruction site



deconstruction site

$W_{deconstr}$	*total EoL stream*
f_{R1}	*fraction of EoL stream that can be reused*
f_{S1}	*pre-sorted fraction of EoL stream that is being pre-sorted*
f_{NS1}	*non-presorted fraction of EoL stream*
$R_{pre\text{-}sort}$	*reused EoL fraction at deconstruction site*
$S_{pre\text{-}sort}$	*sorted EoL fraction at deconstruction site*
$NS_{pre\text{-}sort}$	*non-sorted EoL fraction at deconstruction site*

sorting site

f_{R2}	*reusable fraction of EoL stream*
f_{S2}	*sorted fraction of EoL stream*
f_{NS2}	*non-sorted fraction of EoL stream*
R_{sort}	*reused EoL fraction on sorting site*
S_{sort}	*sorted EoL fraction on sorting site*
NS_{final}	*non-sorted final EoL fraction*

eol treatment

f_{reuse}	*fraction for reuse*
f_{rec}	*fraction for recycling*
f_{comb}	*fraction for combustion*
f_{land}	*fraction for landfill*
W_{reuse}	*EoL stream for reuse*
W_{rec}	*EoL stream for recycling*
W_{comb}	*waste stream for combustion*
W_{landf}	*waste stream for landfill*

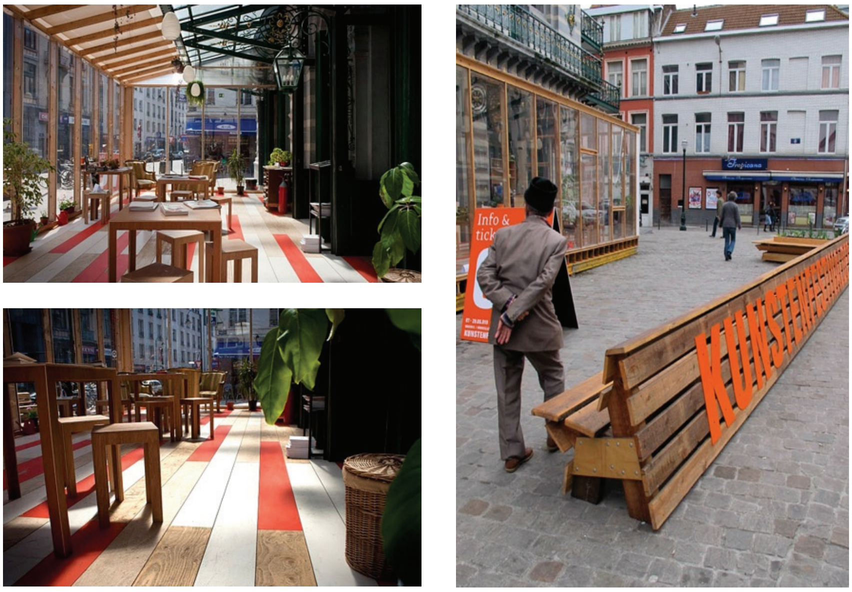
With:

$W_{dem, A}$	*total EoL stream of product Ain demolition scenario (kg or m³)*
$W_{reuse,A}$	*material stream for reuse of product A (kg or m³)*
$W_{rec, A}$	*material EoL stream for recycling of product A (kg or m³)*
$W_{comb, A}$	*material waste stream for incineration of product A (kg or m³)*
$W_{land, A}$	*material waste stream for landfill of product A (kg or m³)*
$f_{reuse, A}$	*fraction of the total EoL stream of product A for reuse (%)*
$f_{rec, A}$	*fraction of the total EoL stream of product A for recycling(%)*
$f_{comb, A}$	*fraction of the total waste stream of product A for incineration (%)*
$f_{land, A}$	*fraction of the total waste stream of product A for landfill (%)*
$R_{pre\text{-}sort, A}$	*sorted fraction for reuse on deconstruction site of product A (kg or m³)*
$S_{pre\text{-}sort, A}$	*sorted EoL fraction on deconstruction site of product A (kg or m³)*
$S_{sort, A}$	*sorted EoL fraction on sorting site of product A (kg or m³)*

$R_{sort, A}$ *sorted fraction for reuse on sorting site of product A (kg or m³)*

The higher the fraction for reuse, the lower the fraction for final disposal is. To optimise the EoL management, the fraction (f_{R1}) can therefore be optimised through design for deconstruction. In addition, end-of-life streams that can be easily pre-sorted on the demolition/deconstruction site, are associated with lower transport distances.

Figure 7.6: Headquarters designed for KunstenFestivalDesArts constructed from materials left over from previous spectacles and renovations by Rotor



Source: Rotor

For the modelling in SimaPro, the environmental residual value at the end-of-life of buildings was not considered in the environmental life cycle assessment, for the same reasons of cut-off than for the recycling of building products. The residual value is introduced as an additional assessment option, in parallel with the life cycle analysis. The evaluation of the residual value of sub component at the end-of-life of buildings is considered separately, to give an indication of the benefits that can be related to the residual value of components, in case of a dynamic design approach.

However, *during* the life cycle of buildings, it was assumed that sub components that can be reused are utilised for the *same application* in which they initially feature, in case replacements/adaptations occur as a result of the specifications of the assessment scenario (see Chapter 8). Reuse of sub components is then only modelled if the sub components meet a range of preconditions. These preconditions are the same as the preconditions set up for the determination of residual value at the end-of-life.

Reuse of sub components and the residual value at the end-of-life, are calculated as a value in function of the *time* parameter. The reuse potential and environmental residual value is esteemed significant and incorporated in the model, under the following set of determined preconditions:

1. the connection techniques must be reversible;
2. the material must be reusable (see Chapter 3);
3. the total initial estimated service life of the component (ESLC) of the considered component A must be longer than 10 years;
4. the remaining service life after the period of analysis must still accounts for half of the value of the initial ESLC;

If these conditions are met reuse of a sub component is considered for the same application in the considered building life cycle. When the service life of this component is reached, this sub component is replaced subsequently. When the end of the service life is not yet reached at the end-of-life of the building – i.e. the end of the period of analysis- the remaining residual value of the sub components can be calculated according to Equation 7.14:

$$RV_A = \left(\frac{\mathbf{ESLC_A} - \frac{\mathbf{T}}{\mathbf{n_A + 1}}}{\mathbf{ESLC_A}} \right)$$ **Equation 7.14**

With:

RV_A	*residual value factor of (sub) component A (%)*
$ESLC_A$	*estimated service life of (sub)component A (years)*
T	*period of analysis (years)*
n_A	*number of replacements during period of analysis of (sub)component A*

For the calculation of the residual value factor of component A, the following can then be said:

If	$RV_A < 0$	component A was not replaced even if its service life span was already exceeded[4];
If	$RV_A = 0$	there is no remaining service life of component A, or, component A was not designed according to DfD principles;
If	$RV_A > 0$	there is remaining service life for component A.

In respect to the financial market value of reused building components, it is assumed that component reuse will mainly take place in lower applications, and therefore, the financial

[4] For instance, if the end-of-life of the building was predicted to take place only some years after replacement of the component would eventually have to take place.

value will strongly reduce. The environmental benefits however, remain equally valuable, since the use of reused materials prevents new materials to be produced for a specific application.

END-OF-LIFE TREATMENT

The subdivision of transport categories for end-of-life treatment of building products is based on the main waste categories currently separated from the building waste stream [BBRI 2010; NIBE 2003]. A first subdivision is made based on the current amount of sorting on the demolition/ deconstruction site, i.e.:

- *Waste types with sorted fraction on site (S);*
- *Waste types non-sorted on site (NS).*

The main groups are further divided in subcategories, based building waste scenarios. The figure being recycled, combusted or disposed, per sub waste category, is represented in Table 7.1.

Table 7.1: End-of-life treatment of main building waste categories [BBRI 2010, NIBE 2008]

	Waste categories		End-of-Life treatment landfill [%]	comb. [%]	recycl. [%]
S	**waste types with fraction sortable on site**				
S_i	Inert waste				
		Concrete, ceramic product and loose materials (sand, etc.)	5	0	95
S_c	Cellular concrete				
		Bricks	85	0	15
S_m	Metals				
		Steel, Aluminium, Zinc, Copper	5	0	95
S_w	Wood Products				
	Type 1: Wood Products (treated)		5	95	0
	Type 2: Wood Product (untreated)		5	20	75
	Type 3: Composite Wood products (e.g. OSB, Particle Board, MDF)		5	75	20
S_p	Packaging				
		Paper and cardboard	3	3	94
		Plastic foils	30	10	60
NS	**waste types non-sorted on site**				
NS_i	Insulation products (1)				
	Based on mineral resources (e.g. glass wool, rock wool, foam glass)		85	5	10
	Based on petrochemical resources (e.g. PUR, XPS, EPS)		5	90	5
	Based on renewable resources (e.g. cork, cellulose fibers)		5	95	0
NS_g	Gypsum Products				
		e.g. gypsum plasterboard, blocks	95	0	5
NS_p	Plastering				
		Internal and external rendering	100	0	-
NS_{gl}	Glass				
		e.g. flat glass of windows	30	0	70
NS_{pvc}	PVC				
	Window frames		10	45	45
	Electric cables and wire insulation		10	40	50
	Membranes, floor finishing, etc.		15	65	20
	Pipes		10	30	50
NS_r	Rest products				
		Other fractions, e.g. carpet, linoleum	40	40	20

7.2.4.3 TRANSPORT SCENARIOS

The environmental impact of the transport to the construction site, and the end-of-life transport of building waste, depends on the means of transportation and the transport distances. To model the transport in the life cycle assessment, transport categories were determined through a limited survey executed by the Belgian Building Research Institute [BBRI 2010] since other data for the Belgian context are lacking. In the survey, contractors, producers and dealers of construction products are questioned about the transportation distance, means and load percentage for different predefined categories of building materials. This report included data for Flanders about typical transport of building products to the construction site, and present-day end-of-life treatment of building waste, and consequently acted as a starting point to set up transport and waste categories for the building products assessed in this research.

Four main categories have been set up for the transport to the *construction site*, based on the assembly at the construction site, the product specificity and the type of building product:

- *Category 1: transport of prefabricated or preassembled building products typically directly transported from the production to the construction site;*
- *Category 2: all transport of in-situ assembled and finished building products, excluding finishing products (e.g. paint);*
- *Category 3: transport of finishing building products(e.g. floor and wall finishing);*
- *Category 4: transport of technical building products.*

Table 7.2: Means of transportation during life cycle of a building product from initial transport to construction site

Category	Transport type		Lorry type used for transport to construction site		
	direct	*indirect*	*directly to construction site*	*transport to intermediary site*	*from intermediary to construction site*
1	100%	-	[Lorry > 16t] 100%	-	-
2 a	40%	60%		[Lorry > 16t] 100%	85% [Lorry > 16t] 15% [Lorry 3,5 – 16t]
2 b			50% [Lorry > 16t] 50% [Lorry 3,5 – 16t]		50% [Lorry > 16t] 50% [Lorry 3,5 – 16t]
3 a	10%	90%	[Lorry 3,5 – 16t] 100%		90% [Lorry > 16t] 10% [Lorry 3,5 – 16t]
3 b					80% [Lorry 3,5 – 16t] 20% [Van < 3,5t]
4	-	100%	-		

[icon]	Lorry > 16t	[icon]	Lorry 7,5 – 16t
[icon]	*Lorry 3,5 – 16t*	[icon]	*Van < 3,5t*

For the transport to the *end-of-life* treatment, transport categories are defined based on the material type. For recycled products, only the transport to the sorting site is incorporated. More background information about all defined transport categories, modelled transport distances and the means of transportation can be found back in Appendix II.

Analysis of the contribution of the transport of materials during the construction and end-of-life phase -only taking place a restricted number of times over an entire building life cycle- reveals that the transport does not significantly contribute to the overall environmental impact of building products. Transport during the occupation phase of buildings due to inhabitants' private transport – as a result of urban design - does play a key role in sustainability [Allacker 2010].

Table 7.3: Means of transportation during life cycle of a building product from demolition site to sorting site and to EoL treatment

Waste category			**Sorted fraction on site**		**Transport from demolition site**	
			sorted fraction s_x	*non-sorted fraction ns_x*	*to sorting site*	*to eol treatment*
	S_i	*inert waste*	75%	25%	90% 10%	100%
	S_c	*cell. concrete*	30%	70%	70% 20% 10%	100%
	S_m	*metals*	85%	15%		
	S_w	*wood products*	40%	60%		
	S_p	*packings*	50%	50%		
	NS	*non-sorted waste*	-	100%	80% 20%	

	Lorry > 16t		Lorry 7,5 – 16t
	Lorry 3,5 – 16t		*Van < 3,5t*

7.2.5 UNCERTAINTIES DURING BUILDING LIFE CYCLE

Various estimations have to be made during life cycle assessment of buildings, influencing the overall life cycle assessment results. Inaccurate assumptions due to data quality, errors in the building description, estimation of the service life of a building and its components, and uncertainties in the impacts assessment method in the executed life cycle assessment may lead to large deviations in results [Lenzen 2006, Allacker 2010, Kohler 2010].

Table 7.4 gives an overview of the effect of errors in LCA and LCC, according to their impact during the initial construction phase and the life cycle of a building.

Table 7.4: Effects of errors inaccuracies in life cycle assessment and life cycle costing (adapted from from [Kohler et al. 2010])

Category	Assumptions	Error	Effect on initial phase	Effect on life cycle
building inventory	element quantities	deviation on element quantities	high	low
	element type	replaced with nearby element	high	low
life cycle	building life span	wrong service life	low	**high**
	component life span	wrong service life	low	**high**
		wrong replacement interval	low	**high**
assessment data	dynamic assessment	discount rate	low	**high**
	energy carrier inventory	different electricity mix	low	**high**

The categories for which inaccuracies in the life cycle assessment and life cycle costing have been identified to have a high influence on the overall life cycle, the sensitivity of the data was taken into account. First, the effect of an incorrect assumed service life of buildings – i.e. the evaluation period - and service life of components has been indicated crucial for the life cycle performance of buildings. These variables will be discussed in the next paragraphs. Secondly, the discount rate is crucial for the life cycle costing results. This will therefore be discussed in the paragraph concerning LCC. Last, the electricity mix was defined to play a significant role for the life cycle analysis. This explains why the Swiss data were adapted to the Belgian situation, as previously discussed.

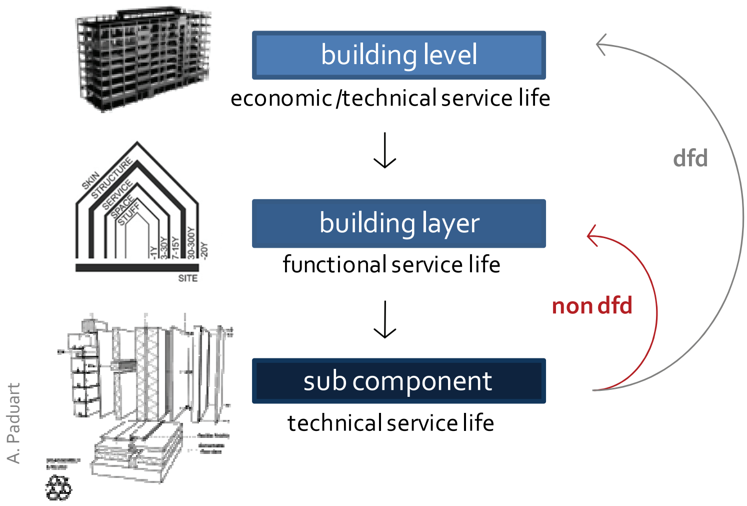
7.2.5.1 EVALUATION PERIOD

In ISO 14040 (2006) it is recommended to review the results over several periods of analysis for a shorter or longer period than the assumed life cycle, since the period of analysis is an important variable in the life cycle performance of buildings. In this research, the period of analysis was based on the remaining service life of the building structure after renovation (45 years), while a short period was considered in parallel. The selected evaluation period and different scenarios are discussed more in detail in Chapter 8.

7.2.5.2 SERVICE LIFE: BUILDING – BUILDING LAYER – SUB COMPONENT

In this research study an additional service life is incorporated which is not generally included in LCA and LCC practise: the functional service life of the *building* layer (e.g. facade layer or partitioning layer*)* defined according to Brand (1995).

Figure 7.7: Service lives on three levels: building - building layer – sub component



The **functional service life of building layer** is different than the service life of the *building* and the service life of *sub components* (in building layers). It is crucial to introduce this additional service life in this research to evaluate the comparison between standard design and dynamic design in the context of this research.

The building service life and component life are typically integrated in life cycle assessment. However, the replacement rate of building layers is generally never included. The inclusion of the service life of the building layer enables to include transformations relating to this building layer, e.g. repartitioning of the internal space in apartments. In this case, the service life of the building layer (i.e. partitioning) is different from the building service life and the components' service lives, meaning that replacements of components have to be *added*, related to this layer service life. Therefore, the integration of this supplementary functional service life was applied to generate a more realistic perspective on the dynamic life cycle of buildings. In addition, the use of the layer service life enables to incorporate benefits relating to DfD design, since multiple transformations enabled by this dynamic design can be evaluated in the LCA and LCC.

To take the uncertainties into account that exist for the determination of the functional service life of the building layer and the building, several building scenarios are formulated in Chapter 8. The determination of the service life of the building and its layers is based on literature, and the survey that was executed in this research.

ESTIMATED COMPONENT SERVICE LIFE (ESLC)

To take into account uncertainties about the component service life, an additional calculation method is required. The information available about the service life of building components is extensive, diverse and very inconsistent [Kohler 2010]. Therefore, the International Organisation for Standardisation (ISO) devised the factor method in accordance with ISO 15686-1 in order to allow a large number of factors to be taken into account influencing the component service life. The service life of any product can be estimated using seven factors which cover the aspects of building component quality, environment and utility (Table 7.5).

Table 7.5: Estimation of the component service life using the factor method [ISO 15686-1]

Component quality	**A**	quality of the component	0,8 - 1,2
	B	design level	0,8 - 1,2
	C	work execution level	0,8 - 1,2
Environment	**D**	indoor environment	0,8 - 1,2
	E	outdoor environment	0,8 - 1,2
Conditions of use	**F**	in-use condition	0,8 - 1,2
	G	maintenance level	0,8 - 1,2

The estimated service life can then be calculated with the following formula:

$$ESLC = RSLC \times A \times B \times C \times D \times E \times F \times G$$

Equation 7.15

With:

ESLC = Estimated Service Life of a Component (years)
RSLC = Reference Service Life of a Component (years)

The key questions when using the factor method are what to assume as the reference service life (RSLC) and where to obtain the values for the factors (factors A to G). A limited number of sources are available for the reference service life of products, amongst which the SBR publication [Huffmeijer 1998] and the publicly accessible BMVBS database [BVMBS 2010], both designed for use in the building sector. The latter database is a result of a research project, which aimed to contribute to a transparent and accountable calculation of component service lives based on the factor method, designed to be an open system so that values may be added or expanded. There are roughly 200 service lives, in 43 different categories, ranging from construction elements to interior finishing [van Nunen 2010]. Furthermore, the values for the reference service life (including a minimum, maximum and average service life) of every building component layer or component part are given for multilayered or assembled building components, whose individual components could have different expected service lives.

The estimated service life can be adjusted for specific circumstances, by giving values to the seven factors, which may result in a longer or shorter service life. In the 'improved factor method', Van Nunen (2010) assumes that additional factors need to be implemented to take into account other types of replacements than replacements than due to technical failure of the components. Therefore, he introduces the factor 'Trends' and 'Related components' to adjust the reference service life according to individual choices related to trends, and replacement of components that are adjoining the component that needs to be replaced.

In this research, these additional aspects are dealt with at the level of the assessment. To deal with the first aspect, the functional service life of the building layer, deals with other replacements (functional) than due to the technical replacement of the components. Secondly, to deal with the replacement of components that are adjoining components which need to be replaced – due to technical or functional end of the service life - a difference is made in the modelling of the building layers, between (sub) components which are assembled using fixed or irreversible connections. For each building layer modelled in the LCA software, it is determined for each building solution, which constituting sub components are permanently connected to each other, and which can consequently not be replaced independently of each other.

Then, to give values to the factors according to the factor method, it was decided to analyse the influence of the extreme scenarios, i.e. the worst case for the estimated service life and the best case, as represented in Table 7.6. The values of the factors (A to G) can vary between 0,8 and 1,2 but ISO 15686-8 recommends to use values between 0,9 and 1,1. Therefore these data are applied as variables in the calculation of both LCA and LCC, in SimaPro software.

Table 7.6: Applied scenarios for Estimated Service Life expectancy of Components

	Minimum ESLC	Typical ESLC	Maximum ESLC
RSLC	median minimum service life expectancy	median typical service life expectancy	median maximum service life expectancy
A, B, C, D, E, F, G	0,9	1	1,1

7.3 LIFE CYCLE COSTING

7.3.1 AIMS AND GENERAL DESCRIPTION

Until recently, investors considered that most financial risk occurs during the construction phase relating to e.g. material shortages, time overruns, defects, and faulty budgeting [Clift 2003]. Nevertheless, investors funding long-term projects, like social housing companies, may start to realise that there is even greater uncertainty in the operational phases of buildings. The lack of understanding of how buildings perform and how often and why they change, and where the need for intervention should occur, makes prediction of future costs unreliable [Clift 2003].

The aim of the economic evaluation in this dissertation does not relate to finding the most optimised building solution, but is to gain insights of the additional/lowered financial costs related to dynamic design. Literature suggests that making new buildings suitable for future transformation may be significantly cost effective, minimising building redundancy whilst optimising sustainability [Geraedts 2008].
Due to the context of this study in renovation, the transformation is limited to dynamic building components added after the building renovation. Therefore, in parallel with the environmental assessment, it is evaluated if the dynamic approach of the new building layers results in benefits or drawbacks over an entire building life cycle. Similar to LCA, LCC requires specification of goal and scope (system boundaries, the object of study, allocation), and alignment with the decisions taken for the Life Cycle Assessment in order to obtain an overall consistent evaluation.

Economic advantages cannot be assessed in isolation from the perspective, and motives of the various stakeholders. In this evaluation, the financial aspects are viewed from the perspective of social housing companies, since it is their responsibility to make initial investments, and they are confronted with the maintenance and end-of-life costs of their building stock.

The technique in this research, takes into account the present value of future costs and benefits of a product by the discounting method. The methodology addresses how LCC can be used as an economic evaluation technique for buildings that integrate dynamic building layers.

7.3.2 PROCEDURE

7.3.2.1 DYNAMIC ASSESSMENT METHOD

In life cycle costing, two assessment approaches can be applied, i.e. including static or dynamic processes. In contrast to static processes - in which economic efficiency is assessed based on investment costs without considering the moment in which they arise - dynamic processes include the exact points in time of occurring costs in the time line of the investment [Kohler 2010]. In dynamic assessment it is possible to select a suitable discount rate, reflecting the time value of money. Discounting means that expenses and savings in the future are not valuated as high as present values. Because currency is subject to inflation and has the ability to earn interest, it is worth more today than currency tomorrow.

The *present value* is a widely applied dynamic method for life cycle costing that enables to calculate a wide variety of specific dynamic indices.

7.3.2.2 TOTAL PRESENT VALUE

Within the present value method, all costs are related to their present value at the time of the original investment. All costs that occur after the construction phase are not entered as their nominal amount but as the sum which would have to be set aside at the present time in order to yield the actual later amount through the application of a preset interest rate.

The present value therefore is the sum of the cash values of all the occurring costs, which can be calculated using a discount rate 'd', defined as *the factor reflecting the time value of money that is used to convert cash flows occurring at different times to a common time'* [ISO1568-5 2006]. The present value a future cost C_t can therefore be calculated as:

$$PV\ (C_t) = \frac{\mathrm{C_t}}{(1+d)^t}$$ **Equation 7.16**

$$PV\ (C_t) = \frac{\mathrm{C_0}\ (1+\mathrm{i})^{\mathrm{t}}}{(1+d)^t}$$ **Equation 7.17**

With

C_t	*Future cost (€)*
C_o	*Cost at present time (€)*
d	*Discount rate*
i	*Inflation rate*
t	*time (year)*

The choice and basis of the discount rate in the calculation is particularly important in the assessment [Kohler 2010]. A discount rate of 0% corresponds to a static calculation, in which future costs are equally important as current costs and thus time does not matter.

This discount rate can be used to perform sensitivity analysis in exceptional cases for long-term considerations or discussions relating to fairness to subsequent generations [Kohler 2010]. This is the case for environmental assessment, in which it is assumed that the environmental impacts today are equally important in the future.

The higher the discount rate, the more importance is given to the near-present and the less importance is given to what happens in the distant future [Gluch and Baumann 2004]. In this case, costs scheduled to be made in the very distant future (e.g. deconstruction costs, end-of-life costs) may be almost insignificant in terms of their net present value.

By discounting, financial cost and gains occurring at different moments during the life span of buildings become comparable and can be aggregated into a total present value, using the following formula:

$$LCF = IF + \sum_{t=1}^{T} PF_t^D + \sum_{t=1}^{T} \mathrm{EOL\,F_t^D} - \mathrm{RV^D}$$

Equation 7.18

To indicate the costs that occur during the life cycle in a clear way, the terminology used by Allacker (2010) has been applied further in this text, using the following representation of the previous equation:

$$LCF = IF + SPV(PF) + SPV\ (EOL\ F) - \mathrm{RV^D}$$

Equation 7.19

With:

LCF	= life cycle financial costs (€)
IF	= initial financial costs (€)
PF^D	= discounted periodic replacement costs of building components at time t (€)
EOL F^D	= discounted end-of-life costs at time t(€)
RV^D	= discounted residual financial value/cost at the end of the building life span (€)
T	= the analysis period (years)
SPV(PF)	= sum of the present values of the periodic financial costs (€)
SPV(EOL F)	= sum of the present values of the EOL costs (€)

7.3.3 INPUT VARIABLES

7.3.3.1 INCLUSION OF COSTS

Within the scope of this research, the *initial financial cost* of a building product (*IF)* is calculated by summing the material costs of each sub component with its labour assembly costs on site.

The *periodic costs* (*PF)*, relating to maintenance, replacements and transformations over the period of analysis are integrated by adding the present value of these future costs to the initial investment costs. These periodic costs include costs associated with the end-of life of components (ESLC), but also replacement costs due to the end of the functional service life of building layers. For instance, if partitioning of a space is adapted, wall partitioning needs to be demolished/deconstructed, according to the assembly techniques (DfD or non-DfD). The need for replacement by a new wall, or the reuse of disassembled sub components depends on the reversibility of the assembly of the sub components. The cost types include labour removal costs, material costs in case of new construction, labour (re)assembly costs and EoL costs concerning the disposed elements.

These *end-of-life* costs (*EOL F*) include the costs for demolition/deconstruction, landfill, incineration and transport. Components to be reused are assumed to be in adequate state -due to the preconditions set for the evaluation if reuse is possible – implying that no form of repair in taken into account.

If there were to be a large difference between the service life of the building and the estimated service life of components, e.g. early building demolition, one can estimate the residual value at the end of the functional life span as the 'selling' value of the remaining construction for other functions.

Costs related to the designer's fee, energy, technical services and land occupation are not considered, since it does not fit into the scope of the research, and it can be assumed equal for all solutions.

7.3.3.2 ECONOMIC PARAMETERS

DISCOUNT RATE

Discounting refers to the application of a selected discount rate so that each future cost is adjusted to present time, i.e. the time when the decision is made. It is important to not confuse discounting with inflation; the discount rate is the investment premium over and above inflation [Langdon 2007]. Inflation is a rise in the general price level, reflecting a decline in the purchasing power of money.

Two types of discount rates are used in computing the present value: a *real* rate or a *nominal* rate. The real discount rate reflects the time value of money without accounting for the effects of inflation and deflation. A nominal rate is applied when all cost data change in value from year to year depending on the general price level. Since buildings have long service lives, causing difficulties to predict inflation in the long term, it is preferable to use constant-currency since it eliminates the need to estimate the rate of inflation over the duration of the study period. Therefore it is recommended to use real costs (excluding inflation) and the real discount rate [ISO 15686-1].

The nominal cost (C_N) is defined as the expected price that will be paid when a cost is due to be paid (i.e. including inflation and price changes due to evolution of technology, efficiency). The real cost (C_R) discounted by the real discount rate (d') is equivalent to the nominal cost, discounted by the nominal discount rate (d). For a component having a nominal cost C_N in year t, the real cost C_R at the base date (year 0) is given by the following [ISO 15686-1]:

$$C_R = \frac{C_N}{(1+i)^t}$$ **Equation 7.20**

The discounted present value (PV) of a future cost in year t is therefore:

$$\begin{aligned} PV(C_t) &= \frac{C_R}{(1+d')^t} \\ &= \frac{C_N}{(1+i)^t(1+d')^t} \qquad (1) \\ &= \frac{C_N \times (1+i)^t}{(1+i)^t(1+d)^t} \\ &= \frac{C_N}{(1+d)^t} \qquad (2) \end{aligned}$$

From (1) and (2) one can derive the real discount rate d':

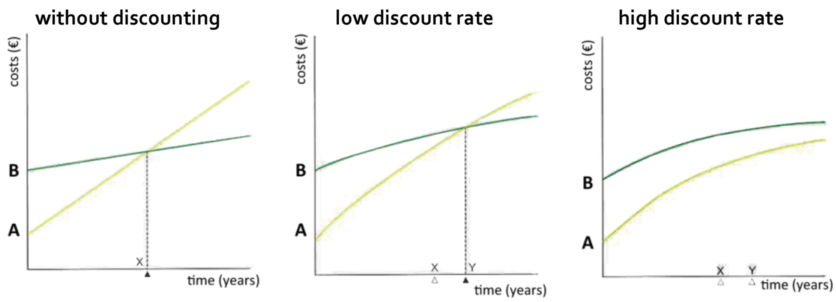
$$\begin{aligned} \frac{C_N}{(1+i)^t(1+d')^t} &= \frac{C_N}{(1+d)^t} \\ (1+d')^t &= \frac{(1+d)^t}{(1+i)^t} \\ d' &= \frac{(1+d)}{(1+i)} - 1 \end{aligned}$$

With:

d = nominal discount rate
d' = real discount rate
i = inflation rate

As the life cycle costs are discounted to their present value, the selection of a suitable discount rate is a crucial decision in LCC analysis. This is illustrated in Figure 7.8. Figure 7.8 compares two variants of a possible investment assuming different discount rates. In this comparison product A always has lower initials costs and higher follow-up costs than B, while the variant B has higher initial costs, but lower follow-up costs. The first graph in Figure 7.8 shows the simplified consideration without discounting and with regular follow up costs, whereas the second graph illustrates the low discount rate, and the last graphs represents a high discount rate. These figures clearly illustrate that the selected discount rate influences the ranking of the two variants.

Figure 7.8: Effect of the choice of discount rate on the trade-off between initial and periodic costs [Kohler 2010]



There is no consensus in literature on what discount rate is the most appropriate [Davis Langdon 2007]. Much of the literature offers little regarding the final selection of an appropriate rate – estimates vary between 3-4% and in excess of 20% - making the he choice of the discount rate one of the most debatable topics in public project evaluation. Investors in the public sector tend to favour much lower levels of discount than their private sector counterparts: in some countries the appropriate public financing authorities recommend rates that are typically between 2% and 5% net of inflation – i.e. real discount rates [Davis Langdon 2007].

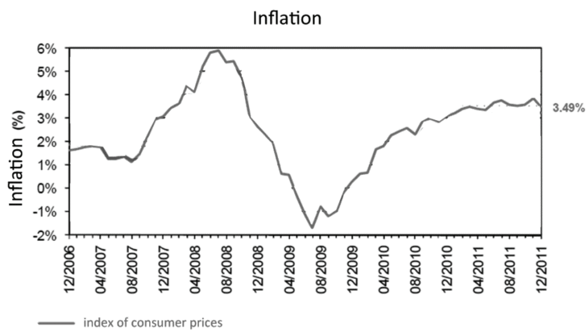
The discount rate within this research should reflect the public owner of buildings interest to invest money in buildings. Therefore, in this research the selection was based on the cost of borrowing funds. The interest rate should match the rate paid by government for borrowed money. This approach is favoured by many agencies and is supported by the argument that government bonds are in direct competition with other investment opportunities in the private sector [Davis Langdon 2007].

The Federal Plan Bureau predicts a long term (10 years) interest rate for the period 2010-2016 of 4.4% [Federaal Planbureau 2011 b] for the Eurozone. Based on these data, a yearly (nominal) rounded discount rate of 4% is assumed. Sensitivity analysis will be done on the results.

The general inflation in Belgium is represented by the 'index of consumer prices', which represents the average evolution of prices of the average consumption pattern of a Belgian citizen [FOD economie 2011]. The index is updated frequently since the consumption pattern is changing over time.

To estimate the growth rates of labour and building material prices, the difference of the evolution in time of these prices in comparison with the general inflation over the same period of time needs to be defined. Figure 7.9 represent the index of consumer prices in Belgium between 2006 and 2011.

Figure 7.9: Growth of consumer prices for the period 2006 – 2011 (Belgium) [FOD Economie, 2011 a]



For 2012, the Federaal Planbureau expects a average year inflation of 2,3% [FOD Economie, 2011 a]]. The assumption of an inflation rate i of 2% is acceptable, in relation to the conservation of price stability[5], which is one of the main aims of the ECB and the central banks of the Eurosystem. Their main objective is to maintain an inflation percentage of about 2%, ensuring that the economy can benefit the advantages of price stability [Lisbon Treaty 2009]. This target offers an adequate margin to prevent the risks of deflation.

Prices of building materials, labour or energy do not change at the same rate as the general inflation rate. Therefore a growth rate, 'g', can be defined which reflects the

[5]In October 1998 the Governing Council of the ECB announced a quantitative definition of *price stability* as "a year-on-year increase in the Harmonised Index of Consumer Prices (HICP) for the euro area of below 2%". With the adoption of the "Treaty on the Functioning of the European Union [Lisbon Treaty, 2009]" price stability becomes an objective of the Union aiming to maintain inflation rates close to 2% over the medium term.

different evolution over time of specific products and/or services [Allacker 2010].To estimate the growth rates of labour and building material prices, the difference of the evolution in time of these prices in comparison with the general inflation over the same period of time needs to be determined [Allacker 2010].

The *ABEX-index* is the most widely used measure in Belgium to express the evolution of costs, related to the building sector. The ABEX-index is determined by the Association of Belgian EXperts and is published in May and November [ABEX 2011]. It is strongly influenced by the supply and demand of the building market, meaning that in times of high demand, the prices rise and subsequently, the ABEX-index increases and vice versa.

The ABEX index is based on the evolution of prices from 2000 to 2011 by deducting a average annual (nominal) growth rate based on the real evolutions. This leads to a rounded ABEX-index of 3% (nominal value), used for the growth rate g, reflecting the faster growth compared to the general inflation due to the specificity of the building sector.

The real growth rate can be calculated similar to the real discount rate, so that the present value of future costs can be calculate with the following equation:

$$SPV\ (\mathrm{PF^D}) = \sum_{\mathrm{t=x,y,z}}^{\mathrm{t=T}} \frac{\mathrm{PF^D}\ (1+\mathrm{g'})^{\mathrm{t}}}{(1+d')^{t}}$$ **Equation 7.21**

With

PF^D	= discounted periodic cost occurring at time x, y and z (€)
x, y, z	= time in which the periodic costs occur (years)
SPV(PF)	= sum of the present values of the periodic financial costs (€)
d'	= real discount rate
g'	= real growth rate

7.3.3.3 DATA COLLECTION

In order to make a comparison between the different financial costs related to alternative building products, sufficient reliable and qualitative data on the construction costs need to be available.

In Belgium, the most relevant sources are the ASPEN index, the BOUWUNIE [BOUWUNIE 2008] database, and the UPA-BUA database [UPA-BUA 2009]. For the financial data collection in this research, the ASPEN index was retained as main database [ASPEN 2009]. This database contains financial data for the Belgian context and is updated every six months. This database provides material and labour (assembly and removal) costs of the most common building materials and products applied within the Belgian context, and includes the transport costs to the construction site and material losses during construction. Data are usually expressed in €/m² or €/m. When specific data are lacking, the BOUWUNIE database is used, or product specific data are sought based on products catalogues and tenders.

Using reference prices in a LCC study, the results are always an approximation of the real price market, since costs in practice may vary due to specific circumstances. The aim of the study however, is to make a relative comparison between products, so deviations of the real price are acceptable.

Value added tax (VAT) is included in the LCC calculations based on the current situation in Belgium for renovation, which means 6% VAT for renovations and replacements.

7.3.4 ASSESSMENT TOOL: MODELLING IN SIMAPRO

7.3.4.1 LCA AND LCC IN SIMAPRO

Since both LCC and LCA conducted in this research are based on the same structure, both assessments can be conducted in the same software based on the same functional unit. SimaPro has been developed to accommodate different evaluation methods, using different impact assessment methods and inventories, while the user can integrate individual preferences about the system boundaries, introduce new parameters, and can even create new assessment methods [Ciroth 2009, van Nunen 2010]. Because of the open structure, Simapro is suitable in the framework of this research to integrate both LCA and LCC.

7.3.4.2 MODELLING OF BUILDING PRODUCTS

Since data for the financial costs are typically given for a reference unit of 1m², building components were modelled in SimaPro in so-called product 'assemblies' for a functional unit of 1m². For each building layer, e.g. the facade, different defined categories were modelled in separate assemblies, composed by each constituting physical layer, and determined by connection techniques.

For the environmental assessment, these assemblies include all (combinations of) materials – and related (industrial) processes – materialising each physical layer, for a reference unit of 1m². Additional data need to be introduced in the software for this reference unit in the framework of LCC, i.e. the material costs for each physical layer, but also labour costs related to the (dis)assembly of each physical layer, transport costs and end-of-life costs of the waste treatment.

The following difficulties were encountered during modelling of these assemblies:

1. Modelling of life cycle costing (LCC) with discounting, introducing dynamic assessment;
2. Modelling of time-based discounting versus regular discounting methods, according to the time in which periodical costs occur;
3. Modelling of sub component replacement according to variable assessment scenarios with variable parameters (variable building service life, building layer service life, estimated component service life);
4. Modelling of reuse of components, depending on the reversibility of connections between (sub) components and the opportunities for reuse;

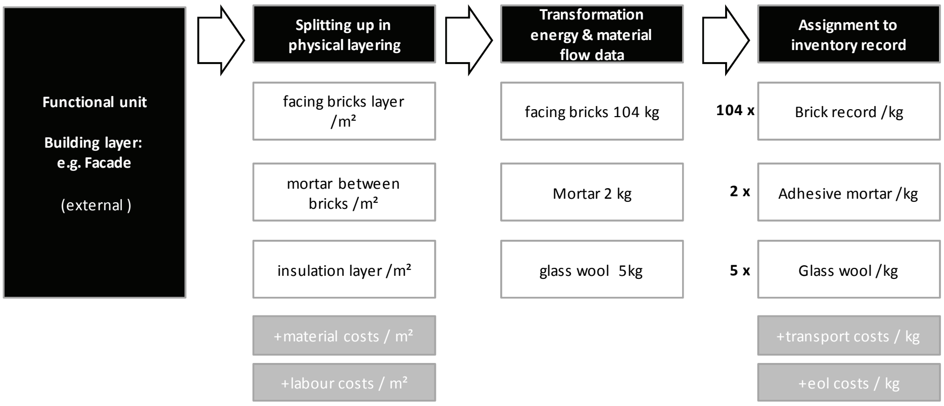
7.3.4.3 FINANCIAL ASSESSMENT METHOD

SimaPro is primarily made use of for the assessment of environmental issues, according to a static assessment method, using widely accepted environmental assessment methods. This means that during traditional LCA in SimaPro, no discounting of environmental issues is incorporated. Discounting is therefore not present in the software as a ready-to-use evaluation option, neither an assessment method for financial costs.
SimaPro software nevertheless provides the possibility to add personalised assessment methods, based on the same structure than environmental assessment methods, i.e. including impact categories, characterisation of impact categories, addition of substances according to the impact category, damage assessment and weighting (and aggregating) of results.

In the modelling of a **new economic assessment method**, for this study four *impact categories* were defined, i.e. *Material Cost*, *Labour Cost* (assembly and removal), *Transport Cost* and *EoL cost*. During the characterisation section, all substances are multiplied with the factor representing the value of the VAT. For new building projects, each substance would be multiplied by a factor of 1.21 (i.e. +21%), while for renovation this factor becomes 1.06 (i.e. + 6%). The discounting cannot be modelled within the method, but needs to be incorporated in the building assemblies including variable parameters.

Next, to make LCC calculations possible, financial data need to be added which are related to the impact categories defined in the new financial assessment method. Like material substances are related to environmental impacts, new economic substances are being created, which can be related to the financial impact categories defined in the new method. Thereafter, process records were made for all material, labour, transport and EoL cost related issues for all defined building layers categories, to which these substances are attached. This enables to establish the link between the defined economic substances, and the modelled assemblies, which incorporate financial information next to the environmental related topics (Figure 7.10).

Figure 7.10: Principal sequences of LCA modelling with addition of financial impact categories



Since dynamic calculations are needed for the financial assessment the product assemblies are constituted by different sub assemblies to deal with the complexity of this issue, each expressed for a reference surface unit of the concerned building layer, i.e. 1m².

The financial records are then associated with the selected discount rate and growth rate modelled as a variable in the 'Parameter' tabs in SimaPro software. These variables are related to the time (t) parameter, also modelled as a variable. The financial records are subsequently attached to sub assemblies of an overall building component 'assembly', hierarchically organised as illustrated Figure 7.11.

Figure 7.11: Modelled building product assembly for financial assessment

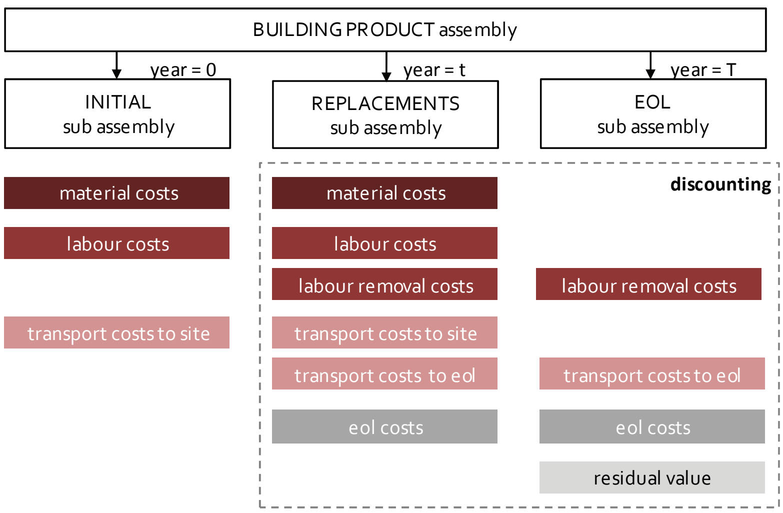
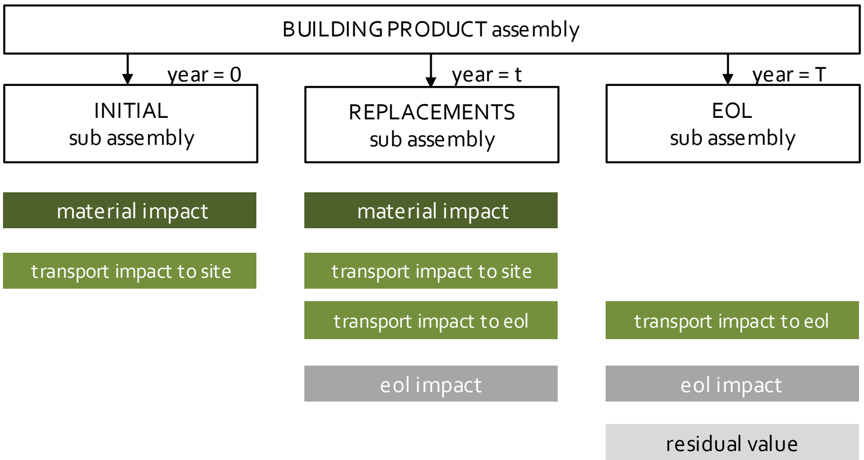


Figure 7.12: Modelled building product assembly for environmental assessment



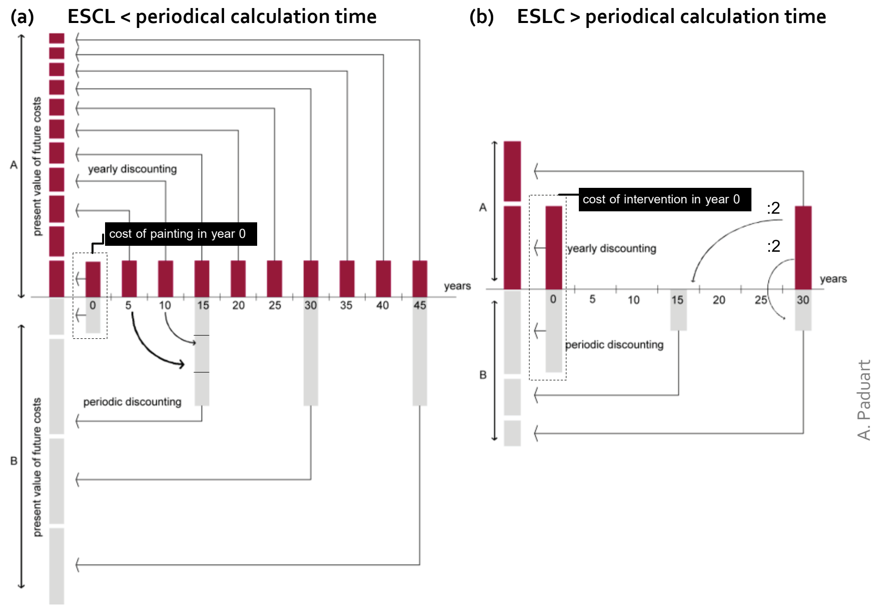
For the transport and EoL costs, new records were created based on specified categories for building product groups, determined by their transport type and EoL options (recycling, disposal, and landfill). These transport and EoL categories expressed for a reference mass unit of 1kg were discussed before. These records were added in the basic material records, since these records are expressed according to the mass units.

7.3.4.4 DISCOUNTING CALCULATION METHODS

The discount factor was parameterised in the 'Parameter' section of the SimaPro software, as a variable in function of the time parameter. In each added financial record, the discount rate acts as a variable for each scenario calculation.

Two types of calculation were compared in the modelling of discounting in this research: a *yearly* discounting method and a *periodical* calculation method. In the first approach (yearly discounting approach) the assessment calculations consider each replacement in its exact positioning in the time line according to the replacement of (sub) components. In each year it is calculated if a replacement of a sub component is required. For instance Figure 7.13 (a) shows that for the yearly discounting approach, walls are repainted every 5 year (i.e. ESCL(paint) = 5 year). In this case, it is defined exactly in which year each replacement takes place, and the discounting of these periodic costs to a present value is calculated based on the specific time in which the replacement takes place.

Figure 7.13: Principle of discounting to present values for yearly and periodic discounting



The second approach, the periodical discounting, calculates the number of required sub component replacements over the total period of analysis. This total number is then divided over a periodical calculation time, for instance over a period of 15 years. This is illustrated in Figure 7.13 (b) on the lower part of the figure. The number of repainting of the walls is calculated every 15 years, instead of yearly. The discounting of the same events happens on a later time. Figure 7.13 (b) represents the situation in which the service life of a component (ESLC) is longer than the period that is selected as the period for re-calculation. It shows that if a replacement is needed every 30 years, half of the costs are divided over each 15 years.

The results of the discounted present values according to both approaches – yearly and periodical – differ to a certain extent because the discounting is different according to the year in which the periodic costs appear. In addition, the selected discount rate also plays a crucial role: if the discount rate is high, less importance is given to the future, and for instance the value A, calculated according to the exact event of replacement, will have a smaller contribution to the present values than for the periodical discounting method.

For the LCC calculations the second approach was used for a set of reasons. First, it was assumed that a mix of components is used with varying component service lives, which balance the overall values. Secondly, it was esteemed that it is difficult to predict when replacements will actually take place, and therefore, a periodic discounting method makes a good average of possible scenarios. In addition, modelling the first method significantly slows down the calculations in SimaPro since in each time step, a calculation is made if replacement of components is required, whereas in the second method, this only needs to be done every periodic step (e.g. every 15 years).

7.4 DISCUSSION

This PhD research started from an environmental subject, in which it was questioned to what extent dynamic building solutions could have beneficial influence on the environment, from a long-term vision in which the use of resources is reduced over hte overall building life cycle. It was only decided in a later stage to include the financial costs, due to the observation that current building practice and its investors still base their decision-making mainly on the financial costs related to building products. In our current-day society, the focus of attention still lies upon reduction of initial costs, for many reasons, amongst which a limited means of investments together with calculation of professional fees of architects and contractors as a percentage of the construction cost [Kelly 2002], or distrust about the certainty of future revenues [Kohler 2010].

Nevertheless, since social housing companies are responsible for all expenses during the life cycle of their building stock, they may benefit from reduced costs and impacts of maintenance, replacements and adaptations interventions during the building life cycle. Therefore, the scope was broadened to LCC evaluation, to investigate if the DfD building solutions imply increased investment costs, and, if life cycle benefits can be related to to this approach in the context of renovation.

Consequently, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are recognised as appropriate approaches to evaluate respectively environmental impacts and financial costs, taking place over the entire life cycle of buildings. However, LCA and LCC imply many uncertainties about the future, explaining why different life cycle scenarios are set up in the next chapter, concerning the building layers, the period of analysis and the number of replacements. Methodological choices in LCA/LCC modelling were made, such as selection of impact assessment method, data inventory, system boundaries and allocation procedures, which can influence the conclusions. For these reasons, conclusions drawn from the evaluations performed in this research study should not be generalised.

The implementation in the context of buildings and their (sub) components remains complex. Different variables exist in a building life cycle, such as the service life of sub components, building layers and buildings, and the life cycle scenario of buildings.
In addition, non-conventional dynamic building products require an alternative way of modelling, compared to traditional building products, when assessing different building scenarios. This requires the introduction of several additional parameters and assumptions

which demands for a transparent methodology in order to enable a correct calculation and interpretation of the results.

The calculation of the environmental life cycle impacts is kept separated of the life cycle costs, i.e. no monetisation of environmental impacts – also referred to as environmental costs or external costs- was introduced[6]. Research of Allacker (2010) demonstrated that the monetised environmental impacts only amount for 10% of the total financial life cycle costs. It is therefore not likely that investors understand the importance of the environmental impacts related to building solutions, through the monetisation of environmental impacts in monetary terms. In addition, the underlying methodologies remain disputable, and are still under discussion by environmental experts and practitioners of LCA [Davis Langdon 2007].

[6] Monetary valuation is used to express in monetary terms how the welfare and wellbeing of current and future generations is affected by the environmental impacts caused by the activities in the building and housing sector [Allacker 2010]. Undesirable effects of building products on the environment cause damage, which can be either described directly or characterized by the cost of their avoidance, reduction, remediation and insurance. Monetization of these negative external effects elate to e.g. pollution, avoidance, evasion or costs to cover long-term risks. An important question in this matter is the estimation of the level of external costs that arise for third parties or society.

7.5 AN ADDITIONAL MODEL: DFD MATRIX

7.5.1 DFD MATRIX

One can question whether Design for Disassembly (DfD) with component reuse is required in each situation. Some building types have a higher need for change, due to an elevated *turnover rate* of specific building parts, e.g. internal partitioning and thermal upgrade. Other building typologies may have low turnover rates in which no changes occur during the building life cycle. According to the definition of Nordby (2009) the turnover refers to the rate at which building artefacts need to be changed (and replaced).

For instance, if buildings upgraded today with low-scale interventions do not possess a long remaining service life of the building structure, it is not necessarily required that re-design of the remaining building incorporates a high degree for change, since the building is likely to be demolished in a short period. If a building layer is not likely to be significantly adapted, because there are not many technical variants, e.g. veneer walls facing a load-bearing cross wall, the components do not necessarily need to be designed to be adapted frequently.

The need for change may not always a requisite, but this has to be evaluated in parallel with the environmental impacts and financial costs associated with the evaluated building element. The relation between the turnover of a building, building layer, or component, and the (sub) assemblies featuring within, is crucial when one considers the environmental impact of buildings and their components.

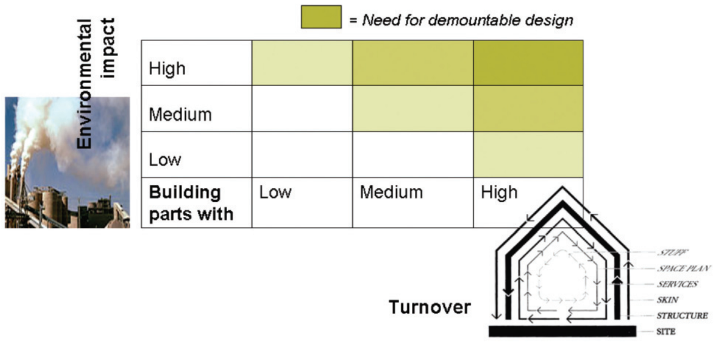
Therefore, when considering application of DfD design in a building project, Nordby (2009) suggest taking into consideration both the fact that most building types are exposed to increasing turnover rates, and the environmental impact of building products due to the extraction, production, and transport of materials. She proposes an evaluation matrix to define the need for DfD design in the built environment.

7.5.2 EXTENSION OF THE ASSESSMENT MATRIX FOR DFD DESIGN

7.5.2.1 ASSESSMENT MATRIX OF NORDBY

Nordby (2009) introduces a mindset that includes both *environmental impact* and building materials *turnover* in scenario-based predictions. She introduces a matrix that considers both the fact that most building types are exposed to increasing turnover or replacement rates and that environmental impacts related to building materials can differ to a wide extent. Figure 7.14 shows the assessment matrix suggested by Nordby (2009).

Figure 7.14: Assessment matrix for demountable design [Nordby 2009]



By intersecting the turnover rate for the building layer in question with its embodied environmental impact, the need for demountable design is visualised in the matrix. A high score on both axes, i.e. materials with high turnover rate and high environmental load, according to Nordby require a higher need to include strategies of Design for Disassembly (DfD). In addition, the concept of *environmental justifiable lifetime*, meaning that a service life of a sub component shall depend on importance of the environmental load embedded in the materials. According to this strategy, high impact materials should be designed for changing demands and salvage to make their high initial environmental impact acceptable [Nordby 2009].

7.5.2.2 EXTENSION OF ASSESSMENT MATRIX

The assessment matrix of Nordby forms an overall conceptual framework to indicate the need for Design for Disassembly when using building components which exhibit high environmental impacts. Analysis of the assessment matrix reveals some important shortcomings.

First, the model is only applied at the level of 'building parts', which in this research is referred to as 'building layers'. However, as illustrated in Chapter 3, strategies for DfD can be applied at three building levels, i.e. building level, component level and material level [Dorsthorst & Kowalczyk 2002; Debacker 2009]. The matrix should be extended to all levels. As discussed in the first part of this chapter, attention must be given to the different turnover of all different building levels.

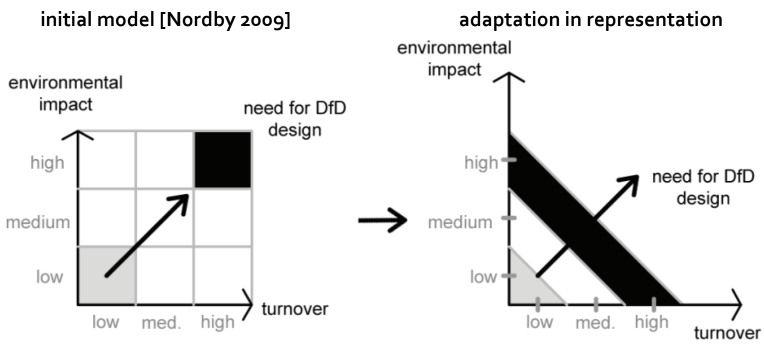
Secondly, only the 'need' for demountable design is expressed, but no indication is given about the opportunities of actual reuse of the concerned building part. Indeed, as discussed in Chapter 3 and 5, not all buildings/building products enable reuse after deconstruction. Materials need to be durable and resistant to handling and transport to ensure that reuse can take place after demounting them, while they must be able to

endure reversible connections. On the other hand, if the component service life is not significant and it appears in buildings with long service lives, DfD will only lead to benefits relating to the ease of deconstruction. The high impacts of the considered building part can then not be balanced against overall life cycle benefits.
Another objection can be found in the definition of *low*, *medium*, and *high* classes for both axes of the assessment matrix. How can a 'high' turnover be defined? When is the environmental impact of a building product 'medium'? These definitions need to be further developed to give a comprehensible and transparent framework. Consequently, it is concluded that the assessment matrix in its present form is unsuitable for application in this research. The formulated objections lead to the development of an *extended* assessment framework, which covers a wider range of properties which – when further developed - may give designers more specific guidelines to explore potential for reuse, and need for Design for Disassembly approaches.

ADDITION OF REUSE STRATEGIES

The form of the matrix proposed by Nordby (2009) represents different intersecting zones in which the degree of the need for a DfD approach is not clearly defined. It is only clear for the zones were both turnover and environmental score are 'high' or 'low' that there is respectively an pressing or very low need for DfD design. Therefore, an adapted representation is proposed that applies three zones defined by the intersections of the categories, i.e. with a low, medium and high need for DfD design (Figure 7.15).

Figure 7.15: Adaptation of assessment matrix



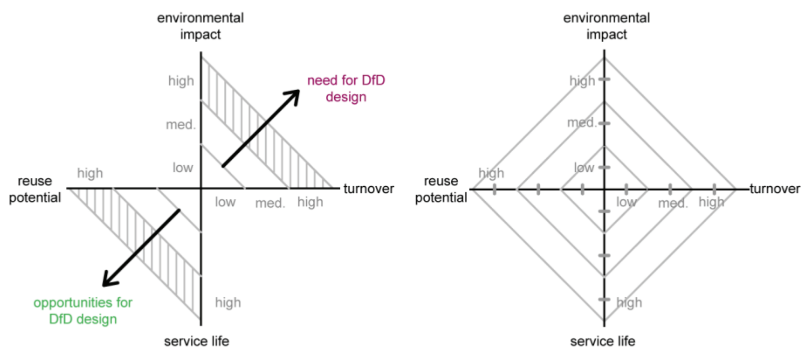
If an artefact is determined by a high environmental impact and a building level with a high turnover, it is situated in the zone with a high need for a DfD approach. Artefacts with a low environmental impact and a low turnover rate do not automatically necessitate a DfD approach in environmental terms. Nevertheless, it must be emphasised that this low necessity does not exclude that a DfD approach offer other life cycle benefits, related to e.g. ease of deconstruction, reuse of sub elements, upgrade potential, etc.

Nevertheless, the identification of need for DfD does not necessarily imply that the concerned artefact has the *capacity* to be designed for DfD. Imagine that the considered artefact is a *ceramic tile* (sub component) used in a floor (*building layer*) frequently updated for aesthetic motives to the latest architectural trends. In this case, ceramic tiles – which exhibit a high initial environmental impact (see Chapter 8) – are combined with a high turnover rate of the building layer (floor). Although there is a high need for demountable design, the properties of ceramic tiles do not make this easy. First, the ceramic tiles are brittle, meaning that they can easily break when handled or transported in atypical dynamic situations - which is the case for multiple reuse of these sub components. Therefore, even if typical irreversible connection methods (mortars) to put ceramic floors in place would be replaced by reversible connections, the reuse of the components may not be suitable due to the material characteristics.

To indicate these restrictions of reuse related to material properties, an additional criterion was added to the initial matrix, i.e. the potential to introduce reuse at the considered building level. At material/component level this implies for example a high material resistance based on adequate material hardness, brittleness and surface resistance. At building level, the reuse potential implies that the building is suitable for reuse, for example versatile buildings (see Chapter 3 and 5). In addition, the success of reuse strategies is also interlinked with the technical service life of the (sub) components or the buildings. If the material resistance is high, but the components have a short technical service life, DfD may not be aspired when applied in a building with a long life cycle. Consequently artefacts with good material reuse properties together with a high service life create opportunities in combination with DfD for reuse. Therefore, the *service life* was added to the matrix, forming a radar representation as shown in Figure 7.16.

Figure 7.16: Extension of assessment matrix with new criteria: reuse potential and service life

addition of criteria **resulting radar graph**



THREE DESIGN LEVELS

The initial matrix only considers the level of DfD approaches at *building layer* level. The two supplementary levels to which DfD approach can be applied, i.e. the component level and the building level, are included in the proposed extended matrix. Therefore, the four axes on the radar chart – turnover, environmental impact, reuse potential and service life – may thus be applied in accordance with each of the three design levels. For instance, if it is evaluated if a gypsum fibreboard (i.e. sub component) for boarding in a wall assembly must be designed according to DfD, the turnover rate concerns the upper design levels, i.e. *building layer* or *building* level, while the remaining indicators point to the properties at *component level*. The turnover rate is defined by the smallest replacement rate, which may be related to frequent update of building partitioning (building layer level) or a short remaining life span of the building (building level).

TURNOVER RATE

To define the level of turnover rate, different design levels need to be considered. The turnover period for a component featuring in a building layer - e.g. carpet as the floor finishing in a separating floor construction- is typically defined by the end of its own service life, or the turnover period of the building layer, i.e. the horizontal *floor* partitioning. If the building is demolished faster than the functional turnover period of the building layer (in this case the floor), the carpet floor finishing has to be evaluated according to the turnover period of the building.

Therefore, in the assessment matrix, the turnover rate considered for the evaluation is determined by comparing each turnover period of the upper design levels together with the service life of the considering layer, and consequently selecting the shortest turnover period. Then, to determine the rate of turnover t_L, the selected turnover period t_P, has to be compared to a reference building life span $SLB_{REF.}$ To define the level of turnover (low, medium or high), the turnover rate t_L can be calculated with the following equation:

$$t_L = \frac{SLB_{REF}}{t_{P,\ x}}$$ **Equation 7.22**

With:

t_L	= the turnover rate (-) (level)
SLB_{REF}	= the selected reference building service life according to which the rate of turnover can be calculated (years)
$t_{P,x}$	= the selected turnover period of the upper design level x with the shortest period (years)

Consequently, the turnover speed can be categorised under the rates low-medium-high according to the next conditions:

If	$t_L > 2$	The speed of turnover is esteemed HIGH;
	$1 < t_L \leq 2$	The speed of turnover is esteemed MEDIUM;
	$t_L \leq 1$	The speed of turnover is esteemed LOW.

These scaling conditions were preliminary set, as an example, and should consequently be further elaborated with further research. This is also the case for the scales for the environmental impact and service life, discussed hereafter. The selection of the *reference* building service life can be determined similar to the period of analysis applied in LCA and LCC calculations. As an example, if wall partitioning has to be adapted every 10 years in a building that is expected to remain for 60 years, the selected turnover period is the one at building layers level, i.e. 10 years. If a reference building service life of 60 years is selected, according to the conditions the resulting t_L of 6 (60:10=6) means that the turnover rate is HIGH ($t_L > 2$).

This approach can be applied for new construction and existing buildings. For the latter, it has to be esteemed how long is the remaining service life of the building, as a result of the renovation interventions proposed (e.g. based on the remaining technical service life of the load-bearing structure).

In this research, the scope within renovation also means that the evaluation at building level cannot be included, since the building already exists. In other words, a temporary building (high turnover rate at building level) can be designed according to DfD in new construction, but an existing building can no longer be entirely rebuilt for change, since the main building layers are already present (e.g. the load-bearing structure) and cannot be designed according to DfD. Only at building layer level, this evaluation can be applied.

ENVIRONMENTAL IMPACT

The considered environmental impact can concern the initial environmental impact of the building sub component, building layer of building – according to what is being evaluated.

Similar to selecting a reference building service span, a reference initial environmental impact can be selected to compare the impact of the building part in question. In addition, the end-of-life treatment can be added to the environmental impact, to gain more insight on the materials' impacts over an entire life cycle.

Then, to determine the level of environmental impact e_L it has to be compared to a reference environmental impact $e_{REF.}$ To define the scale of the environmental impact (low, medium or high) e_L can be calculated with the following equation:

$$e_L = \frac{e_{REF}}{IE}$$ **Equation 7.23**

With:

e_L	= the level of environmental impact (-)
e_{REF}	= the selected reference environmental impact (selected indicator of environmental impacts, e.g. EcoPoints)
IE	= the initial environmental impact (including or excluding the EoL treatment (selected indicator of environmental impacts, e.g. EcoPoints)

Then, the environmental impact e_L can be categorised under the rates low-medium-high according to the next conditions:

If	$e_L > 2$	The environmental impact level is esteemed HIGH;
	$1 < e_L \leq 2$	The environmental impact level is esteemed MEDIUM;
	$e_L \leq 1$	The environmental impact level is esteemed LOW.

The reference environmental impact can be determined by LCA practitioners for typical sub components – building layers - buildings, enabling to categorise the environmental impacts similar to the turnover rate. The selection of this reference value may be ambiguous; a possible selection of a reference could be based on the environmental impact of a standard building solution. However, it is clear that the subjectivity in choosing a reference must be restricted.

SERVICE LIFE

Similar to the categorisation of environmental impacts, a reference service life can be determined. To define the scale of the service life (low, medium or high) SL_L can be calculated with the following equation:

$$SL_L = \frac{SL_{REF}}{SL}$$ **Equation 7.24**

With:

SL_L	= the level of service life (-)
SL_{REF}	= the selected reference service life according to the considered building level for the evaluation (years)
SL	= the service life according to the considered building level for the evaluation (years), i.e. ESLC (estimated service life of component), SLBL (service life of building layer), or SLB (service life building).

Then, the environmental impact SL_L can be categorised under the rates low-medium-high according to the next conditions:

If	$SL_L > 2$	The service life is esteemed HIGH;
	$1 < SL_L \leq 2$	The service life is esteemed MEDIUM;
	$SL_L \leq 1$	The service life is esteemed LOW.

MATERIAL SUITABILITY FOR REUSE

The suitability for reuse of sub components, building layers can be defined according to the criteria illustrated in Chapter 4, according to the material resistance needed to ensure reuse. Suitability of buildings to be reused can be determined according to reuse strategies a t building level, including versatility and flexibility, as discussed in Chapter 5.

1.1 *EXAMPLES*

Figure 7.17 shows some examples of a building artefact with specific properties represented on the radar chart. It is clear that each example requires a more specific definition of reference units, as discussed here above.

Figure 7.17: Examples on the radar chart

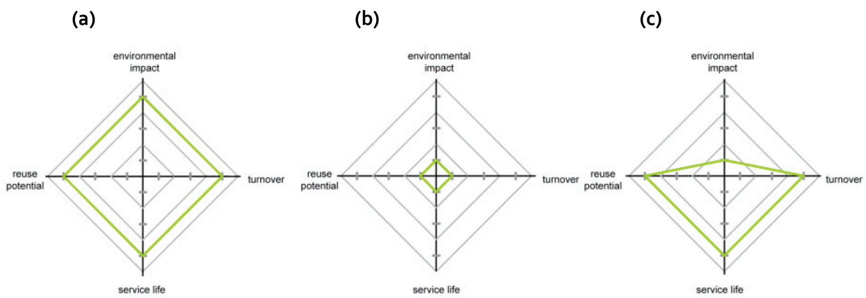


Figure 7.17 (a) represents a building artefact, for instance laminate flooring like Quick Step, using reversible connections and with a high material resistance finishing. This floor finishing is characterised by a high initial environmental impact (see Chapter 8), e.g. compared to linoleum, but has a high reuse potential and long service life, due to the product specifications. The turnover rate shows that the floor finishing is used for an application in which changes rapidly take place. This might be the case for a temporary building, in which a building is frequently deconstructed and re-assembled elsewhere. There is thus a high need for DfD design, while the floor finishing provides the required material characteristics, ensuring reuse of the sub components.

Figure 7.17 (b) can represent, for instance, gypsum plasterboard as boarding in wall assemblies applied in building that have a short life span. The initial environmental impact of gypsum plasterboard is low (see Chapter 8), while it has no potential for reuse – due to its lack of material resistance – and a limited service life. However, since there is a low demand for change, and the environment impact is not significant, this solution does not require necessarily a DfD approach.

Figure 7.17 (c) represents, for instance, facing bricks in facades of buildings. Facing bricks have a high potential for reuse and are characterised by a long component service life, but the typical connections are not reversible and require demolition with reclaiming bricks of the waste stream to enable the reuse. In facade compositions with frequent thermal upgrade, the bricks can thus not be easily disassembled, enabling upgrade in situ and re-assembly. If facing bricks are combined with reversible connection methods, this becomes possible, while in addition the relatively low initial environmental impact can be better developed.

7.5.3 DISCUSSION

Today there is still a lack of knowledge on how a designer can consider future reuse and which materials and (sub) components may offer beneficial environmental opportunities over a building life cycle, including environmental impacts and turnover rate defined in buildings. The aim of the extension proposal on the matrix proposed by Nordby (2009) is to offer guidelines for designers on how to evaluate priorities in DfD design. A first indication can be given in the first design step without having to make a total environmental life cycle (performance) assessment of detailed building solutions. For a complete assessment it is clear that LCA still needs to be performed in the ultimate step for a correct interpretation of the impacts related to the entire life cycle of building artefacts.

Several additions were made to overcome the identified shortcomings in the matrix model of Nordby(2009), including an answer how to deal with the identification of levels for low, medium and high turnover rate and environmental impact for building components, the extension to more building design levels, and the actual capacity of building artefacts to introduce reuse strategies.
However, it is clear that in order to develop such a model, several objective selections would have to be made, similar as in LCA and LCC practice. This can eventually lead to subjective interpretations.

The methodology was illustrated for environmental impacts, but the same methodology can in analogy be used for financial costs. The environmental impacts (IE) must than simply be replaced by the financial costs (IF) associated with the considered building artefacts.

08

ASSESSMENT OF BUILDING LAYERS

The methodological framework elaborated in the previous chapter ensures that building solutions applied in renovation can be evaluated methodically over the total life cycle of buildings, in environmental and financial terms. Hence, in this chapter the environmental and financial benefits and drawbacks can be revealed of a dynamic approach to the design of building solutions – as a complementary strategy to energetic upgrade of buildings today. In Chapter 6, alternative 'dynamic' building layers were proposed in order to anticipate future building alterations, such as further thermal upgrade and layout adaptations, while enhancing multiple reuse of sub components.

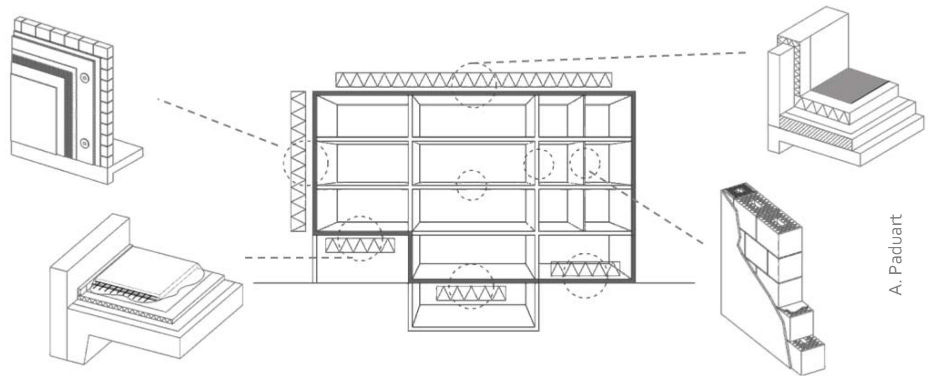
In this chapter, this alternative Design for Disassembly (DfD) design approach in order to *materialise, dimension, detail and compose* dynamic building products is evaluated and compared to standard solutions applied in renovation of post-war buildings. For a range of building scenarios the feasibility of diminishing the total life cycle environmental impacts and financial costs by reducing the material consumption and waste production as a result of component reuse is analysed.

The Re-design for Change approach is evaluated at *component* level, meaning that evaluation of building solutions is expressed for representative functional units of 1m² for each building layer. The results of this chapter can subsequently be incorporated for the evaluation of a representative case study of renovation of post-war buildings in order to obtain an evaluation at *building* level; this will be the subject of Chapter 9.

8.1.1 DYNAMIC ALTERNATIVE FOR STATIC BUILDING LAYERS

In this chapter, building solutions are evaluated which typically are subject of upgrade during renovation of post-war buildings, namely the building *skin - facade and roof* - and *space partitioning - wall partitioning* and *separating floors*[1].

Figure 8.1: Assessment at component level for the main building layers



It is assumed that the load-bearing structure layer (*building structure*) of the original building is retained as the new *frame*, functioning as the base for new 'generic space' tomorrow - according to Leupen's concept (2005) discussed in Chapter 3. This explains why this building layer is excluded from this analysis. The technical building layer (*services*) was also excluded, since the selection of building services concerns a decision at building level, strongly depending on each individual building context[2].

Table 8.1 represents the key properties of the building layers based on the results of the performed multi-criteria analysis, designed according to a traditional - i.e. *static* - design approach and a *dynamic* design approach. Dynamic solutions may use the same materials than conventional solutions; however, the combination of reversible assembly techniques, a multi-layered composition and selection of reusable materials determines the difference between dynamic and static design approaches over a building life cycle, as it determines to what extent building assemblies can efficiently respond to occurring scenarios.

[1] The so-called *stuff layer* - the furnishing of buildings - was not considered in this analysis, although it is assumed to play a key role in sustainable design of buildings and can be designed in analogy with dynamic building layers as discussed in Chapter 3 [Lommée 2010].

[2] Nevertheless, the *approach* in which the technical distribution is incorporated in each building layer, e.g. fixed in a screed floor or loose-laid in raised access floors, has been incorporated.

Table 8.1: Key conceptual differences between building layers according to Design for Change and conventional building design

Key differences	DfD renovation solutions	Standard renovation solutions
Upgrade and adaptability of:		
- building facade	+	- to +
- roof	+/-	-
- internal partitioning	+	-
- floors	+	-
- ceilings	+	-
Speed of renovation of:		
- building facade	+	- to +
- roof	+/-	-
- internal partitioning	+	- to +
- floors	+/-	-
- ceilings	+/-	- to +
Reuse of components of:		
- building facade	+	- to +
- roof	+/-	- to +
- internal partitioning	+	-
- floors	+	+/-
- ceilings	+	-

(-) limited; (+/-) average; (+) substantial

In the next paragraphs, the static and dynamic proposal of the building layers upgraded during renovation are assessed and compared in environmental and financial terms over a range of life cycle building scenarios defined in the next paragraph.

8.1.2 EVALUATION SCENARIOS

Three life cycle scenarios are defined to explore the effect of unanticipated events over the course of a building life cycle, assuming that the building's function remains residential.

Scenario 1: Shortened life span due to early demolition

The analysis period is an important variable in life cycle analysis, as costs occurring outside the period of analysis may significantly influence the costs of ownership. Such costs may include heavy maintenance costs due to a longer actual building service life than the analysis period, or unanticipated demolition costs due to preliminary building degradation. It is therefore necessary to review results over several periods of analysis [ISO 2006].

Therefore, a first scenario is set up to model *early - unanticipated - demolition of buildings*, after a short period of 15 years, for other motives than structural failure of the building. Financial or functional considerations of housing companies may form sudden motives to decide for demolition of buildings (and new construction). In the case of early demolition, buildings still incorporate numerous **valuable materials** containing residual environmental and financial life cycle benefits. A re-design for change approach anticipates these unpredictable scenarios, through maximised reuse of building components and materials, therefore bypassing the wasteful process of early demolition.

Scenario 2: No interventions during dwelling/building life cycle

This scenario is representative for the current perspective on renovation. As it departs from the idea that renovation must represent current living and comfort trends, while complying with today's building regulation. There is no anticipation for further future building alteration and thus, the service life of each building layer (e.g. facade, partitioning) is assumed to be equal to the period of analysis. Components featuring in these building layers are only replaced by identical ones at the end of their service life defined by the estimated service life of components (ESLC) in Chapter 7.

To estimate the global analysis period, the technical service life of the load-bearing structure was selected - a decisive parameter for the final demolition of the entire building structure. The technical service life of concrete load-bearing structures has been estimated to last between 50 and 100 years [BCIS 2006] for new structures. In this research multi-storey buildings of the 1970s are considered which are still in good structural condition. Based on these assumptions an overall analysis period of *45 years* is used for this scenario.

Scenario 3: Specific intervention scenario for each building layer

The third life cycle scenario consists of *trend projection*, assuming a periodic sequence of phases in life cycles of buildings. In other words, each building layer - the *generic space* – is characterised by a periodic *need for change* in the permanent *frame* - the load-bearing structure. For instance, insulation and air tightness of facades require regular upgrading in comparison with the structural support of a building [Morgan and Stevenson 2005].

Therefore, the third life cycle assessment scenario incorporates periodic upgrade of each building layer according to its defined turnover rate over the analysis period. The result of the survey held in Chapter 4 indicated that the highest degree of change was required for internal partitioning and the roof, an intermediate degree of change was required for dividing walls and the facade, and that the need for change was lower for floors/ceilings as a consequence of the typically reduced storey height in post-war construction. The main motives for change for each building layer are represented in Table 8.2.

While components still need to be replaced at the end of their estimated service life, components also need replacement when building layer in which they feature needs periodical upgrade. The response of standard components and DfD designed components to this scenario is fundamentally different: while static components generally need integral replacement by new components, DfD components can be deconstructed and (partially) reused.

Table 8.2: Motivation for change of building layers over the life cycle of buildings

	Building Layer	Turnover	Motivation for change
1	**Internal wall**	High	*Internal flexibility / technical upgrade*
	Roof		*Hygro thermal upgrade*
2	**Partition wall**	Intermediate	*New layout plan / functional upgrade*
	Facade		*Hygro thermal upgrade*
3	**Floor**	Low	*Technical upgrade*

Estimation of the periodic turnover was based on literature, the survey and anticipation based on EPBD policy regarding thermal performance of (residential) buildings. The life span of the building layers based on literature (summarised in Table 8.3) leads to adapted values represented in Table 8.4. This table also represents the service lives for each building layer according to each defined life cycle scenarios.

Table 8.3: Functional service life of each building layer

Service life (years)				**Reference**
structure	*skin*	*services*	*space*	
50	50	15	5-7	[Duffy 1989]
30-300	20-60	7-15	3-30	[Brand 1994]
50-75	25	8-10	2-8	[Durmisevic 2006]

Table 8.4: Adapted service life of building layers for scenarios 1-3

	Building layer	**Estimated service life (years)**		
		scenario 1	*scenario 2*	*scenario 3*
	load-bearing structure[3]	15	45	45
1	internal partitioning	15	45	10
	roof	15	45	10
2	building envelope	15	45	15
	partition walls	15	45	15
3	floors and ceilings	15	45	20

[3] This life span of the load-bearing structure was deducted from the remaining life span for a refurbished multi-storey apartment building of the 1970s and is used for the period of analysis for each scenario except for the short building scenario (scenario 1).

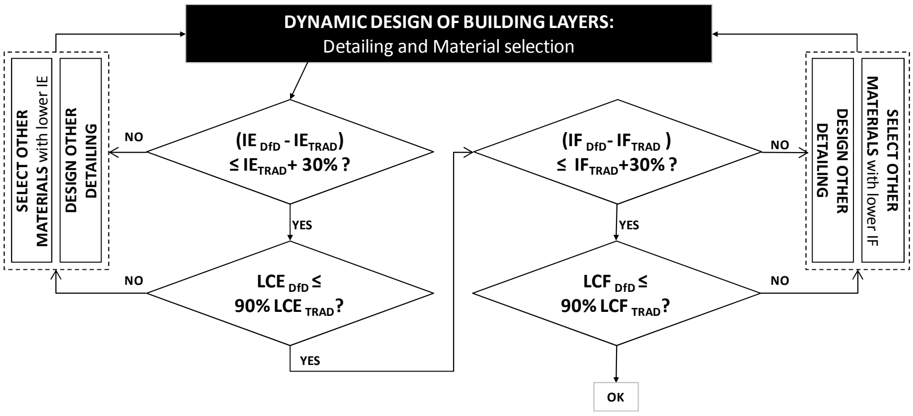
Future building data contain more uncertainties than initial information we acquire about the products we use in construction today. This is an important motive for investors and architects to base their decision-making on the initial phase when they evaluate the performance of building products [Kohler 2010]. Building products or techniques which return the investment cost over a short period are preferred over techniques with a return cost over a long period. This short-sighted view over building products can result in much higher building costs than were initially expected: important contributions due to maintenance, repair and replacements are overlooked while these play a crucial role in the life cycle building costs. Nevertheless, since future events are relatively unknown, it always includes a risk to introduce building solutions with significantly higher investment cost or disproportionate initial environmental impacts compared to standard solutions - even when predicted to result in major cost reductions and environmental benefits on the long term. Indeed, life cycle assessment also contains the danger of focusing only on future gains: uncertainties about recent developed building products, unknown future building use or early demolition of a building may cause pioneering building products to add more impacts than conventional products. Therefore, it is always important to make a balanced consideration between future gains, while reducing the initial impacts whenever possible.

For this reason during the design of dynamic building layers (Chapter 6) a feed-back step was introduced in the design process: each design proposal was first assessed and compared with conventional solutions, and alternatives were selected if the *initial* environmental or financial impact was disproportionate compared to existing solutions, i.e. when the difference between the traditional and dynamic equivalent was more than 30% of difference for the initial environmental impact (IE) and the initial financial cost (IF).

The methodology applied for the design of dynamic alternatives in Chapter 6 is shown in Figure 8.2. In order to keep the initial environmental and financial impacts related to dynamic design comparable to standards solutions, the initial environmental impact of each proposal was first compared to standards solutions, so that the impact would not surpass +30% of the impact related to standard solutions. Besides the objective to reduce the total life cycle environmental impacts with 10% compared to the reference solutions, it was also the objective to keep the financial costs low.

Consequently, Figure 8.2 shows that DfD solutions that add up less than 30% to the initial environmental and financial situation compared to the reference solutions, and reduce both environmental and financial life cycle impacts are highly desirable. The different steps in this methodology tree can be followed up to the moment that the solutions have been optimised.

Figure 8.2: Methodology for alternative dynamic design of traditional building systems



In the next paragraph (§8.2), dynamic and standard solutions for the building facade, the roof, partitioning, floors and ceilings, are evaluated and compared - expressed in absolute values[4] - to reveal the influence of dynamic design in relation to the *initial* environmental impacts and financial costs. Subsequently, in the following paragraph (§8.3) implementation of the integrated environmental and financial *life cycle* assessment aims to reveal if Design for Change is enviable in order to decrease environmental impacts related to material use over a total life cycle, while related financial costs are acceptable.

[4] The absolute data in this research are purposed to indicate the scale of environmental and financial aspects related to the analysed solution categories. The aim is to make a correct comparison possible in the framework of this research and to gain insight about the origin of the impacts due to used materials and construction techniques. These data were thus set up in the context of this research and are therefore not intended as consultation data for third parties.

8.2.1 FACADE

8.2.1.1 OVERVIEW CATEGORIES

Thermal performance is generally perceived as the most important criteria for renovation of the facade today. The *U-value* of the total external wall composition according to the current regulatory framework is therefore chosen as the base for comparison of the defined facade categories. An U-value of approximately U = 0,3 W/m²K [EPB 2010] is calculated for each external wall category in order to make a correct comparison per square unit of the facade surface. The U-values differ to a certain extent, due to limited amount of available dimensions of insulation products on the market. A supporting (interior) wall of 14 cm brickwork is supposed for all facade compositions. This means that the supporting structure can be left out of the assessment when focussing on the external leaf of the facade. Hence, the comparison can also be made for renovation in which the external wall is load-bearing, and only layers can be added externally to the existing facade to upgrade thermal performance. An overview is shown of all thermal upgrade categories for the facade in Table 8.5, ordered from monolithic rigid assemblies using wet connection techniques (category 1 -2) to multi-layered dynamic assemblies using reversible assembly methods (category 5 and 6)[5].

As a summary of the standard solutions used today: **category 1** consists of *external rendered thermal insulation systems* (ETICS); **category 2** is defined as *facing bricks facades* and **category 3** as *warm panel facades* (using sandwich panels) while **category 4** consists of *dry rain screen facades*. This last category is subdivided in two frequently applied types: *wooden rebating* mounted against a wooden substructure (**category 4a**) and *dry covering* (sheets/panels/tiles) mounted against an aluminium substructure (**category 4b**).
Category 5 and 6 represent the added dynamic alternatives derived from the dynamic design methodology described in Chapter 6, with **category 5** as a solution that combines dynamic facade design with preassembly, clustering several facade sub layers in a preassembled unit. **Category 6** takes the dynamic sub layering of the supporting wall a step further, by replacing the monolithic supporting brickwork wall with dry wall construction. Since the preassembled units are externally connected to the floor slabs, the supporting external wall is not required. This category incorporates the highest degree of functional sub layering with the highest degree of reversibility according to DfD principles.

[5] The composition and construction techniques applied for each category were extensively discussed in Chapter 4 for conventional solutions and in Chapter 6 for dynamic solutions.

Table 8.5: Composition of standard facade categories with U-value = 0,3 W/m²K

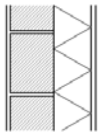
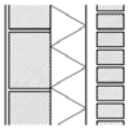
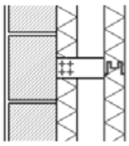
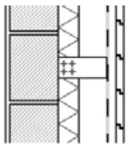
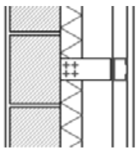
	Category	Composition	
category 1	 ETICS	(*concrete block* + *rendering*) adhesive for insulation XPS synthetic rendering + paint	140 mm 7 mm 120 mm 15 mm
category 2	 facing brick wall	(*concrete block* + *rendering*) glass wool cavity clay / concrete facing bricks[6]	140 mm 120 mm 30 mm 90 mm
category 3	 warm panel facade	(*concrete block* + *rendering*) glass wool vertical steel profiles [7] + mechanical brackets aluminium sandwich panel[8]	140 mm 100 mm 40x80 mm 60 mm
category 4a		(*concrete block* + *rendering*) glass wool	140 mm 140 mm
		wooden battens (horiz) wooden battens (vertic) wood rebating + paint	80x40 mm 60x40 mm 22 mm
category 4b	 rain screen facade	vertical aluminium profiles [9] -aluminium/steel sheets[10] -ceramic tiles/ fibre cement tiles -glass tiles -synthetic tiles -wood composite board -wooden board untreated/treated	40x80 mm 2 / 1 mm 40/90 mm 15 mm 12 mm 16 mm 18 mm

Table 8.6: Composition of the dynamic facade categories with U-value = 0,3 W/m²K

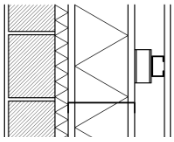
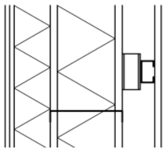
[6] The facing brick walls are supposed to use cementitous mortar.

[7] T-profiles with thickness of 15 mm and b= 80 mm and h= 40 mm.

[8] Built-up systems with 60 mm of rock wool insulation sandwiched between two profiled aluminium sheets of 0,7 mm thickness.

[9] Additional horizontal aluminium profiles are needed for heavy-weight covering such as ceramic tiles, glass tiles and wood composite boards.

[10] Metal sheeting for facades typically made from pressed metal panels, e.g. aluminium, stainless steel, zinc or copper which are either painted or anodised and fixed to the building via mechanical brackets. Zinc and copper are left out of the assessment because they are less frequently used with enhanced costs due to hand dressing of the panels [Addis 2006].

	Category	Composition	
category 5	**preassembled DfD facade**  *+ supporting wall*	(concrete block + rendering) wooden framework glass wool insulation osb boarding vertical aluminium profiles covering (see category 4b)	140 mm 160 mm 160 mm 18 mm 40x80 mm
category 6	 *+ dry interior wall*	(metal sections + glass wool + gypsum plasterboard) wooden framework glass wool insulation OSB boarding vertical aluminium profiles covering (see category 4b)	 160 mm 160 mm 18 mm 40x80 mm

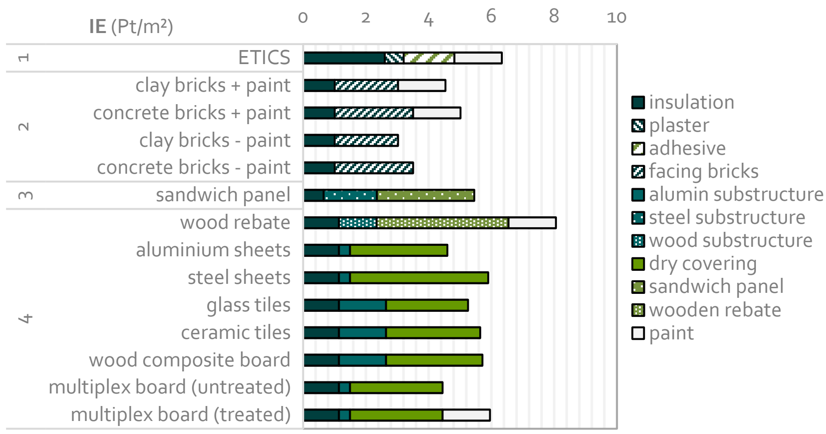
8.2.1.2 INITIAL ENVIRONMENTAL IMPACT

The initial environmental impacts[11] (**IE**) related to the standard facade categories are wide-ranging due to the *variety of building materials* (e.g. bricks, plaster, sub frame, covering tiles, wooden rebating), *(dis) assembly techniques*, and sub layering applied large differences in facade solutions.

When we only consider the short-term environmental effects of the facade categories using *current environmental impact assessment* methods, and the *materials we know today*, the monolithic facing bricks walls (**category 1**) may seem suitable from an environmental point of view[12].

[11] Using an impact assessment method with equal weighting for all damage categories, absolute values of environmental damages are calculated in ecopoints per m² facade area. These aggregated normalised results are based on the default ReCiPe (H/A) impact assessment method, as was discussed in Chapter 7.
[12] Additional finishing (painting), eventually applied in these facing bricks walls, but also applied in ETICS and wood-based covering systems, is associated with a significant increase of the initial environmental impact (20-30% of initial environmental impact).

Figure 8.3: Initial environmental impact related to sub components of facade categories



In **category 1**, the rigid insulation material XPS, typically applied in ETICS, adds to the overall environmental impact, compared to other facade categories in which glass wool can be used. In addition, plastering and adhesives add up to the environmental impacts.

When we look at the dry multi-layered facade **categories 3 and 4**, important contributions to the environmental impact can be attributed to the following aspects:

1. **Increase of sub layering compared to monolithic structures**;
   The introduction of multiple functional sub layers may result in higher initial environmental impacts. In rain screen facades the subdivision of functions over multiple layers (insulation + water proof layer + substructure + brackets and covering) introduces more sub components adding up to the environmental impacts compared to single-layered masonry walls (insulation + brickwork) which incorporate all functions with a minimal number of sub components.

2. **Introduction of reversible connections;**
   To enable interventions in the different sub layers of the facade composition, additional reversible connectors are introduced (such as linear rails) which are often associated with high production related impacts (e.g. aluminium or steel connectors), adding to the overall initial environmental impacts.

3. **The selection of materials for the dry sub layers;**
   In the current-day building practice sub layers are offered a wide range of possible executions, e.g., the structural sub frame of rain screen facades can be executed in galvanised steel, wooden battens and aluminium. A sub frame of galvanised steel or wooden battens corresponds to higher initial environmental

impacts compared to light-weight aluminium (see Appendix II) according to the current environmental impact assessment methods.

Also, the selection of the covering materials is crucial for the overall environmental impact. For instance, metal and wood-based sheets/panels are associated with higher environmental impacts, while heavy-weight covering panels (e.g. glazed tiles, ceramic tiles) require higher dimensioned structural sub frames, adding to the overall impact;

As a result, the additional sub layering and use of reversible connection systems augments the initial environmental impact of dry facade systems, compared to monolithic static designed building solutions, but the differences remain acceptable. For rain screens, materials may be developed which result in sub components with lower related environmental impacts due to more sustainable energy mixes and/or production processes than the materials selected in this research. Consequently, the assessment of life cycle scenarios must reveal if important benefits, such as reduction of environmental impacts, can be attributed to these dynamic systems, making this initial increase acceptable. This is therefore further explored in paragraph (§8.4.2).

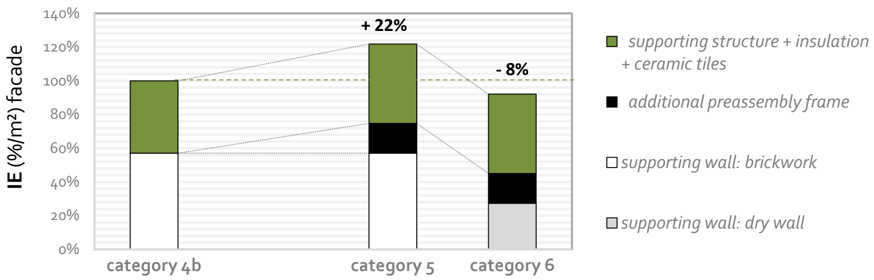
Environmental assessment of the dynamic categories (category 5 and 6) confirms the revealed ambiguity for the initial context of sustainable dynamic design. An additional structural framework is required to ensure clustering of several facade layers off-site, while it incorporates the benefits of fast (de)construction as a semi-finished unit. Benefits that can be obtained on the long-term, nevertheless, initially result in higher environmental impacts due to supplementary layers compared to in-situ assembled dry facade categories (category 4).

Figure 8.4 shows that the wooden structural framework in preassembled facade units (category 5) in relative terms adds 22% to the environmental impact compared to the equivalent rain screen facades connected on site (category 4b) for the example of covering with ceramic tiles.

For the facade category 6 – in which the *monolithic* interior brick wall of categories 1 to 5 is replaced by a *multi-layered* interior dry wall - the overall environmental impact can be reduced. This is due to the high environmental impacts related with the expanded clay brickwork walls – as supporting external walls - compared to dry walls, which will be discussed further in §8.2.2. In category 6 an interior dry wall is applied which balances the environmental impacts: the initial impact can be decreased with 8% compared to the equivalent dry facade category 4.

Further life cycle assessment in §8.4.2 will explore if preassembled facade units result in a reduction of future impacts, since opportunities for future (thermal) upgrade are provided whilst reuse of the entire facade unit and fast deconstruction is optimised.

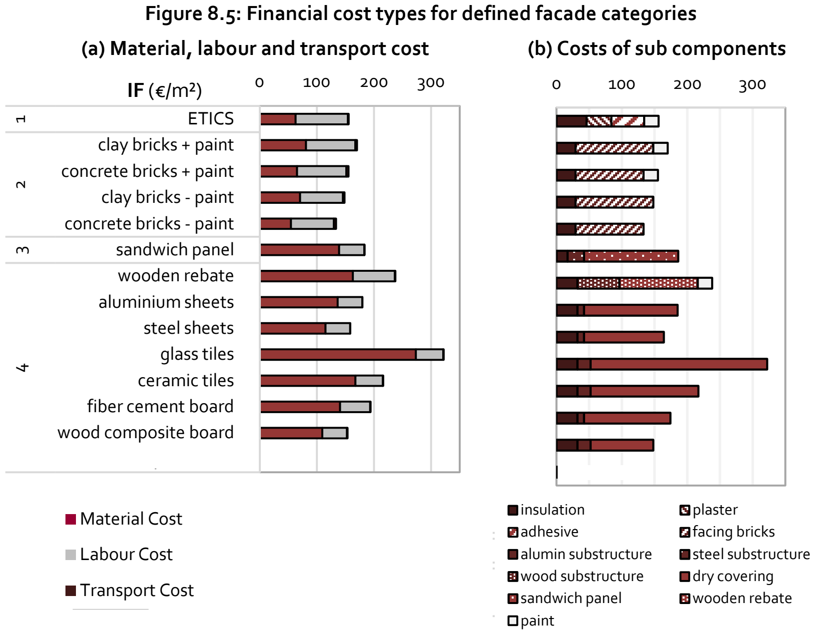
Figure 8.4: Initial environmental impact of categories 4 - 6 for ceramic covering



8.2.1.3 *FINANCIAL INVESTMENT*

Whereas the initial environmental impacts of facade categories mainly relate to *materials*, in financial assessment the included *labour* costs also play a crucial role for the initial construction. The financial analysis shows that the *assembly techniques* of facade solutions have a significant influence on the financial cost types, as represented in Figure 8.5. In this figure the financial investment costs (**IF**) of all facade categories are represented (excluding the interior supporting wall): while the left graph (Figure 8.5 a) shows the global contribution of material, labour and transport costs, the right graph (Figure 8.5 b) shows financial costs associated with each individual sub component in the exterior facade leaf.

Figure 8.5: Financial cost types for defined facade categories



The financial analysis shows that initial investment costs of facade categories solutions using wet assembly techniques (category 1 and 2) are of the same order of magnitude. On the contrary, dry connected rain screen systems (category 3 and 4) can require wide-ranging investment costs in relation to the material selection of the covering and its sub frame type[13].

In addition, the *distribution* of *material and labour cost types* is fundamentally different between facade categories using wet techniques (category 1 and 2) and dry techniques (categories 3 and 4).
In **categories 1 and 2** main costs are related to *labour costs* as a result of wet connection techniques, multiple small components delaying the speed of assembly, and specialised skills needed for placement. These categories require a high quality of execution to avoid water infiltration, cracks and condensation problems since all wall functions are clustered in one layer that cannot be changed later. The material costs are relatively low, since widely available sub components such as bricks, mortar and plaster are applied.

In **categories 3 and 4** the contribution of *materials costs* is much higher due to the use of specific aluminium sub frames and their connections, together with material cost related to aesthetic covering panels. Low labour costs typical for these wall categories are therefore a crucial element to make dry facade solutions able to compete with traditional labour-intensive brick walls and ETICS. Indeed, dry external wall systems reduce the overall labour costs by speeding up the assembly since they implement principles of Design for Assembly [CIRIA 2004] amongst which:

- *Standardisation of covering elements and connection systems;*
- *Simplification of the execution (e.g. no need for watertight weather screen in ventilated cavities);*
- *Use of straightforward and fast connections, including assembly tolerances.*

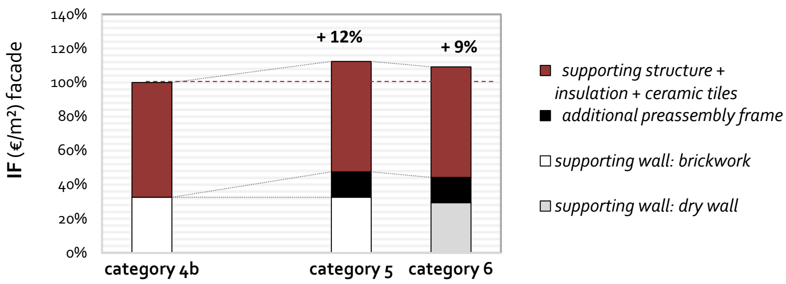
However, when too much multiple small-sized components are used and/or when the complexity of assembly increase - similarly to brick walls - the labour cost of dry systems increases, as is the case for wooden rebating[14] [CIRIA 2004, Crowther 2002].

[13] For instance, the selection of glazed covering panels results in almost two times the investment of dry covering using steel sheets, as a result of the elevated material price of lazed tiles, together with the additional costs related to a sub frame that can carry the additional loads.
[14] The relatively small wooden battens connected on a wooden carrier framework generate a higher labour cost compared to covering solutions with larger dimensions and fast connection systems using linear rails and brackets.

Nevertheless, the *speed of (de)construction* – a crucial aspect for renovation – of conventional dry facade systems which still must connect various elements on site, can still be further optimised. Therefore, renovation speed is taken into account in the design of **categories 5 and 6** by **preassembling** sub components, clustering external wall functions in unitised assemblies. Material and labour costs can thereby be reduced due to off-site production and assembly in a controlled environment. The dynamic facade proposal combines the advantages of preassembly, with future upgrade and reuse of composing elements. Additional costs related to preassembled units mainly concern the supplementary structure needed to group sub components into one preassembled unit. Labour work on site is limited to positioning and connecting these assemblies to the existing floor slabs and finishing. Due to reduction of material waste, purchase of materials on large-scale and controlled production conditions, material and labour assembly costs are assumed to drop with respectively 10% and 25%, based on literature [Haas 2000, BRE 2001].

As a result, Figure 8.6 shows that the categories 5 and 6 only add 12% and 9% to the investment cost of the equivalent solution of category 4b, respectively for category 5 and 6, as a result of the additional clustering framework.

Figure 8.6: Additional investment of preassembled facade units[15]



The results of the initial environmental and financial assessment led to the conclusion that investments for preassembled facade units are competitive with standard solutions and that the added environmental impacts are acceptable compared standard dry facade systems (category 4b). The analysis of the dynamic preassembled proposal also indicates that category 6 has the best score for both the initial environmental and financial impacts/costs.

[15] Figure 8.6 shows a minor reduction in the financial cost of the internal wall associated with the preassembled facade (category 5) compared to the in-situ connected dry facade (category 4). This is due to lower financial cost of the implemented interior dynamic wall.

8.2.2 VERTICAL PARTITIONING

8.2.2.1 OVERVIEW CATEGORIES

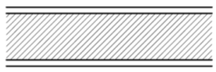
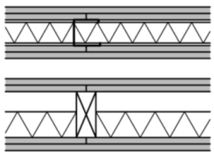
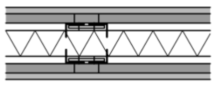
Three categories - from rigid to dynamic - are analysed for the vertical wall partitioning: plastered *masonry walls*, *dry system walls* and *DfD designed walls*. To define the functional unit, a combination had to be made between requirements for the sound and thermal performance and the fire safety.

The *airborne sound insulation* has been identified as the most stringent design criterion for wall partitioning in renovation of post-war social housing [Giebeler 2009, VMSW 2008, Paelinck 2008]. This was confirmed by the outcome of the survey held in this research. Since acoustic insulation is a complex issue which involves a holistic approach and calculation including the entire room/building, [Kuttruff 2006] for practical reasons, a minimal R_{w}-value was set for the determination of the functional unit. For partitioning walls a minimum **R_w-value** of 52-54 dB (category II a) was set, while for internal partitioning a minimum R_w-value was set of 47 - 49 dB (category II b) in order to comply with requirements set by the VMSW [VMSW 2005].
Moreover, *thermal* EPB regulation sets a maximum U-value for partition walls and separating floors of **U_{max}= 1,0 W/m²K** [EPB 2010]. In general, this precondition can easily be responded since insulation required for acoustic reasons also copes with these low thermal requirements.
The *fire resistance* of partition walls - also considered as a minimal requirement - is set to ≥ **R_f 1 ½ h** to comply with required fire resistance in social housing for divisions between different fire compartments – in this case between different dwellings or partition walls adjacent to the central hallway [VMSW 2005].

Clearly, it is impossible to achieve two walls with exactly the same performance for all these preconditions. Therefore, different wall types are determined for each category that comply with the minimum requirements, with frequently applied dimensions resulting from their availability of their sub components on the current construction market.

For **internal** *walls*, this leads to a functional unit defined by different types of brickwork for **category 1**. For dry wall systems (**category 2**) the materialisation of the framework is realised with metal studs or wooden battens. The materialisation of **category 3** was based on the design discussed in Chapter 6, for three proposals that differ in relation to their dynamic degree as a result of the applied boarding/finishing. An overview of the analysed solutions is given Table 8.7.

Table 8.7: Composition of the defined INTERNAL wall categories

Category		Composition	
category 1	 **masonry wall**	brickwork: a) perforated clay bricks b) sand-lime bricks c) cellular concrete blocks e) expanded clay blocks plaster (2-sided) painting (2-sided)	 140 mm 140 mm 150 mm 100 mm 12 mm
category 2 [16]	 **dry wall**	a)metal studs [17] b)wooden battens [18] glass wool insulation gypsum plasterboard painting	50 mm 38 x 89 mm 40(a)/ 70 (b)mm 2x 12.5 mm
category 3	 **DfD wall**	a)metal framework b)wooden framework glass wool insulation osb boarding + *a) MDF boarding* *b) gypsum fibreboard* *c) gypsum plasterboard* painting	50 mm 75 mm 40(a)/ 70 (b)mm 15 mm 12.5 mm 12.5 mm 12.5 mm

For **partitioning** walls, different brickwork materials are analysed for **category 1**, whereas for the dry system walls (**category 2**) two different wall compositions are determined, both responding to the minimal functional preconditions. The sub types of category 2 and 3 reach equivalent performances applying another approach: type 1 increases the mass of the external boarding; type 2 enlarges the wall cavity while disconnecting the wall leaves (type 3).

The dynamic variants (**category 3**) were selected from the design catalogues presented in Chapter 6 according to the equivalence to these two dry wall types. However, the exact acoustic insulation and fire resistance are not easy to determine. Acoustic software to

[16] The assembly of a dry wall with wooden battens generally requires a higher degree of accuracy than a metal stud frame, has lower acoustic performance and can encounter some deformation during use (due to e.g. moisture). However, wood is also a product that is easily available in different dimensions, that is simple to process and to work with. Both solutions are therefore considered as possible dry wall solutions, though with different physical characteristics.

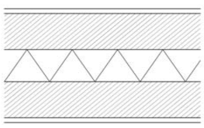
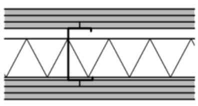
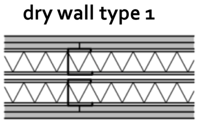
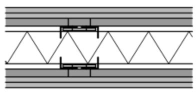
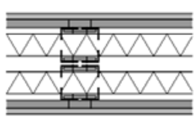
[17] The metal studs have a thickness of 0,6 mm and are positioned every 60 cm.

[18] The length of the used wooden battens (38 x 89mm) for 1m² is 2,1m and 0,8m for respectively the vertical and horizontal battens.

define the R_w-value of the different wall categories, i.e. *Insul* and *Bastian*, do not allow much deviation from traditional building solutions. The use of studs differing from the traditional metal studs is complex to model, while additional dry connections cannot be integrated in the basic software. However, since no other software tools were available for this research, assumptions were made about the acoustic performance of the dynamic wall categories based on equivalent acoustic solutions.

An overview of the analysed solutions is given in Table 8.8. The detailed properties of each wall category/type can be found in Appendix II.

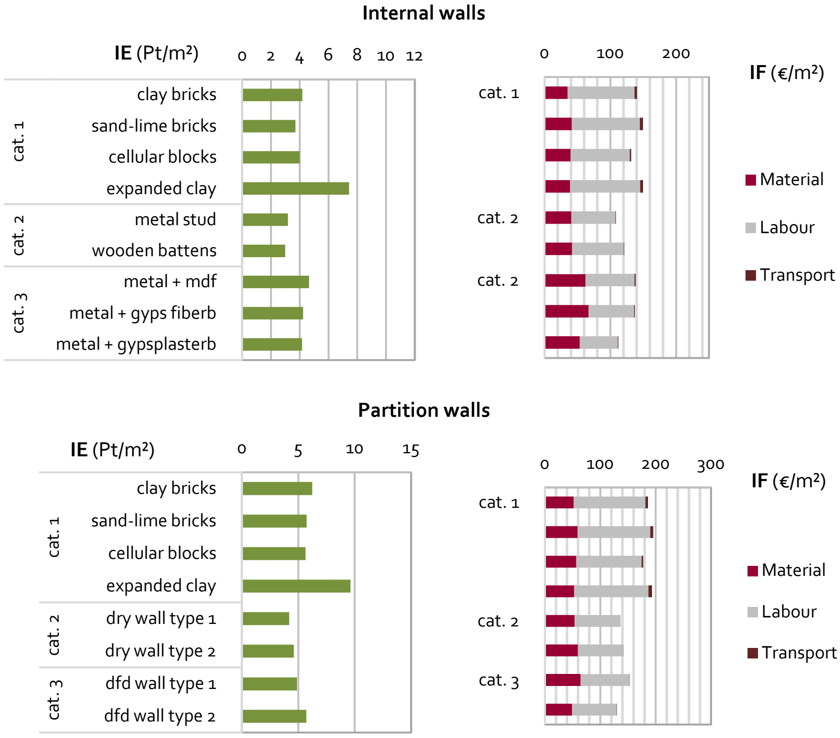
Table 8.8: Composition of the defined PARTITION wall categories

	Category	Composition	
category 1	 **brick wall**	brickwork: a) perforated clay bricks b) sand-lime bricks c) cellular concrete blocks d) expanded clay blocks glass wool insulation plaster + painting	 90 +140 mm 90 + 140 mm 70 + 150 mm 90+ 140 mm 40 mm 12 mm
category 2	 **dry wall type 1**	metal studs glass wool insulation gypsum plasterboard painting	100 mm 75 mm 3x 12.5 mm
	 **type 2**	metal studs[19] glass wool insulation gypsum plasterboard	2 x 50 mm 40 + 40 mm 2x 12.5 mm
category 3	 **DfD type 1**	metal framework glass wool insulation osb boarding gypsum fibreboard painting	100 mm 75 mm 18 mm 2 x 12.5 mm
	 **type 2**	metal framework glass wool insulation osb boarding gypsum fibreboard painting	2 x 50 mm 40 + 40 mm 18 mm 12.5 mm

[19] The metal studs have a thickness of 0,6 mm and are positioned every 60 cm.

Figure 8.7 shows the analysis of the initial environmental impacts and the financial investment, for each internal and partition wall category. First, these figures show that dry wall systems (**category 2**) have the lowest overall initial environmental impact and financial cost for both internal and partition walls. The low investment cost can be explained by the wide availability of dry wall systems on the building market today together with the simplicity for non-experts to erect these non load-bearing wall assemblies. The environmental impacts are limited due to the low environmental impacts associated with the production of gypsum plasterboard and glass wool insulation, together with use of thin metal sections.

Figure 8.7: Initial environmental impact and financial investment of wall categories



In contrast, **category 1** again involves labour-intensive assembly, while the environmental impact related to masonry blocks and their mass in order to achieve elevated sound performance levels is relatively high compared to sub components in dry walls.

For **category 3**, three internal dynamic wall types were analysed, i.e. three material boarding types arranged in order of reuse potential: MDF – gypsum fibreboard – gypsum plasterboard. For *internal walls*, Figure 8.7 shows that selection of boarding introduces

significantly higher initial environmental impacts, compared to traditional gypsum plasterboards and fibreboards. Alternative wall boarding materials were selected, namely wood-based OSB for the structural boarding of the preassembled wall, in combination with additional external boarding materials (gypsum plasterboard - gypsum fibreboards - MDF) depending on required degree of change. The down side of the reusable wood-based boarding is that it introduces higher initial environmental impacts and investment costs, compared to conventional gypsum plasterboards. The general idea about wood-based materials - like MDF, OSB and particleboard are engineered wood-based sheet materials in which wood chips are bonded together with an adhesive synthetic resin - is that these are environmentally-friendly materials, since they are 'based on wood' which is associated with 'good' environmental impacts. However, the production processes of these panels and the binders used are responsible for high overall environmental impacts[20].
In financial terms, the benefits of preassembly on labour cost reduction keep the investment costs comparable to equivalent dry wall categories. Dynamic design of preassembled partition wall assemblies results in addition of 8% to investment costs and 30% to the initial environmental impacts compared to dry walls.

For the *partition* walls, Figure 8.7 shows that category 3 adds 15% to 25% to the initial environmental cost, and respectively adds and reduces the financial investment with 13% and -8%, for the wall types 1 and 2. The relatively high environmental impacts compared to category 2 relate to the reusable OSB boarding combined with gypsum fibreboard (to provide a better fire resistance) together with selection of a thicker metal framework to enable reuse. Indeed, to enhance dynamic design, building materials are selected and dimensioned to be reused in future building applications. In contrast, dimensioning of sub components in stud walls and selection of boarding material (gypsum plasterboards) are optimised to meet up initial assembly preconditions. This implies that impacts related to the components in conventional dry walls (category 2) are relatively small since their dimensions have been optimised for one single and finalised application. For instance, the structural profiles in dynamic preassembled walls (category 3) demand for larger steel sections than for traditional metal stud walls, to ensure that sections can be reused after dismantling.

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20 For instance, to produce MDF, input materials include co-products from the production of other wood manufacturing processes, i.e. the wood residue comprised of shavings, sawdust and chips (89%), urea-formaldehyde resin (10%) and paraffin wax (0,75%) [Eco-Invent 2010]. The embodied energy to produce MDF consists of fuels and electricity used to generate and deliver fuels and electricity to the mill, and to manufacture input materials such as wood (for example energy required for felling the trees), resin, and wax. This results in high environmental impacts, related to the electricity use. In addition, the effects of the current waste disposal options for MDF production plants must also be considered. Today, 75% of waste produced from MDF manufacturing in Belgium goes to incineration with energy recovery and 5% goes to landfill [BBRI 2010].

In addition, the selection of reusable materials suitable for facing boarding of walls is ambiguous, as discussed in Chapter 6. Gypsum plasterboards – widely used for wall applications – incorporate good characteristics to answer the major design requirements of wall compositions (acoustic, fire and surface requirements), while their environmental impact and investment cost are relatively low. One crucial aspect in dynamic design however is missing: the ability to reuse these boards. Indeed, brittle materials must be avoided since repeated manipulation of elements during construction, deconstruction and transport make these materials vulnerable for (surface) damage [Debacker 2007].

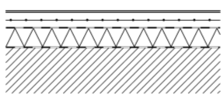
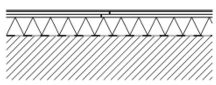
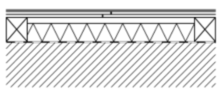
In order to comply with regulatory design therefore a compromise was made for the external boarding in dynamic partition walls: although gypsum fibre boarding may be reused, the detailing to comply with the acoustic and fire resistance requirements leads to the sacrifice of this layer when adaptations are required. The remaining sub components of the dynamic wall composition, however, still can be entirely reused in case of interventions in the buildings. The influence of this dynamic design on the total life cycle will be discussed further on (§8.3.2).

8.2.3 FLOORS AND CEILINGS

8.2.3.1 OVERVIEW CATEGORIES

Three floor categories were discussed in Chapter 6 with the objective to upgrade the acoustic insulation with regard to impact sound of separating floors in existing apartment buildings. An overview of the categories is given in Table 8.9 and Table 8.10.

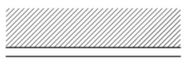
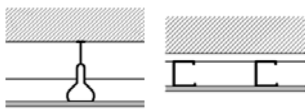
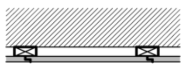
Table 8.9: Composition of defined floor categories from static to dynamic design

	Category	Composition	
category 1	 **screed floor**	linoleum finishing reinforced anhydrite screed moisture and vapour control layer PUR insulation (damp proof membrane) **existing concrete floor slab**	2,5 mm 60 mm / 40 mm /
category 2	 **continuously supported dry floor**	linoleum finishing particle boarding[1] moisture and vapour control layer glass wool insulation (150 kg/m³) (damp proof membrane) **existing concrete floor slab**	2,5 mm 22 mm / 30 mm /
category 3	 **self-supporting dry floor**	linoleum finishing particle boarding wooden battens (treated wood) glass wool insulation (80 kg/m³) (damp proof membrane) **existing concrete floor slab**	2,5 mm 22 mm 50 x 50 mm 30 mm /

Category 1 represents rigid screed floors, in which technical ducts are entirely integrated in the screed subfloor layer. **Category 2** represents intermediary dynamic floors in which unplanned interpenetration of technical ducts and insulation takes place. The third category (**category 3**) raises the dry subfloor to take full advantage of created voids to separate the technical layer from the insulation and subfloor layer. Hence, technical upgrade of floors can take place without interfering with remaining floor layers.

For the ceiling categories static and dynamic solutions have widely diverging properties due to the fact that the only requirement is the manner of *finishing* ceilings. Combination of solutions on the upper and lower floor side depends on several building parameters such as storey height, thickness of the floor slabs, flanking sound transmission and load-bearing capacity of the existing building structure. Impact sound improvements is in general dealt with on the upper side of floor, while on the lower side interventions are restricted in order to maximise the available storey height. Therefore, only the upper floor solutions are discussed in this chapter.

Table 8.10: Composition of defined ceiling categories

	Category	Composition	
category 1	 **plastering**	plaster paint	20 mm
category 2	 **dry ceiling**	(metal hangers) metal studs gypsum plasterboard paint	 60 mm 12,5 mm
category 3	 **dfd ceiling**	wooden battens laminate finishing	22 x 55 mm 12 mm

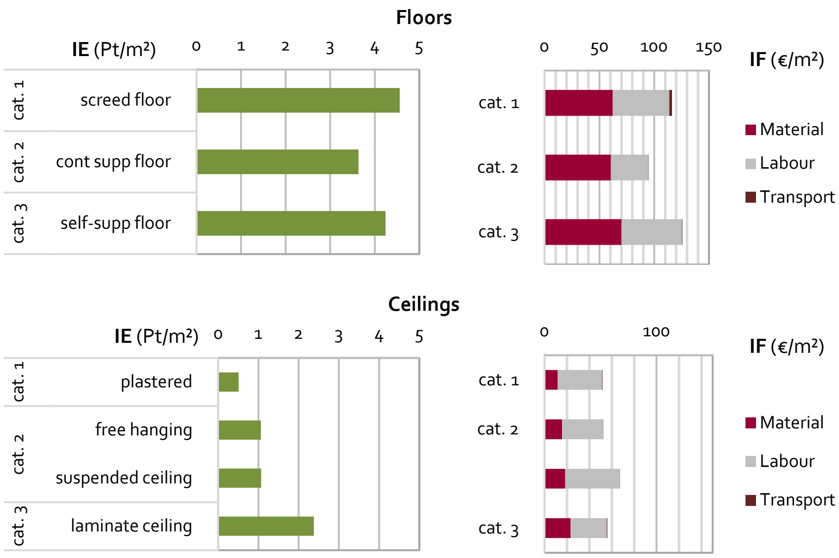
In addition, the floor finishing is an important layer in order to increase dynamic design of underlying floors. If dynamic floors are combined with floor finishing that requires destructive removal techniques it is clear that dynamic benefits of the subfloor will be lost. Therefore, an additional assessment on floor finishing is performed (see §8.5.1). For the general assessment, linoleum was selected as floor finishing for all evaluated categories[21].

[21] It is assumed that the linoleum layer can be removed without destructive methods.

Category 1 makes use of the mass-principle to increase the sound insulation, whereas dry subfloors make use of the mass-spring-mass principle. Therefore, these floor categories can be compared to the different categories in wall partitioning, i.e. massive brick walls versus dry walls. Similarly to the internal and partitioning walls the required mass in screed floor is responsible for the higher initial environmental impact compared to dry subfloor categories.

For the financial investment, the dynamic floor solution (category 3) involves investment cost comparable to screed floors (category 1) due to the high labour costs involved with both solutions. Therefore, it is assumed that impacts/costs related to the initial construction phase of the dynamic floor category are acceptable.

Figure 8.8: Initial environmental impact & financial investment of floors/ceiling categories

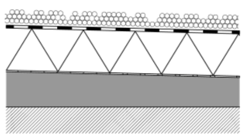
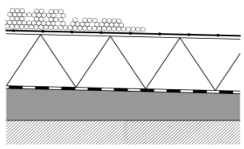


8.2.4 ROOFS

8.2.4.1 OVERVIEW CATEGORIES

Two *flat roof* categories for thermal upgrade of post-war apartment buildings are retained from the qualitative assessment discussed in Chapter 4. The first category (**category 1**) upgrades a roof to a warm deck roof, in which new thermal insulation is laid over the existing roof membrane (functioning as a vapour barrier) and a new waterproof layering is fixed over the new insulation. In **category 2**, a warm deck roof is created, in which the thermal insulation is laid loose on top of the existing roof membrane without additional waterproof layering and the insulation layer is finished with a movable sheeting and ballast, such as gravel, to keep the insulation in place. The MCA assessment indicated that this second category has a high overall score (including adaptability criteria), explaining why this category was retained as the dynamic category for this assessment. Both solutions have a U_{max}-value of 0,3 W/m²K according to the EPB [EPB 2010].

Table 8.11: Composition of the defined roof categories

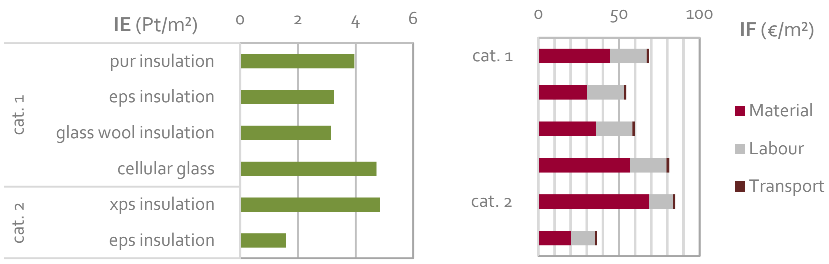
Category		Composition	
category 1		ballast (gravel) bitumen insulation a) PUR b) EPS/ glass wool c) foam glass **existing roof construction**	50 mm 5 mm 100mm 140 mm 2 x 80 mm
category 2		ballast (gravel) PE-foil insulation a) XPS insulation b) EPS insulation **existing roof construction**	50 mm 180 mm 180 mm

8.2.4.2 ANALYSIS OF INITIAL SCENARIO

The initial environmental impact of the dynamic roof category (**category 3**) is significantly higher for XPS insulation than for EPS insulation, due to the higher density of XPS and high environmental impacts related to insulation materials derived from petrochemicals in general, compared to most mineral insulation products. XPS (extruded polystyrene) and EPS (expanded polystyrene) are both insulation materials derived from petrochemicals – causing resource depletion and pollution risks from oil and plastics production. Furthermore, styrene is produced from benzene, another chemical with both environmental and health concerns, explaining the high related environmental impacts.

XPS is slightly stronger than EPS, and although it is applied in many equal applications as EPS, it is more suitable where extra loading and/or impacts might be anticipated, like in this case - a flat roof with ballast.TV 215 [BBRI 2001] therefore recommends XPS as the most appropriate insulation material for roof systems where insulation is placed over the roof membrane, also as a result of its limited moisture absorption due to the direct contact of the insulation with rain water.

Figure 8.9: Initial environmental impact and financial investment of roof categories



Although the impacts and costs related to XPS are significantly higher than EPS, compared to the other roof categories 1 and 2 the total initial environmental impact and financial costs of this dynamic roof category are still acceptable.

8.3 LIFE CYCLE SCENARIOS OF LAYERS WITH HIGH TURNOVER

8.3.1 DATA FOR LIFE CYCLE SCENARIOS

8.3.1.1 NUMBER OF REPLACEMENTS

The assessment of scenarios - which integrates a wide range of parameters such as variable estimated service life of components (ESLC), period of analysis and turnover of the building layer - is not common in LCA modelling. To make these ranges of calculations possible for each scenario these variable parameters were modelled in the SimaPro software as discussed in Chapter 7. The number of changing sequences is defined the turnover rates defined in each life cycle scenario scenario, whilst replacements are calculated based on the estimated component service life.

It would be impossible to predict the service life of each building component, nor to forecast exactly in which timeframe components will actually be replaced. Therefore, assumptions are made about the service life span of (sub) components (ESLC) and the time in which replacements are taking place. Two extreme life expectancies (short and long) of sub components have therefore been calculated according to the methodology described in Chapter 7, to take the worst and best case scenario in account in terms of technical service life.

Replacements are only modelled to take place when the estimated component service life is ≥ 10 years and the remaining period of analysis after replacement is higher than half of the component service life (≥ 0,5 ESLC). In Table 8.13 the number of required replacements for each sub component of all building layer categories is calculated over a period of analysis of 15 years for scenario 1, and of 45 years for scenario 2 to 3, for the best (long ESLC) and worst (short ESCL) case scenario. The number of replacements for each building layer can be found back in Appendix II.

8.3.1.2 END-OF-LIFE TREATMENT

The end-of-life treatment of the (sub) components was derived from a research report set up in cooperation with VITO, WTCB and ASRO executed for OVAM [WTCB 2010]. This report included data about the present-day end-of-life treatment of building waste in Flanders. It was used as a starting point to set up waste categories, discussed in Chapter 7. The levels of recycling, combustion and landfill are based on available data of waste treatment practice of today. Based on the waste categories, end-of-life treatments shown in Table 8.12 are applied for the assessment of the environmental impacts related to the end-of-life treatment of modelled building products[22]. An overview of the end-of-life treatment for sub components in each building layers can be found in Appendix II.

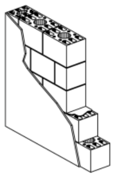
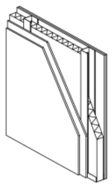
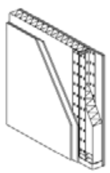
Table 8.12: Overview of end-of-life treatment of the main sub components of defined internal and partition wall alternatives

	Sub component	Material	End-of-life scenario		
			landfill [%]	comb. [%]	recycl. [%]
masonry wall	wall bricks	*clay*	5	0	95
		sand-lime brick	5	0	95
		cellular concrete	95	0	5
		concrete	5	0	95
	insulation	*glass wool*	85	5	10
	plaster	*gypsum plaster*	5	0	95
	paint	*alkyd paint*	100	0	0
dry wall	structure	*metal studs*	5	0	95
		wooden battens	5	95	0
	insulation	*glass wool*	85	5	10
	boarding	*gypsum plasterboard*	95	0	5
	paint	*alkyd paint*	100	0	0
DfD wall	structure	*metal frame*	5	0	95
		wooden frame	5	95	0
	insulation	*glass wool*	85	5	10
	boarding	*osb*	5	75	20
		mdf	5	75	20
		gypsum plasterboard	95	0	5
		gypsum fibreboard	95	0	5
	paint	*alkyd paint*	100	0	0

For the following discussion of life cycle assessment of building products, a subdivision is introduced for the building layers based on the turnover rate of the building layers: building layers with a *high* turnover rate (internal walls and roof), *intermediate* turnover rate (partition walls and facades) and *low* turnover rate (floors and ceilings) as was illustrated in Table 8.4. Not all performed assessments are included in this chapter, but an overview of all performed assessments is included in Appendix II.

[22] Possible further evolution towards more efficient recycling practice has not been taken into account since this is difficult to predict. Recycling of materials has thus been cut-off.

Table 8.13 : Estimated service life span (ESLC) of components of defined INTERNAL wall alternatives and number of replacements during three scenarios

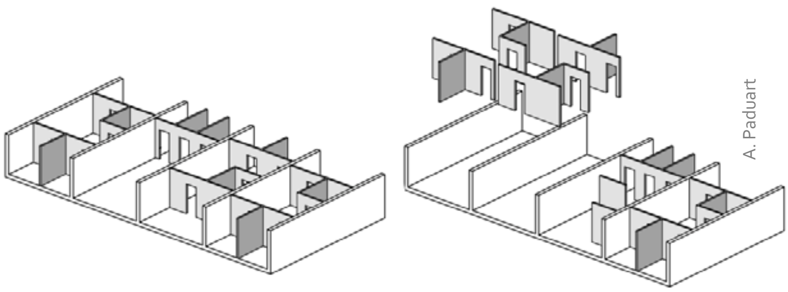
Internal wall categories	Sub components	ESLC (years)		Maintenance	Reuse	# Replacements					
						scenario 1		*scenario 2*		*scenario 3*	
						ESLC		ESLC		ESLC	
		min	*max*			*short*	*long*	*short*	*long*	*short*	*long*
	**category 1**										
	brick wall										
	bricks	40	145	↘	-	/	/	/	/	2	2
	plaster	10	60	↗	-	1	/	4	/	4	2
	paint	5	15	↗	-	2	/	8	2	8	2
	**category 2**										
	dry wall										
	metal studs	30	60	↘	+/-	/	/	2	/	2	2
	wooden battens	20	95	↘	-	/	/	2	/	2	2
	glass wool insulation	20	85	↘	+	/	/	2	/	2	/
	gypsum plasterboard	15	70	↘	-	/	/	2	/	2	2
	paint	5	15	↗	-	2	/	8	2	8	2
	**category 3**										
	DfD wall										
	metal frame	30	60	↘	+	/	/	2	/	2	/
	glass wool insulation	20	85	↘	+	/	/	2	/	2	/
	gypsum fibre board	15	70	↘	+/-	/	/	2	/	2	2
	osb boarding	15	70	↘	+	/	/	2	/	2	/
	paint	5	15	↗	-	2	/	8	2	8	2

8.3.2 FLEXIBLE INTERNAL PARTITIONING

Wall partitioning in residential buildings today is mainly executed as an element which subdivides space in different rooms. Secondary functions - such as electrical appliances, heating devices - are integrated as a physical supplement or extraction of this assembly, using destructive methods (i.e. cutting slots for technical linings in brick walls) and static placement techniques of the building services. As a result, when technical services have been put in place according to the specification of the space configuration *today* it requires radical measures to make any adaptation related to technical organisation (e.g. positioning of light switches and electric sockets) or functional upgrade (e.g. acoustic upgrade). For instance, when renovation works are evaluated and a poor insulation level is measured on site - due to poor assembly execution of the detailing leading to acoustic leaks - further acoustic upgrade is impossible due to rigid connection techniques.

As a response, the proposed dynamic wall design (Chapter 6) is conceived as a multi-layered vertical assembly that combines multiple functions, amongst which only *one* is partitioning. Each function is added as a separate layer to make adaptations/upgrade possible in any layer without having to interfere in all layers, while maximising the reuse of sub components. Benefits of this dynamic approach for wall assemblies can principally be explored by analysing the third assessment scenario, set up according to the outcome of the survey which indicated a high request for flexible internal wall partitioning. Indeed, the VMSW considers adaptability as an important objective in the framework of 'Lifelong living" projects [ENTER 2009].

Figure 8.10: Flexible repartitioning of the internal space



Lifelong living design departs from the global concept that houses should match with the needs of inhabitants instead of inhabitants adapting themselves to their houses. Therefore designers should provide an adaptable structure which enables simple adaptations with minimal costs for inhabitants to live in configurations adapted to their age and use of space. In this context, the materialisation of internal walls is of crucial importance to repartition spaces without major cost implications and adding up of the building waste stream.

8.3.2.1 *ENVIRONMENTAL LIFE CYCLE ASSESSMENT*

RESULTS OF THE ANALYSIS

Figure 8.11 illustrates the influence of *building assessment scenarios* and the *estimated service life of components* (ESLC) on the results of the environmental life cycle assessment of internal wall categories. In the graphs the initial and life cycle environmental impacts of different wall categories are represented: **large** icons represent the life cycle impacts related to the **short ESLC** (S) and **small** icons represent the **long ESLC** (L). The **initial environmental impacts** (**IE**) on the X-axis are of another order of scale than the **life cycle environmental impacts** (**LCE**) expressed on the Y-axis, to enhance readability[23].

The first chart (Figure 8.11) illustrates scenario 1 in which the building service life amounts 15 years assuming early tear-down of the building. The second chart shows scenario 2 in which during the period of analysis of 45 years no building interventions are assumed except for replacement of failing components and maintenance interventions. The third chart represents **scenario 3** in which internal walls are subject to regular repartitioning due to changes in the apartment layout.

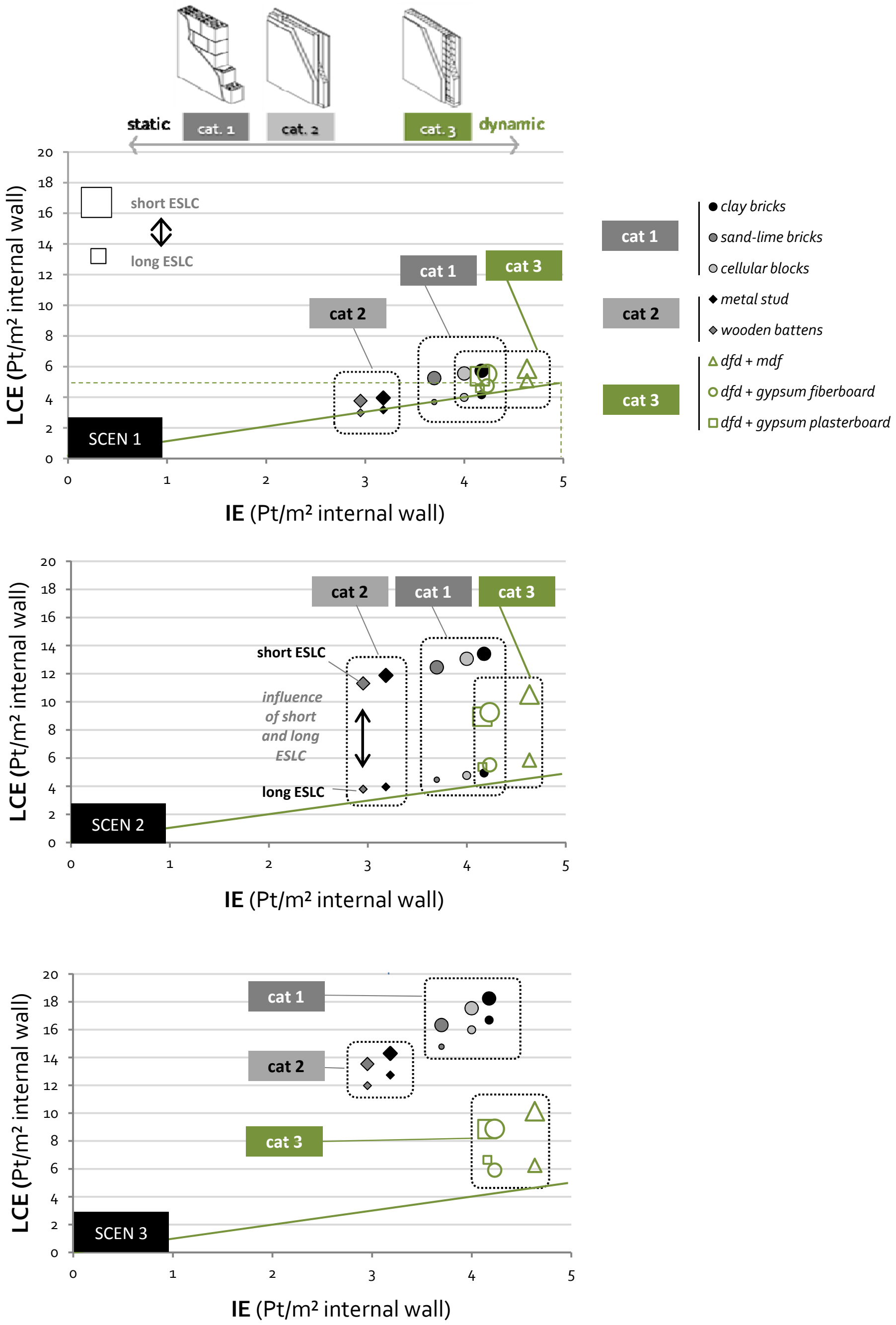
A first overall observation is the significant influence of the service life of the sub components (ESLC) on the overall LCA results. Indeed, an excessive amount of replacements of components and heavy maintenance due to shorter life spans than initially expected (i.e. short ESCL) adds considerable contributions to environmental life cycle impacts. This is best illustrated in scenario 2, in which no interventions are assumed, only the replacement of components at their end-of-life. In addition, attempts of reuse strategies extending materials' useful lives cannot be fully taken advantage of in this case.

Second, the building scenarios show to be relevant for the formulation of benefits attributed to wall categories.
Category 2, i.e. the traditional dry walls, show lower life cycle environmental impacts compared to the other categories for both **scenarios 1 and 2**, in which no life cycle interventions are considered. However, from the moment on that alterations are needed (**scenario 3**), their life cycle impacts increase significantly, as can be seen in Figure 8.11 (scenario 3) due to the high turnover rate of internals walls (every 10 years).

---

[23] Attention has to be given to the fact that the axis indicating the life cycle impacts (i.e. Y-axis) increases more rapidly than the X-axis, which may lead to the wrong interpretation that the contribution of periodic impacts to the life cycle impacts are relatively small. Therefore, a straight line was introduced in the graph, connecting the same value on both axes. The further the distance between the LCE results and this line, the higher the value of the LCE.

Figure 8.11: Environmental life cycle assessment for internal wall categories: scenarios 1-3



Scenario 3 considers frequent alteration of internal plan layout, which naturally takes place in buildings in order to respond the changing needs of the future inhabitants. Consequently, this is when the influence of dynamic design becomes tangible in the results of the life cycle assessment of building scenarios. As discussed in the previous paragraph, additional layering of components and use of supplementary dry connectors adds up to the initial environmental load. If the period of analysis is short as in scenario 1 (15 years) the life cycle impacts attributed to each wall category are closely related to the scale of its initial impacts. Since it was already discussed for the initial environmental impact that dynamic design increases the initial impact the result for this short period of analysis are similar. In the second scenario (scenario 2) it is assumed that no radical interventions will occur during the following 45 years. This scenario embodies the current vision on building design, and consequently, is also closely related to the relative scale of the initial impacts. However, for an elevated turnover rate of partitioning (scenario 3) Figure 8.12 shows that for benefits of reuse of components in dynamic design (**category 3**) weigh up against the initial higher impact of DfD walls (category 3) and the higher investment cost (this will be discussed further in §8.3.2.1). In scenario 3 it is modelled that buildings are not static products that do not evolve over the years – in contrast to how building are conceived today - but that on the contrary, buildings undergo series of events of change.

In this case, the reference wall assemblies (categories 1 and 2) must face up against major impacts associated with each replacement, including entire demolition of walls and new extraction of raw materials for the production of similar wall components. DfD solutions (category 3) are then significantly reduce the environmental life cycle impacts with 50% on average - compared to the metal stud walls of category 2.

Figure 8.12: Environmental impact per sub component of each internal wall category for assessment of scenario 2 and 3 (short ESLC)

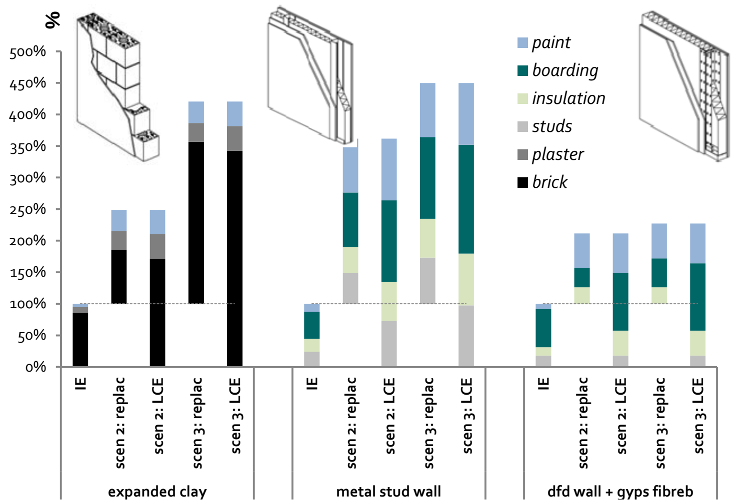


Figure 8.12 shows that dynamic wall partitions therefore are characterised by stability regarding to their life cycle impacts, independently of the considered life cycle scenario, in contrast with standard wall categories.

An additional added aspect has not yet been discussed, i.e. the residual value of sub components after the period of analysis. Dynamic design incorporates more environmental benefits than merely reductions of the environmental impacts over the total building life cycle. Reuse potential of components also offers major benefits at the end-of-life phase of buildings. Since dynamic wall categories may still incorporate residual (environmental) value after a short building scenario (scenario 1) an additional evaluation was made regarding residual value of components at the end-of-life of building scenarios.

RESIDUAL VALUE OF COMPONENTS

The residual value of components was calculated and derived from deconstruction aspects related to the wall categories and minimal functional requirements that enable reuse. First, to enhance 'reuse' of components connections must be reversible and materials must allow reuse. Secondly, a functional set of requirements was modelled in order to evaluate if the remaining service life of components is adequate to consider benefits of residual value. The applied methodology is discussed in Chapter 7.

Figure 8.13: Residual values for 3 scenarios of INTERNAL wall categories

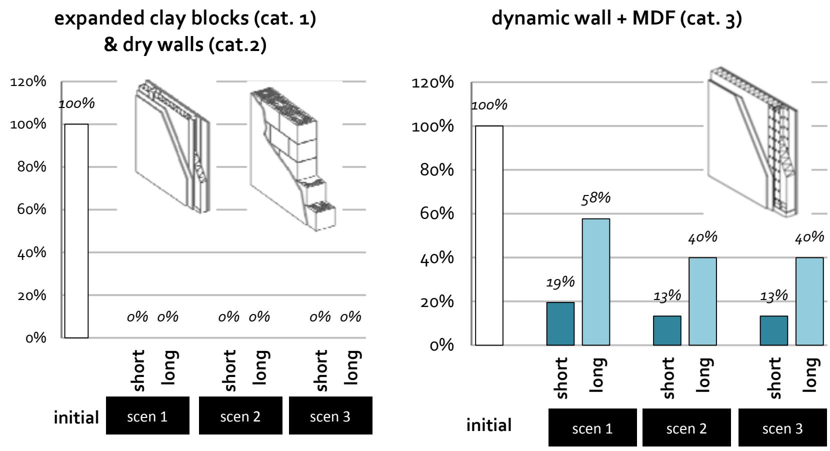


Figure 8.13 shows the residual environmental value of wall categories for the three life cycle scenarios. These charts illustrate that static buildings systems hinder components to be reused even when they still have remaining material benefits. Whereas categories 1 and 2 have no residual value, the dynamic wall category (category 3) still contains 13% to 58%

of residual value for e.g. MDF boarding, compared to its initial value, depending on the scenario and the ESLC of sub components.

The differences between the short and the long ESLC are relatively high, since reuse opportunities of sub components with short ESLC are restricted, due to the functional requirements set up for residual value. For instance, the remaining service life of sub components after each scenario must amount a minimum of 10 years to be taken into account in the calculation.

INTERPRETATION OF RESULTS

When no replacement/upgrade/repositioning of internal walls is taking place during the building life cycle (scenario 1) or when the building only remains for a short period after renovation (scenario 2), dynamic building systems may have relatively high life cycle impacts compared to conventional building solutions. That is why in a design vision – that does not consider replacement - static solutions may seem beneficial compared to other solutions. However, the addition of a dynamic assessment scenario in this research together with analysis including residual value of building components shows that these results need to be put into sharper focus.

Indeed, the results of the third scenario show that when regular interventions are needed significant environmental gains are observed in dynamic wall layers, compared to static design of partitioning. Besides, the dynamic design maximises the residual value of sub components after deconstruction, for reuse in (other) applications at any point in the future. Reusing components is an efficient approach to avoid extraction of raw materials to produce new materials.

Nevertheless, it is clear that several conditions have to be met to enable these benefits to be maximised. The quality of components and the execution level are crucial to prolong the component service life and essential to make reuse achievable. **Preassembly** may play a key role in this matter, since the controlled conditions of manufacture and assembly have been indicated to have positive influence in this matter [BRE 2001].

8.3.2.2 LIFE CYCLE COSTING

The financial life cycle assessment of building solutions may differ to a large extent from the environmental assessment since not only the *material* cost is considered but also the *labour* cost for assembly, replacement, upgrade or removal are taken into account for the total assessment. Figure 8.14 illustrates the **life cycle financial costs** (**LCF**) of each internal wall category compared to its **initial financial cost** (**IF**) for the three assessment scenarios (for short and long ESLC). Figure 8.15 shows both the relative comparison between the initial environmental impacts/financial investments of each internal wall category and the overall life cycle environmental impacts/financial costs related to each building scenario.

The results of the three building scenarios give similar results as for the environmental assessment. For the first two scenarios (**scenario 1 and 2**) the categories with lowest life cycle costs are directly related to the categories which had the lowest initial costs, i.e. the dry wall system category (category 2). However, in the third category preassembly - reducing the labour costs - reduces the overall costs related to the dynamic wall type using gypsum plasterboard.

S**cenario 3** shows that in addition to environmental gains also financial gains can be attributed to dynamic design of wall systems. In this scenario, the life cycle financial cost of rigid brick walls and dry walls increases with more than 200% (for long ESLC) compared to scenario 2. However, since labour costs are incorporated, reuse of components adds up removal and repositioning labour costs when upgrade/repositioning of walls is required. Therefore, the life cycle costs of dynamic wall systems in scenario 3 also increase with 110% compared to scenario 2. Still, for this scenario dynamic building systems show to be a better financial alternative than categories using rigid building systems. In this scenario, a overall financial gain of **1% to 8%** can be made with the dynamic wall category, respectively using gypsum fibreboards facing boards, and MDF boards - compared to the dry walls. The gypsum plasterboards - assumed to be demolished and replaced with new boarding - add 11% to the life cycle financial costs.

Since **labour costs** contribute for over more than 50% to the overall life cycle costs (see Figure 8.16) it represents an important design factor for dynamic wall assemblies. Therefore, when a long set of assembly actions have to be done on the construction site a possible barrier for dynamic re-design is identified as the extensive amount of labour involved with its multi-layered assembly. The dimensions, amount, size and weight of elements to be assembled on site all influence the assembly costs, explaining why masonry walls - with its multiple small components - have higher labour costs than dry walls as represented in Figure 8.16.

Figure 8.14: Financial life cycle assessment for internal wall alternatives: scenarios 1-3

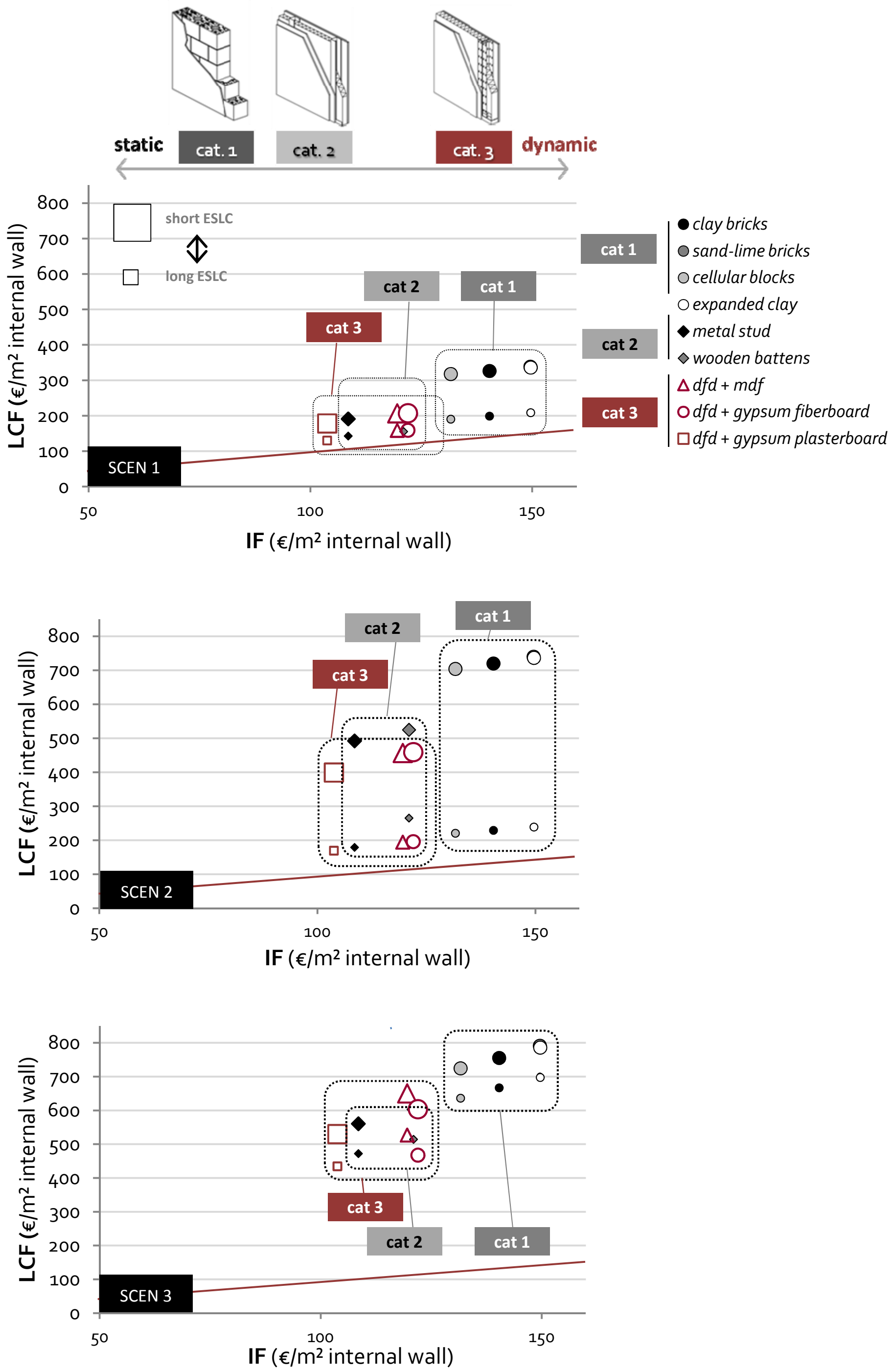
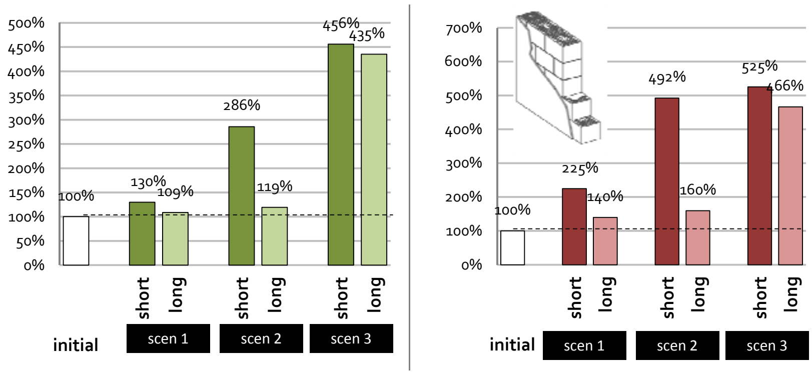


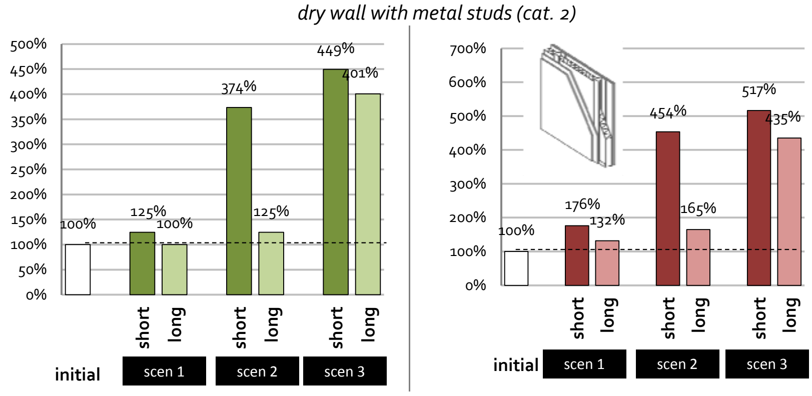
Figure 8.15: Relative comparison between initial environmental impact/ financial cost of internal wall categories and total life cycle cost for 3 building scenarios

environmental **financial**

masonry wall (expanded clay) (cat. 1)



dry wall with metal studs (cat. 2)



dfd wall with MDF (cat. 3)

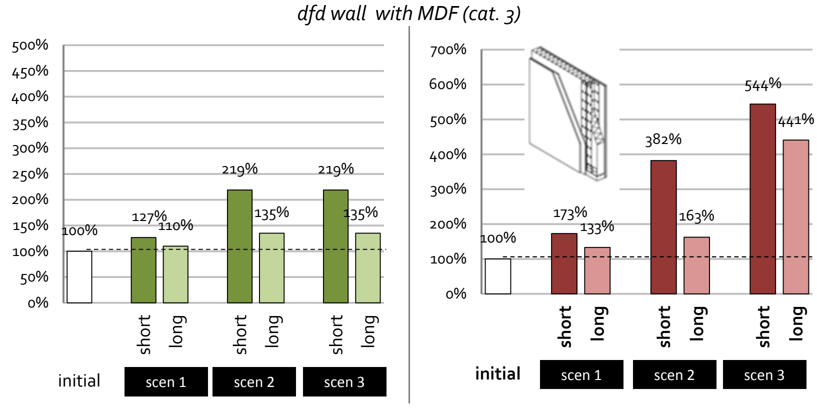
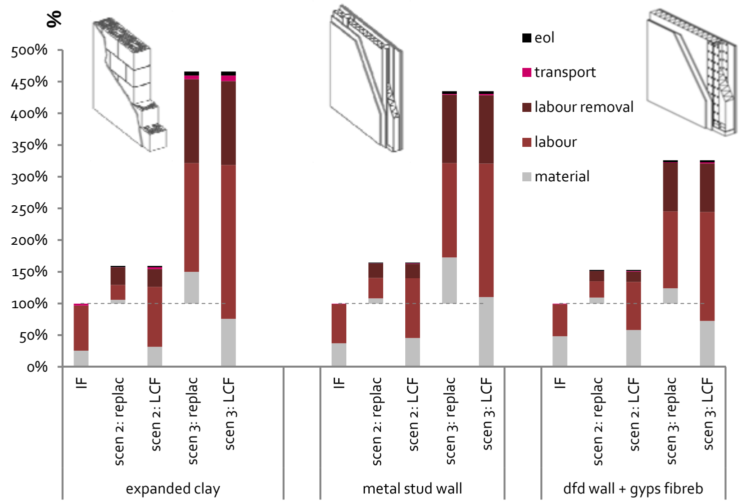


Figure 8.16: Financial cost types for assessment of scenario 2 and 3 of internal wall categories (long ESLC)



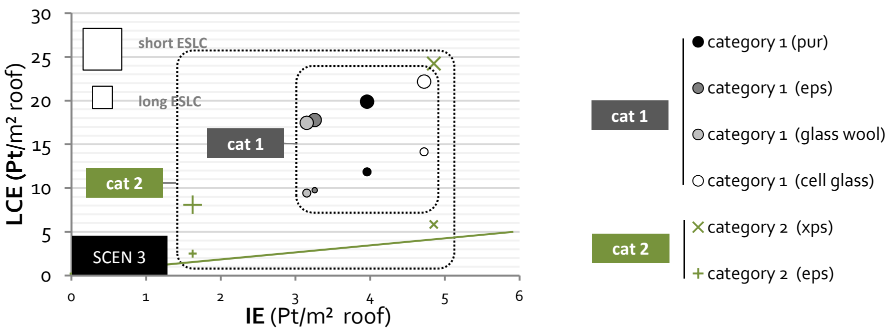
The proposed preassembly of wall assemblies (Chapter 6) enables to tackle this problem. In case of dynamic design of assemblies, indeed, particular attention has to be devoted to the execution of reversible connections, which are responsible for potentially increased assembly costs compared to dry walls - if constructed integrally on site. Preassembly of dynamic walls enables to decrease the labour costs due to preassembly of sub components under controlled off-site conditions, thus resulting in lower labour costs on site.

The financial gains attributed to dynamic design in case of a dynamic building scenario are smaller than the environmental gains for two main reasons. First, the potential to adapt building layers may have material benefits, but when including labour costs the high relative contribution of this cost type reduces the overall financial benefits that can be gain by reusing components. Secondly, when new components need to be re-inserted due to future building interventions the related future material and labour costs are being *discounted* - since present costs are esteemed to be more important than future costs. This means that future interventions resulting in supplementary material costs do not contribute in the financial assessment with same order of magnitude as for environmental assessment because in the environmental assessment no discounting is introduced in this research.

The roof is a crucial building layer when it comes to thermal upgrade of buildings, while flat roofs enhance the simplicity of future improvements. Several studies [Audenaert 2010; EcoFys 2005; 3E et al. 2008] indicate that values for the thermal transmittance - the U-values - resulting from the E-level of the current EPBD (Energy Performance of Buildings Directive) standards today are not sufficiently stringent, meaning that revisions will be made in the near future. For instance, the maximum U-value of external walls of U_{max} = 0,3 W/m²K until recently, will be limited to U_{max}=0,24 W/m²K from 2014 onwards [EPB 2014]. Social housing societies which are planning to renovate their building stock are aware of these revisions, as became clear in the discussions taking place during different sessions of the 'Flemish Energy Platform for Social Housing' organised by the VMSW[24]. This knowledge forms an important motive for housing societies to delay renovation works since all societies aim to comply with most updated thermal building regulation. As a result, many housing societies postpone renovation since they perceive renovation as an end-state building intervention which can no longer be upgraded in a further stage. Consequently, introducing the dynamic roof category can be advantageous, since predictable and unpredictable scenarios can be anticipated by its dynamic design.

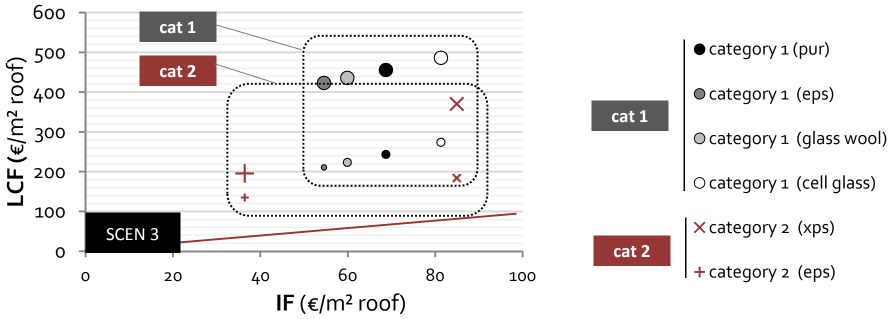
Figure 8.17 and Figure 8.18 show the benefits attributed to dynamic design of roofs, in which thermal upgrade takes place every 10 years by replacing loose-laid insulation.

Figure 8.17: Environmental assessment for ROOF categories for building scenario 3



[24] In the context of the European project 'Power House Europe' (PHE) the **Flemish Energy Platform for Social Housing** was established in May 2009. This creates a platform for the social sector for partners to share their vision on different energy related topics.

Figure 8.18: Financial assessment for ROOF categories for building scenario 3



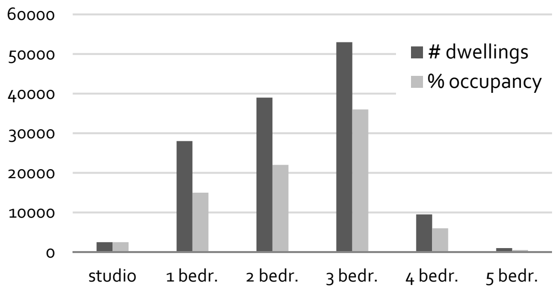
In case of a long estimated service life, significant environmental gains can be made with the loose-laid insulation roofs, since upgrade op the flat roofs in this case can be easily applied without destructive removal of any roof layer. For roofs of category 1 however, this is the case due to the adhesive assembly techniques used.

8.4.1 PARTITIONING WALLS

8.4.1.1 PARTITION WALLS VERSUS INTERNAL WALLS

The survey indicated a higher demand for flexible *internal* partitioning compared to *partition* walls. Nevertheless, regular update of the apartment typologies is still necessary to respond in an efficient manner to the specifications of the households which make an appeal to social housing[25]. Inefficient occupation of apartments is a well-known phenomenon in social housing. The occupancy of social housing – defined as the number of inhabitants with reference to the number of sleeping rooms - amounts on average 63% [Bosmans 2006]. Under-occupancy of dwellings is the result of evolved households, such as children leaving the parental house, divorce or co-parenting.

Figure 8.19: Social patrimony in Flanders – Occupancy



Source: [VMSW 2006]

Subsequently, flexibility of partition walls is essential to enable apartments to be updated regularly to the actual demand of candidate-occupants. Therefore, in the third scenario a regular update every 15 years was assumed to make technical and/or organisational adjustments/alterations of the space. To comply with building standards - which are more stringent for internal walls - the assessed dynamic wall variants make use of facing gypsum fibreboards, finished to comply with the acoustic and fire resistance standards.

[25] It is clear that this is also depending on the load-bearing structure of the building that is being considered for re-design for change. In case of cross-wall structures, the cross walls form permanently the partition walls between two dwellings (see Chapter 5). The considered structure is thus enabling a relatively free partitioning with free-standing partition walls.

8.4.1.2 LIFE CYCLE SCENARIOS

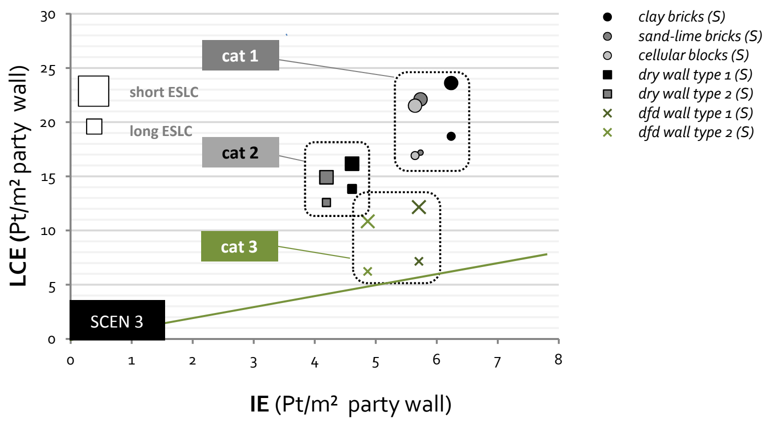
Scenario 1 and 2, in analogy with the assessment of internal partitioning, relate closely to the initial environmental impacts and financial investments due to the short period of analysis (scenario 1) or to the absence of interventions (scenario 2). In comparison with internal wall partitioning, the dynamic partition walls (category 3) add less environmental initial impacts compared to standard solutions. Further functional sub layering of partition walls results in a lower relative contribution of the wood-based boarding to the total wall composition, explaining the lower added initial environmental impact of dynamic partition walls. Nevertheless, for the first two scenarios the initial supplementary environmental impacts result in higher life cycle environmental impacts of **25%** (scenario 1) and **22%** (scenario 2), compared to the equivalent dry walls of category 2.

However, **scenario 3** shows again that significant benefits can be attributed to dynamic design. Figure 8.20 (c) displays that for wall type 2, life cycle benefits can return environmental and financial gains, of, respectively **50 % and 14%** - compared to the dry wall category. In addition, the residual value of sub components in dynamic walls is significantly higher in each scenario (Figure 8.21).

Therefore, although the replacement rate of partition walls is lower than for internal wall partitioning, and thus the potential benefits of dynamic design related to regular change are smaller, the environmental gains compared to conventional wall solutions are of the same order of magnitude. This can be explained by the higher overall environmental impacts related to partition walls compared to internal walls. As a result, the initial supplementary environmental impact due to dynamic design of wall category 3 (due to reasons that were discussed in the previous paragraphs) contributes less to the total impact of wall assemblies. Therefore, the environmental gains for scenario 3, relating to the potential to reuse sub components, can be better developed than was the case for internal walls.

Figure 8.20: Environmental and financial assessment of partition wall categories for building scenario 3

(a) Scenario 3: Environmental assessment



(b) Scenario 3: Financial assessment

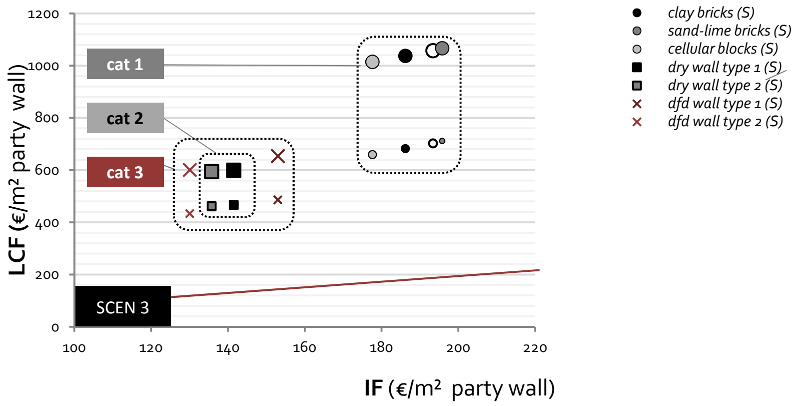
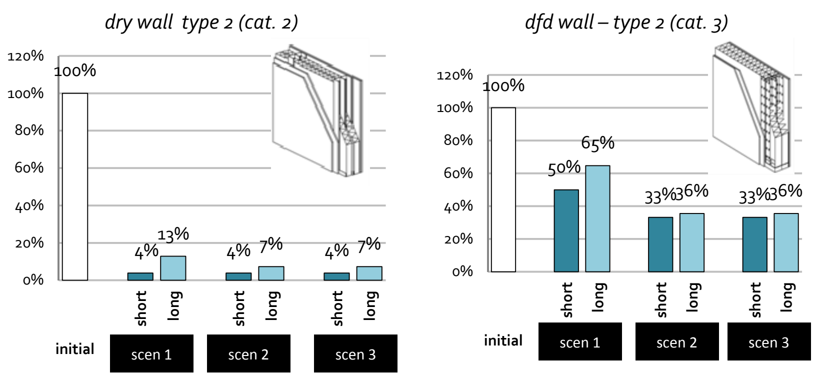


Figure 8.21: Residual values for 3 building scenarios of partition walls



8.4.2 FACADES

8.4.2.1 REGULAR THERMAL UPGRADE

The external skin of any building has a number of functions to fulfil, most of which involve protection from the climate, although aesthetics also play an important part. It may be tempting to specify bonded elements for a building skin which combine insulation, cladding, and finishing with water and wind tightness such as ETICS systems and solid brick walls. These facade solutions might fail in the long term given that attempts for upgrade or deconstruction are difficult. It is crucial to ensure that insulation levels can be upgraded without damage or disruption to the structural forms of the building, and also that the skins of the envelope can be repaired or replaced without disruption to the insulation and air tightness [Morgan and Stevenson 2005]. In scenario 3, the setting was explored in which thermal upgrade of the facade is taking place every 15 years to give, for instance, answer to more stringent EPBD regulation in the future.

The weathering skin of the dynamic facade (category 5 and 6) was therefore designed in an adaptable and removable way, with reachable and upgradable insulation layers, reusable sub components, and semi-finished facade unit speeding up the renovation process.

8.4.2.2 LIFE CYCLE SCENARIOS

The life cycle assessment of the environmental impacts in scenario 2 and 3 is represented in Figure 8.22. In **scenario 2** -which only considers replacements of failing components- one can see the importance of finishing: frequent repainting of wooden rebating (category 4a) and ETICS facades (category 1) in combination with replacement of other quickly layers (short ESLC) may increase life cycle impacts to respectively three or five times the initial environmental impact. For the remaining categories (category 1, 3, 4b, 5, and 6) shortening the service life span of components causes the life cycle impacts to double compared to the long service life scenario. As was the case for the partitioning the quality of the execution level is crucial to reduce life cycle impacts.

Facing bricks walls (category 2) show to have a good environmental score for the two first scenarios, in which no changes occur during the entire building life cycle, due to the low need for maintenance and the long service life of facing bricks. In the third scenario however, the rigid design of category shows to have some crucial drawbacks compared to more dynamic categories. The static design of the facade categories 1 and 2 implies that for thermal upgrade to more stringent energy regulations, the exterior leaf needs to be taken away and/or replaced with a new external leaf for each thermal upgrade intervention. This results in an increase of the environmental impact with 20% to 55%

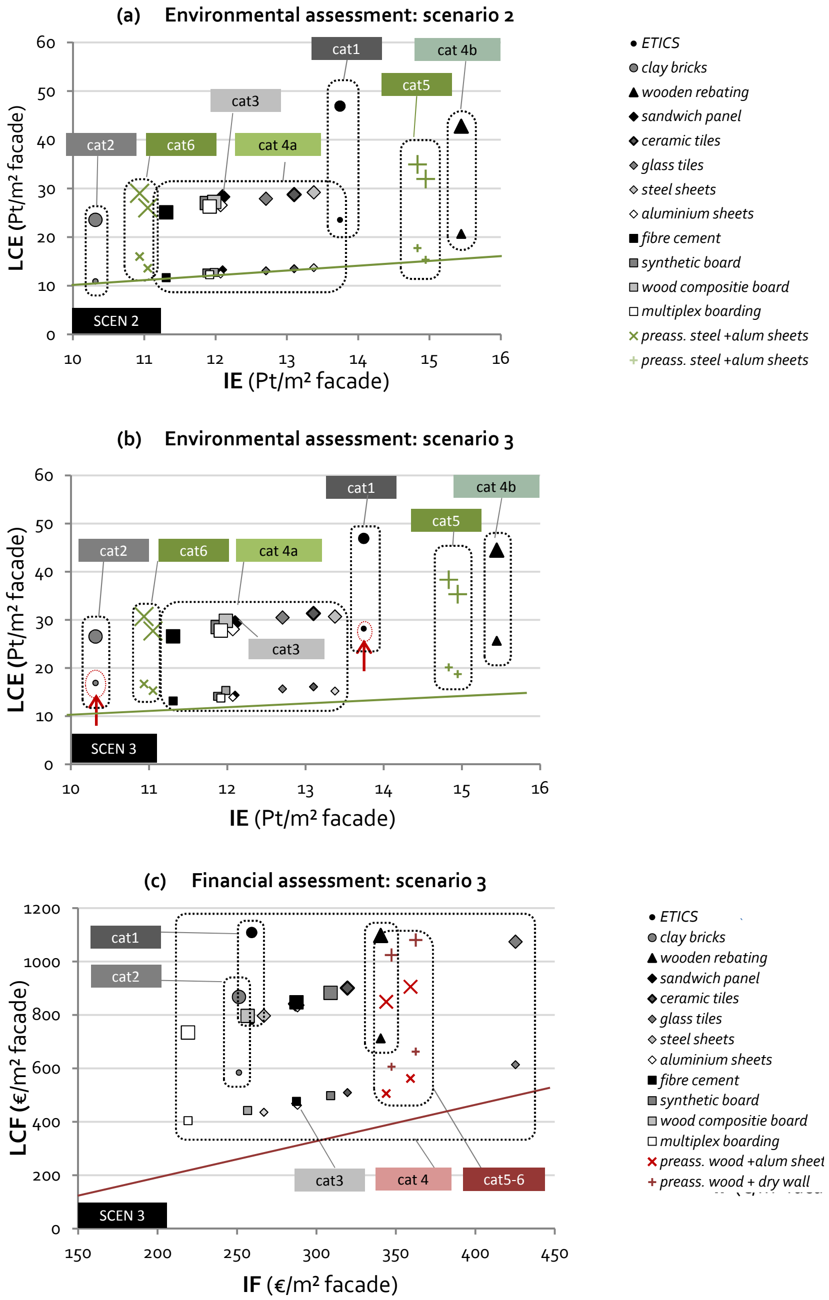
compared to scenario 2, respectively for the ETICS facade and the facing brick wall. In this scenario the dynamic building systems with a 'stable' environmental impact show to be a better environmental alternative than categories using rigid building systems

The environmental gains attributed to dynamic facade systems are clearly reflected in the results of the assessment **scenario 3** represented in Figure 8.22 (b). Environmental life cycle impacts of –dynamic– dry facade systems (category 4b) do not increase significantly in case of multiple upgrade- when a good execution and quality level of components can be ensured. Dynamic designed building layers can be dismantled, upgraded to new standards and take advantage of the reuse of facade components. The environmental impact of dynamic facade layers subsequently does not increase significantly (since only the impact of upgrading insulation layers is added). In this third scenario, an overall environmental gain of 15% to 20% compared to the facing brick walls can be made with existing dynamic facade categories (cat 4b).

The life cycle environmental impacts of the dynamic preassembled facade category (category 5 and 6) are of the same order of magnitude than facing brick walls, due to their increased initial environmental impact compared to dry walls built on site (due to supplementary layering).Therefore, the results of scenario 3 show that dynamic building solutions on the market today (category 4b) exhibit good properties concerning design for change. Benefits of the existing solutions also are confirmed by the financial assessment (Figure 8.22). Existing dynamic solutions built on site are therefore existing, valid alternatives for static ETICS and facing brick walls when designing for change in both environmental and financial terms. In recent years ventilated rain screen facades have been widely developed to provide external upgrade for existing building facades. These systems can incorporate a high degree of adaptability and reuse when a suitable sub frame is selected in combination with covering which can be assembled using reversible connections. Qualitative components together with a good execution level of the connections and standardised covering systems which reduce the complexity level, result in good environmental and financial properties associated with Design for Change.

The preassembled facade categories (cat. 5) may result in higher life cycle impacts. Nevertheless, they also exhibit additional benefits that are not incorporated in the life cycle analysis. First, in order to guarantee a long component service life for all facade categories good workmanship, qualitative execution and good detailing are required. Since the quality level is difficult to guarantee with on-site construction, preassembly of components offers good perspectives. The designed preassembled facade units have a higher chance to optimise the execution level of the dry facade techniques and leave minor space for execution faults on-site. The qualitative execution of preassembled modules prolongs the life span of the inherent components, leading to more efficient reuse of sub components in case of extensive upgrade.

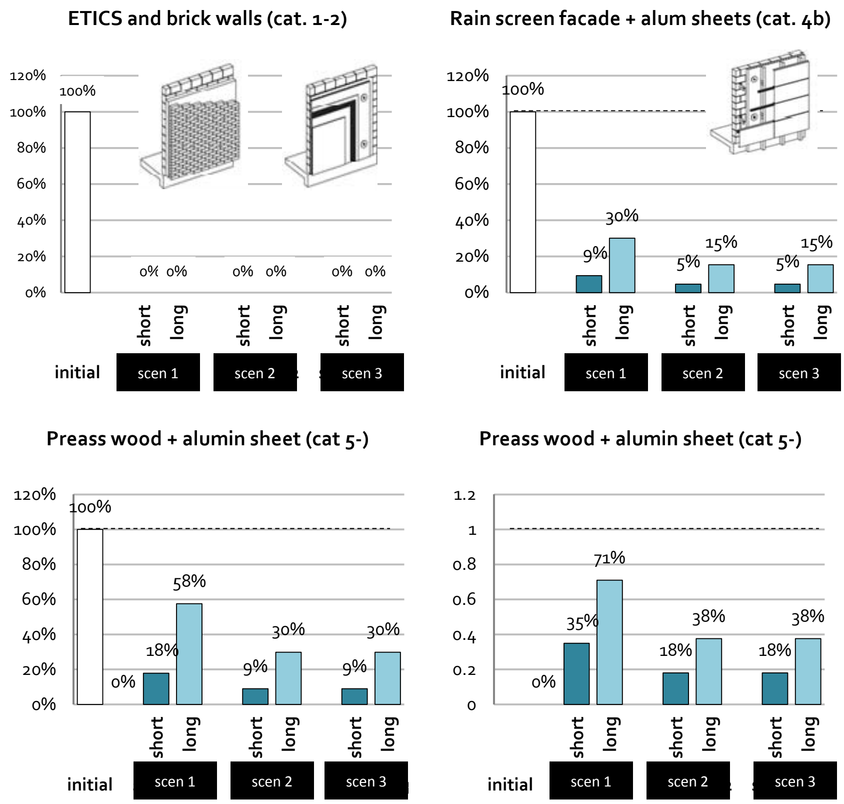
Figure 8.22: Environmental assessment and financial assessment for defined facade alternatives of building scenarios 2 and 3



Secondly, unitised preassembled facade assemblies offer great potential to speed up renovation processes by enabling the erection of insulation, airtight barrier as well as the supporting framework in a single operation on site with no need for a separate framework.

Finally, category 6 combines the benefits of the dry wall categories – featuring as the interior facade leaf instead of massive brickwork- with the benefits of preassembly. This means that facades of category 6 set up facade solutions of which the interior leaf can be more easily adapted than for a supporting masonry wall (i.e. category 5). This may result in solutions that can be more easily reconverted to facades with, for instance, adapted types of openings for windows in the future.

Figure 8.23: Residual values for 3 building scenarios of FACADE categories



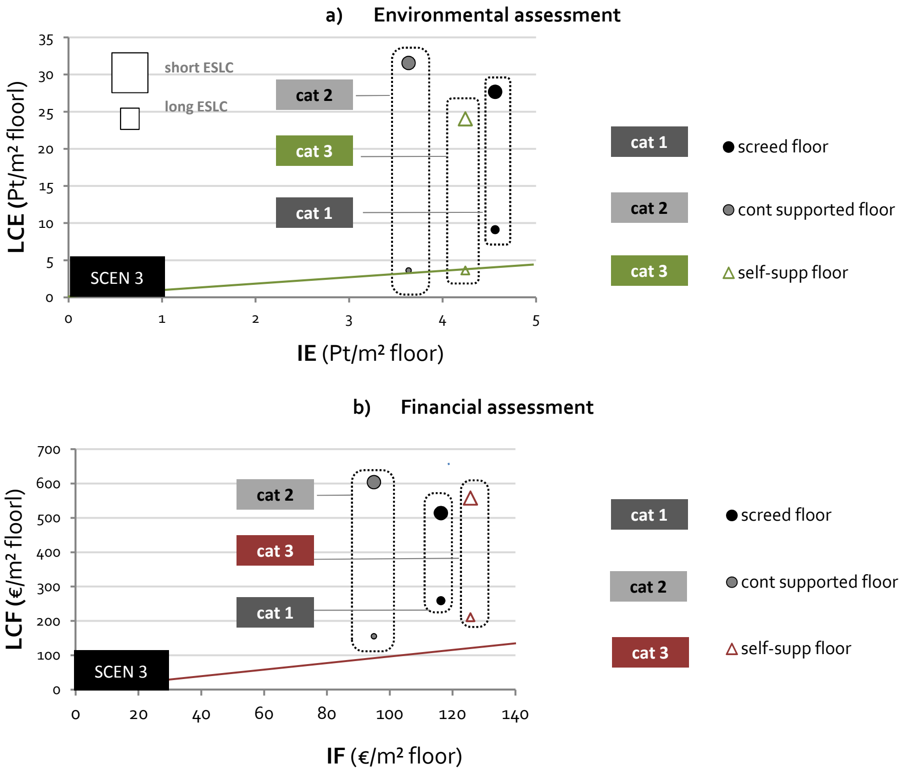
Clay brick walls showed to have a low initial environmental impact, but when facades need to be intensively changed in the long run, the lack of dynamic design causes these external walls to be entirely replaced. The advantages of brick components may be combined with the advantages of preassembled dry facade systems. This will be discussed for the case study of renovation in Chapter 9.

8.5.1 FLOORS

8.5.1.1 LIFE CYCLE SCENARIOS

The survey revealed a low request for change in floors, explaining why the turnover rate of floors was estimated to be 20 years. Upgrade of the floor layer mainly concerns upgrade of acoustic performance of the floor and update of building services incorporated in the floor layer. Figure 8.24 shows the result of the life cycle assessment of the third building scenario in which floors are subject to update of technical services every 20 years. Whilst floor categories using dry subfloors can be easily upgraded, due to the rigid assembly screed floors can no longer be adapted once they have been installed. As a result, Figure 8.24 illustrates the added environmental impacts and financial costs related to integral removal and replacement of screed floors. In addition, dry floor categories speed up the renovation process significantly compared to screed floors, since for 4cm of cement screed flooring 26 days of drying time are required [Tichelmann 2008].

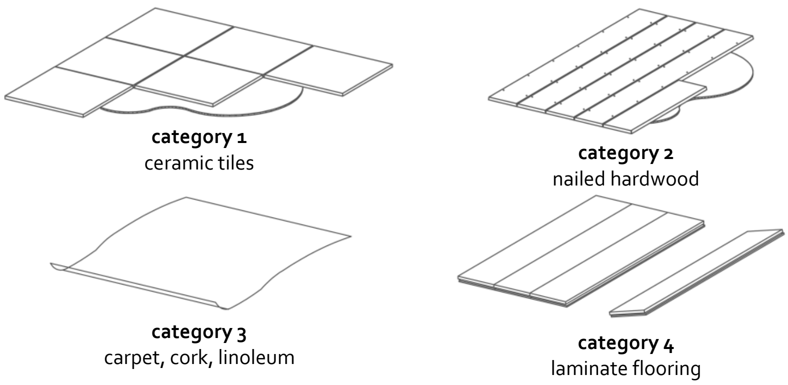
Figure 8.24: Life cycle assessment for FLOOR categories for scenario 3



In summary, although dynamic floor design in renovation of post-war buildings is not a necessity it incorporates potential benefits - compared to screed floors – like renovation speed and restricted additional weight of the existing load-bearing structure. Addition of flexible floor finishing is only a valuable surplus if flexible installations would be foreseen in floors. Since the floor height in post-war buildings is typically restricted this feature is not a highly desirable feature.

Nevertheless, as an additional evaluation, four categories were determined for the floor finishing, from categories using rigid connections such as mortars and glues (category 1) to dynamic flooring using tongue-and groove connections (category 4). The floor finishing was modelled based on Environmental Product Declarations (EPD) of fabricants[26].

Figure 8.25: Floor finishing categories



Laminate flooring (category 4), which enables reuse of the laminate prefabricated floor elements, showed to offer good properties in environmental and financial terms compared to the other floor finishing alternatives[27]. This may be an important additional dynamic feature in buildings in which floor flexibility is more important since the evaluation showed that the floor finishing contributes significantly to the total impacts of the floor[28].

[26] The modelling information based on these EPD's is consultable in Appendix III.

[27] The assessments can be found back in Appendix II.

[28] In the assessed floor categories, linoleum was used as a floor finishing, representing around 40% of the environmental impacts and financial costs of the entire floor composition.

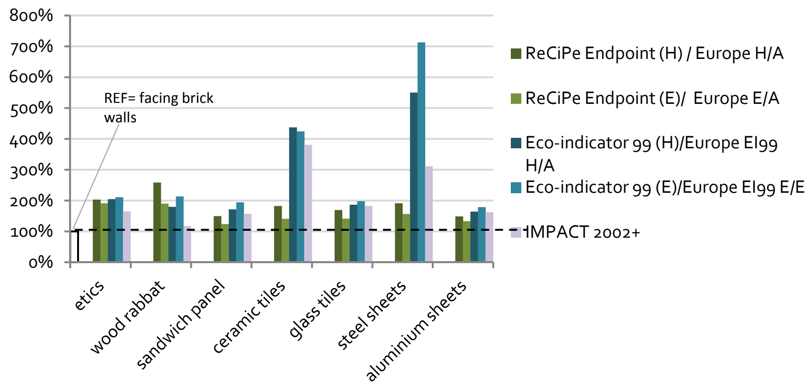
8.6.1 ENVIRONMENTAL ASSESSMENT

A sensitivity analysis was done in relation to impact assessment methods, to capture the effect of environmental load modelling on the result of the assessment. The default ReCiPe endpoint method was applied to generate the assessment results of this chapter, namely the *hierarchist* version, using European normalisation and average weighting set (ReCiPe Endpoint method (H) - Europe ReCiPe H/A). To determine if selection of other impact assessment methods influenced the overall results, the following impact assessment methods were used for the sensitivity analysis[29]:

- *ReCiPe- Egalitarian version,*
- *Eco-Indicator 99 – Hierarchist version,*
- *Eco-Indicator 99 – Egalitarian version, and*
- *IMPACT 2002+.*

The results of assessment of initial environmental impacts of a range of facade categories is shown in Figure 8.26, using the facing brick walls (category 2) as a reference.

Figure 8.26: Initial environmental impact of facade categories assessed according to different impact assessment methods



The results of assessments according to each impact assessment method show discrepancies between the generated environmental impacts of facade solutions in

[29] These LCIA-methods are each related with a specific perspective on the importance of environmental impacts. As discussed in Chapter 7 ReCiPe 2008 is the most recent impact assessment method.

relation to the brick wall. For instance, for rain screen covering with ceramic tiles or steel sheets the associated initial environmental impacts resulting from the Eco-Indicator methods are significantly higher than with ReCiPe methods.

However, what is more important is that the environmental gains related to use of DfD solutions in dynamic building scenarios remained equal in relative terms. In addition, this analysis teaches us that it is dangerous to base design decisions merely on environmental 'scores' of materials. A holistic approach is needed that can reverse - if needed - decisions which seemed environmentally-friendly at the time of construction but may turn out different over the course of time. In addition, these results show the danger of focussing on a limited set of materials, which have been assessed in this study as being appropriate for the assessed environmental criteria. This could lead to overconsumption of a limited set of materials, leading to depletion of valuable resources in one area of materials.

A suitable approach is therefore to use variety in materials, but of which assembly and design prolongs the service life of materials, as is the case for the Re-Design for Change approach proposed in this dissertation.

8.6.2 FINANCIAL ASSESSMENT

There are several uncertainties concerning the life cycle financial assessment of building solutions, including *cost data* and *price evolutions*.

First, the uncertainty about cost data related with material and assembly costs of building products of today may be dependent on the contractor and production conditions. Since the aim was to gain insight into related material and labour cost aspects, depending on the building product and its assembly the generic cost database of ASPEN was applied. The comparative character of this analysis in which only major cost differences between variants are of interest justifies the use of this generic cost database.

On the other hand, uncertainty exists about future price evolution of products. A building is a product with a long life cycle - even after renovation- which explains why the uncertainty of price evolution is an important aspect requiring a sensitivity analysis of the economic parameters [Allacker 2010]. Sensitivity was done on the *discount rate*, using a value of 0%, 2% (default value) and 4%. The higher the value of the discount rate, the more importance is given to the near-present and the less importance is given to the financial costs that take place in the distant future.

The sensitivity analysis is illustrated for internal wall partitioning, in which the internal layout is changed every 10 years (scenario 3) over a building life span of 45 years.

Figure 8.27: Relative life cycle financial cost of internal partitioning solutions compared to life cycle cost of stud walls for scenario 3 (long ESLC)

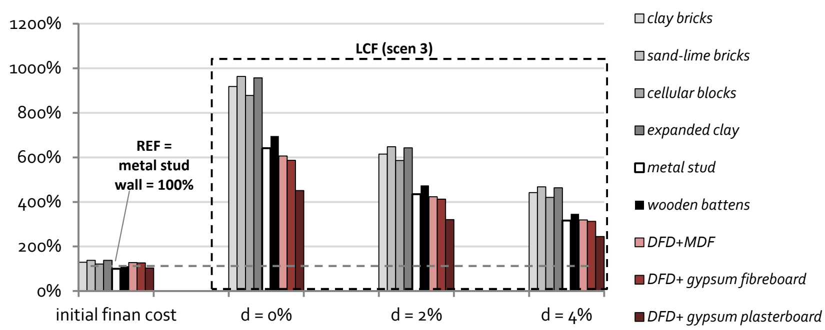


Table 8.14: Relative life cycle financial cost compared to the life cycle cost of metal studs walls for scenario 3 (long ESLC)

Internal wall categories	IF	LCF		
		d = 0%	d = 2%	d = 4%
clay bricks	129%	918%	615%	442%
sand-lime bricks	138%	963%	648%	467%
cellular blocks	121%	878%	586%	420%
expanded clay	138%	957%	643%	463%
metal stud	**100%**	641%	435%	317%
wooden battens	112%	696%	474%	346%
DFD+MDF	128%	606%	423%	319%
DFD+ gypsum fibreboard	127%	587%	413%	313%
DFD+ gyps. plasterboard	103%	452%	321%	245%

The result show that when the discount rate equals 0% -implying that future costs are equally important as current costs and thus time does not matter [Allacker 2010] - dynamic building solutions are responsible for a significant decrease of the financial life cycle costs. However, the less importance is given to cost occurring in the future, the more dynamic solutions lose their benefits compared to standard wall partitioning.

8.7 DISCUSSION

In general the LCA and LCC results attribute a positive role to dynamic design of building layers as a *complement* to low carbon policies in order to reduce overall resource depletion during the total life cycle of buildings after renovation.

The turnover rate of building layers has been identified to play an important role for the feasibility of dynamic design. In building layers with frequent replacements dynamic solutions are highly desired in both environmental and financial terms. In this scenario many alterations will be needed over the life cycle, and reuse opportunities of DfD assemblies can be fully taken advantage of. It was revealed that Design for Disassembly may in the short term add environmental impacts and economic costs, but on the much larger scale of life cycle of resources long term benefits are potentially much greater.

For instance, for internal wall partitioning, in scenario 3 - which considers a dynamic built environment - the static reference wall assemblies (dry walls and brick walls) must face up against major impacts associated with each replacement, including entire demolition of walls and extraction of raw materials in order to produce similar new wall components. The DfD wall proposal significantly reduces the environmental life cycle impacts with 50% on average - compared to the metal stud walls since it can make use of the initial sub components when re-placing the partitioning elsewhere in the space layout. Hence, the service life of components can be extended and significant resource depletion can be avoided. In addition, the results of the life cycle financial costs of the dynamic solutions show that financial costs of dynamic design of most building layers does not necessary lead to excessive increase in investments costs, while in addition, in some cases, it may also lead to reduced financial life cycle costs.

Nevertheless, for building layers that have a low rate of change, i.e. in a building environment that rarely gets adapted, DfD solutions are not necessarily advantageous since they may add environmental impacts in the initial construction stage. The revealed causes for this initial increase, as discussed in this chapter, have different origins, related to DfD and reuse strategies.
First, the additional physical layering which is typical for dynamic design enhances the potential to intervene in one functional aspect layer, without destroying the remaining ones. However, excessive physical layering may result in an increase of the environmental impacts compared to solutions we know today.
Secondly, the need for non-destructive assembly techniques requires (sub) dry connection, meaning that additional connecting elements -and thus materials- need to be incorporated to enhance reuse. For instance, to reuse facade covering the covering tiles are mounted with brackets against additional aluminium rails placed against the vertical

carrier framework. If reuse neither adaptation is the main objective, the covering tiles can simply be glued to the carrier framework without additional need for linear rails or other flexible connections.
Finally, to enable multiple reuse of building (sub) components, materials with a high surface resistance are required to allow handling and transport. This precondition may result in use of more heavy-weight materials in dynamic design compared to conventional building materials. Due to increased use of mass, or due to lack of reusable materials with low impacts related to the extraction and production process, associated environmental impacts may initially be more elevated than traditional building solutions.

In financial terms, a possible barrier for dynamic design may be the labour costs involved: when multiple components have to be assembled using dry connections on site the resulting assembly time influences strongly the labour costs. Preassembly is therefore a powerful tool, to reduce the assembly costs on-site. As techniques for deconstruction improve and subsequently productivity improves labour costs should see a reduction in the near future [Endicott 2005]. With these improvements, in time, deconstruction techniques will become more competitive with current demolition practice [Greer 2004]. Threat of limited landfill space in the future, rising tipping fees, and increased environmental pressures necessitate a resilient solution. Dynamic design for reuse and transformation of structures is a better alternative to demolition, primarily in its consistency with recent trends in environmental life-cycle awareness [Endicott 2005].

To conclude, an accurate analysis in renovation projects could be made, evaluating/predicting which building layers may have a high rate of alteration or estimating which building layers are expected to need future upgrade. Nevertheless, need for change is never predictable, and thus, when the assessment of dynamic building solutions reveal that they are viable in environmental and financial terms, even in building layers with a low change rate, it is always safer to introduce dynamic design. In that way, unpredictable building needs can still be responded without taking part in the environmental degradation.

09

RE-DESIGN FOR CHANGE: A BUILDING APPROACH

In this chapter the (relative) benefits and drawbacks of a Re-*Design for Change* approach for post-war apartment buildings are being analysed at *building level* for a representative case study of renovation. The outdated social building blocks of the second construction phase at the *Model City* (Laeken) built in the 1970s form a representative case for many obsolete (social) housing blocks seen along the Belgian highways. A dynamic approach is formulated in response to the static renovation taking place today, summarising the methodology summarised in this PhD dissertation.

Dynamic building solutions are selected from Chapter 6 for the concerned buildings layers complying with equal building standards as the 'reference' renovation. The environmental and financial benefits - which were assessed at component level in the previous chapter - are explored for this case study in which a realistic need for change is assumed. The building properties of building block IX exhibit a high degree of flexibility according to the principles discussed in Chapter 5. Therefore, it offers good opportunities for Re-Design for Change. However, the limited storey height, together with the asymmetric floor plan and abundant presence of load-bearing columns in the horizontal plan make the Re-Design for Change approach a true challenge.

The comparison between a *dynamic* renovation approach and the *reference* renovation approach enables to gain insights about possible financial and environmental merits attributed to dynamic design. The results of the life cycle evaluation at building level enable to indicate building layers with high contribution to the overall environmental and financial burden. For these layers DfC design can offer a sustainable long term alternative.

Consequently, the aim of this chapter is therefore to understand in which way and to what extent dynamic re-design can give complementary and additional value to established renovation strategies of today both at component and at building level.

9.1.1 MODEL CITY AT HEYZEL – BRUSSELS (EXPO '58)

In 1956 Fernand Brunfaut - architect and chairman of the "Foyer Laekennois" - came up with the plan to develop an utopic urban residential district on the occasion of the World Exposition in 1958 (Expo 58), a so-called 'Model City'. This Model City - a garden city of 17ha located on the Heyzel plateau in Brussels - is one of the main examples of urbanism according to Modern Movement principles. It was built as collaboration between a heterogeneous group of architects, engineers and urbanists[1] with Renaat Braem as one of the leading figures. The project aimed to offer visitors of the expo a clear picture of modern designs in the area of social housing in Belgium and illustrated the advanced urban ideals of the time providing social housing which took natural benefits from sun, air and greenery [Moutury 2002].

Figure 9.1: Model of the Model City (Laeken-Brussels)

Source: La Maison, 1960

Source: Archief van de Stad Brussel (ASB)

[1] Architects, urbanists and engineers: Braem, Coolens, Groupe l'Equerre (Fitschy, Klutz, Parent), René Panis, Groupe Structures (Boseret-Mali, Stenier, Van Hove), Van Dosselaere, Lesage Nonc.

The Model City represents one of Belgium's first experiments in rational prefabricated construction. High tower blocks on pilotis were combined with extended longitudinal building blocks, free-standing low building blocks and one-family houses organised in a green setting offering a wide diversity of housing typologies with 1027 social apartments in total. The Model City was to have formed an almost self-sufficient unit equipped with cultural, social, commercial and medical centres, a church, schools, a gymnasium and sports fields. With these idealist collective social services a radical departure from the traditional architecture was aimed for. This was one of the few progressive (social) housing complexes built in Belgium adhering to the modernist principles of the charter of Athens, together with other projects amongst which Plaine of Droixhe (Liège)[2], Kiel at Antwerp[3], St. Maartensdal at Leuven[4] and Watersportbaan (Ghent).

The Heyzel complex together with other modernist housing complexes were initially received positively by the public until - from the 1970's on - a general change in attitude led to growing hostility towards large-scale high-rise construction [Moutury 2002]. However, at the Model City the response of the inhabitants has for the most part remained positive over the years due to the architectural comfort of the green environment and the good standard of living.

9.1.2 BUILDING BLOCKS IX - XII

9.1.2.1 BACKGROUND

During the Expo of '58 only a small-scale model of the Model City was shown to the audience. The construction works only started in 1957 and it would take about 20 years to complete the entire Model City [Braeken 2010]. The central part of the garden city - consisting of three towers on pilotis with external circulation galleries around a central square (building I to III) - was executed in the first construction stage (1957-1966) according to the first plans. Two peripheral lower towers (V and VIII) were later constructed, and finished in 1966. With view on reduction of investment costs the circulation of these buildings was reorganised replacing external circulation galleries for interior corridors.

During the second construction stage (1970-1975) more cost-reducing measures were introduced. The tower blocks IV and VIII, and the longitudinal building blocks (blocks VI and VII) were executed using low cost prefabrication systems such as the Cauvet system,

[2] Groupe E.G.A.U., 1951-1956.
[3] Braem, 1949-1958.
[4] Braem, 1955-1971.

replacing the Barets system used in the previous construction phases. The initial cross-wall units which were mounted as one unit (Barets) - including technical infrastructure and wall finishing - were replaced by individual wall segment systems interconnected on site (Cauvet system) [Braeken 2010]. Furthermore, the initial master plan undergoes more radical changes to maximise the cost-effectiveness of the remaining space on the Model City. The initial plan to include one-family houses was altered as four clustered medium-rise building blocks (*buildings IX to XII*) were built instead in order to increase the number of living units and reduce financial expenditures. The design and construction of these apartment buildings was executed by Groupe Structures (1972). However, due to the imposed substantial savings to be made these buildings offered little of the initial modernist ideas and initial purchased quality of detailing.

Today, a global renovation of the Model City is urgent to bring all living units and additional accommodation to contemporary functional, technical, architectural and social standards. Since the Model City is inhabited for nearly 100% the local social housing company - Foyer Laekenois – called for a renovation approach which can take place in stages to reduce inconvenience for inhabitants of the Model City. The European competition was won by ARCHI +I, Jan Maenhout en Wessel de Jonghe and A33, of which the latter was responsible for renovation of other modernist housing complexes, such as the Albert building complex of Léon Stynen and St. Maartensdal in Leuven.

When comparing the different construction phases in the Model City it can be pointed out that the outdated architectural value, poorly executed construction detailing and low contemporary comfort of the buildings constructed during the second phase have led to the general perception of inferior quality of these buildings. Therefore, the renovation works of these medium-rise building blocks - buildings IX to XII - started in 2008 and are predicted to be completed in 2013.

As a case study for dynamic re-design, building IX is representative for a wide range of multi-storey apartments buildings built during the period 1950-1970 in Belgium characterised by a pressing urge for renovation to tackle architectural, functional, hygro thermal, acoustic and environmental problems.

9.1.2.2 BUILDING DESCRIPTION

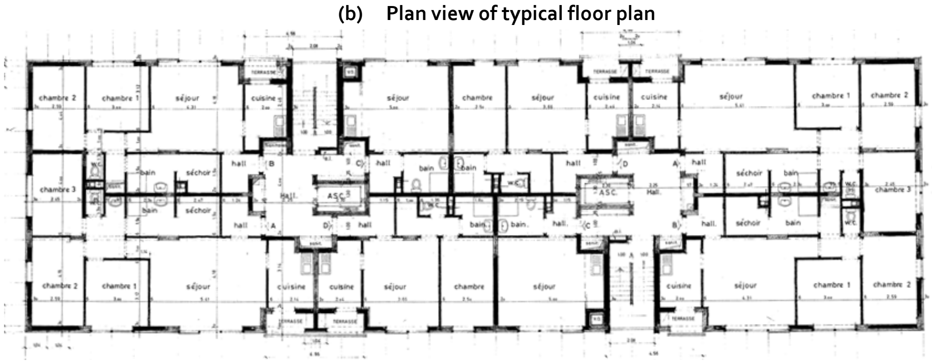
Building block IX is a seven-storey medium-rise building of 25 meters high with a basement floor and technical roof level. The long side of the building is oriented to the east-west and the floor plan is asymmetrically mirrored along the longitudinal axis. The load-bearing structure of the building is formed by a concrete skeleton: columns, beams and floors were built in-situ using reinforced concrete. The skeleton structure is filled with prefabricated (non load-bearing) concrete-based facade panels. Two elevators and staircases provide centralised access to each four apartments from a collective hall.

Table 9.1: Building block IX at the Model City (Brussels) before renovation

(a) Building IX before renovation works

Source A. Paduart

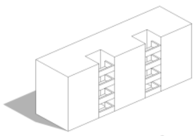
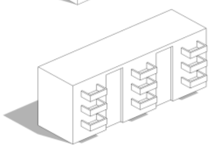
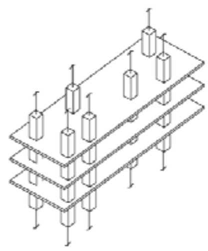
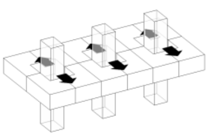
(b) Plan view of typical floor plan



Source: Archief van de Stad Brussel (ASB)

Table 9.2 gives a summarised overview of the main characteristics of the building subdivided in parameters that determine the flexibility of these buildings. The building properties indicate that according to determined parameters for flexibility (discussed in Chapter 5) building IX incorporates a high degree of flexibility enhancing the opportunities for Re-Design for Change.

Table 9.2: Overview of the main physical characteristics of building block IX

Building Layer	Description
Structure 	**Skeleton concrete structure** The load-bearing structure consists of a skeleton of in-situ (reinforced) concrete. This offers a high degree of flexible partitioning of the horizontal space. The staircases and elevators function as bracing of the structure, and interfere to a limited degree with the horizontal flexibility.
	**Open staircases in building envelope** Two mirrored staircases are organised laterally on the longitudinal side of the building. The staircases and collective halls are not closed to the external space.
	**Cantilever balconies** At the longitudinal sides of the building cantilever balconies are present without thermal break between the internal floor slabs. These cantilevering balconies form important cold bridges in the building skin.
Skin 	**Non load-bearing prefabricated facade panels** The building facade is not load-bearing; this makes high-scale interventions possible in the building envelope. The prefabricated facade panels are hung to the floor slabs through additional heels positioned on the building floors. Facade panels included single-glazed windows (wooden frame) and sandwich panels.
Space partitioning	**Non load-bearing partitioning** The internal partitioning of the building consists of non load-carrying walls, materialised either in gypsum based boards, clay brickwork or concrete in-situ built walls. The concrete floor slabs are finished with non-floating screed floors.
Services 	**Clustered supply of technical services** The distribution of water, electricity and gas is centralised in the collective hall providing access for maintenance and interventions. **Disperse drain of sanitary water** The drain pipes for sanitary water are spread over the central zones over the horizontal floor plan. **Heating and ventilation** The heating installation is situated on the technical roof storey. Calorimeters are the only indication of heat consumption inside apartments; gradual (thermostatic) mixer taps are not present. No significant ventilation infrastructure is present.
Circulation 	**Double centralised circulation** Two centralised vertical circulation cores (staircase + elevator) offer access to each four apartments from two collective halls per storey. The loss through horizontal circulation space is therefore minimised.

9.1.2.3 FUNCTIONAL PROBLEMS

Building IX was built on a modernist urban site initially inspired by ideological concepts of progressive architects like Braem which based their design on the CIAM principles [Braeken 2010]. Nevertheless, like many similar social housing projects due to practical and financial concessions which had to be made the final execution of plans often deviated in such an extent from the preliminary design that initial progressive aspirations were never reached. Poor execution of the construction works and cheap construction techniques led to buildings that must face up to urgent update to contemporary comfort and energy performance standards.

Figure 9.2 shows the four present apartment typologies in building IX, which – although designed larger than the average apartments of the 60s – are no longer well-suited to contemporary minimal living standards introduced by the VMSW [VMSW 2008].

Figure 9.2: Floor plan existing apartment typologies in building block XI

Source: A. Paduart

Table 9.3: Apartment typologies of block IX compared to minimum standards

Minimum surface area		**Surface of apartment typologies in building IX**			
apartment type[5]	*minimum surface*	type C (0 rooms)	type D (1 room)	type B (2 rooms)	type A (3 rooms)
		27 m^2	45 m^2	61 m^2	80 m^2
0/1 (studio)	*30 m^2*	×			
0/2 of 1/1	*44 m^2*	×	✓		
1/2	*52 m^2*		×		
2/3	*62 m^2*			×	
2/4	*70 m^2*			×	
3/4	*76 m^2*				✓
3/5	*86 m^2*				×
3/6	*94 m^2*				×

[5] Indicates the ratio (number of sleeping rooms / number of inhabitants) in a living unit.

The interior layouts consist of two principal apartment typologies: studios without sleeping room (27 m²) and apartments with one (45m²), two (61 m²) or three sleeping rooms (80 m²). These small surfaced apartments are not able to respond today's minimal surface requirements for social housing [VMSW 2008] as Table 9.3 indicates.

Secondly, the initial static building design did not allow easy conversion of the apartment typologies to layouts for diverging household compositions of today. The rigid masonry partitioning together with the organisation of the vertical circulation (acting as a physical obstacle in the horizontal floor plan) and scattered positioning of technical services made it an impossible task to reconfigure the existing apartments to the living trends of today. The execution plans of the building blocks IX to XII were not concordant with the technical clustering typical for Braem to enhance plan flexibility. Figure 9.3 shows the scattered hierarchy of sanitary zones and ducts of these buildings. The rearrangement of apartments and the upgrade of outdated facilities to modern standards are not easy to combine with the existent scattered organisation of sanitary zones and vertical ducts. Increased comfort standards require larger apartment layouts of which the reorganised sanitary zones do not necessarily match with the position of the original vertical ducts.

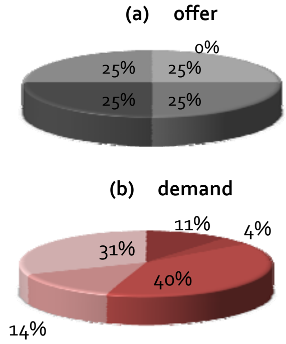
Figure 9.3: Plan view of scattered clustering of sanitary functions (Building IX - Model City)

As a result of the complexity to adapt current apartments to contemporary typologies Table 9.4 shows the divergence between actual demand for typologies at Model City today and the current offer of apartment typologies in building IX. Demand for small studios and apartments with one sleeping room is low (15% in total) whilst it represents 50% of the available typologies in building IX. Moreover, a relatively high demand emerges for apartments with more than three rooms for larger households - in sharp contrast with the non-existence of this apartment typology in building IX.

The offer and demand clearly cannot be set in accordance with each other without any major destructive intervention, due to the initial static construction method and lack of flexibility in the organisation of the circulation and technical services.

Table 9.4: Offer and demand for apartment typologies at Model City

Typologies in building IX		offer	demand
studio	*type C*	25%	11%
apartment 1 room	*type D*	25%	4%
apartment 2 rooms	*type B*	25%	40%
apartment 3 rooms	*type A*	25%	14%
apartment 4-9 rooms	/	0%	31%



Source: ARCHI+I

9.1.2.4 STRUCTURAL PROBLEMS

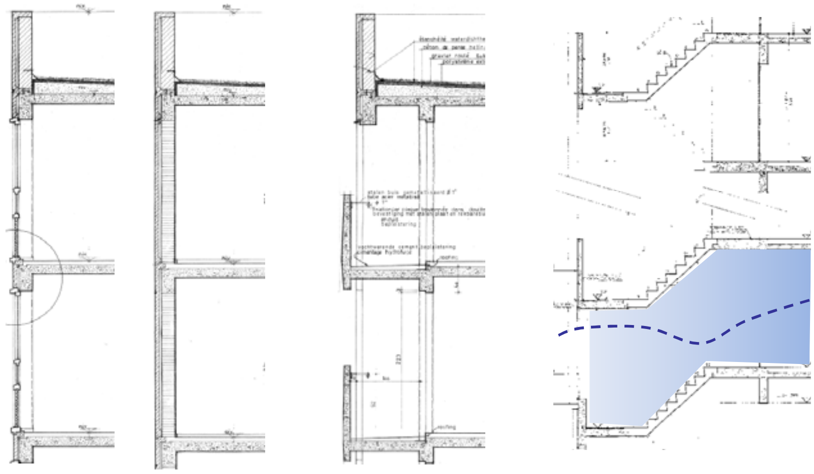
Preliminary studies carried out by the ARCHI+I office indicated that the concrete skeleton is still in good structural condition. Although the external facade panels suffered some degree of degradation (leaking joints) no significant signs of concrete rot, corrosion of the reinforcement or other degradation phenomena were perceived. In addition, the load-carrying capacity of the floors was calculated in order to resist acceptable new additional loads as a result of renovation processes [Detemmerman 2010].

9.1.2.5 HYGRO THERMAL PROBLEMS

Moisture problems are one of the principal problems in post-war large estate buildings. Due to the lack of integrated thermal insulation and cantilever concrete balconies cold bridges and condensation problems usually are common in the building structure [De Naeyer 2007 b]. Building block IX is a good illustration of highly energy-consuming buildings predating the oil-crisis of the mid-70s: the cavity behind the (non-insulated) facade panels was not insulated while the sandwich panels in the single-glazed window panels provided insignificant insulation levels. The heating installation were - when compared to high-efficiency heating infrastructure available today - poorly efficient.

In addition, the cantilever concrete balconies executed without thermal break create perforations in the main building envelope which result in condensation, internal moisture and mould on the underside of the concrete slab. In case of sufficient (natural or mechanical) building ventilation these moisture problems can be minimised. However, building IX was constructed in a time were ventilation was not yet a relevant building factor. Since all apartments of building IX are single-oriented east or westwards neither natural nor mechanical ventilation is being facilitated since mechanical exhaust is only foreseen in sanitary rooms.

Table 9.5: Sections of building facade of building block IX



low thermal insulation *cantilever balconies* *open air staircases*

Source: Archief van de Stad Brussel (ASB)

The cold bridges created by the cantilever balconies and lack of facade insulation are subsequently also responsible for extensive heat loss throughout the building envelope. In addition, the open staircases without enclosure from the external climate increase the surface of the protected area of the building significantly causing a higher heat loss for an equal building volume.

9.1.2.6 ACOUSTIC PROBLEMS

Until 1970 there was no concern for acoustic insulation in residential building construction. The experienced problems in the building block IX today are caused by the applied construction systems. The structural skeleton was executed as one structural unit without acoustic (neither thermal) breaks causing significant flanking sound transmission through the structural building parts. In addition, the depth of the floor slabs was restricted and did not incorporate floating subfloors. Therefore the impact sound and airborne sound insulation of the separating floors is very poor.

9.1.2.7 FIRE SAFETY

Fire safety of the building structure is related both to the use of materials and the regulations in use for residential buildings [De Naeyer 2007 a]. Generally, post-war skeleton structures do not cause specific fire safety problems in relation to the structural building properties. On the contrary, important problems emerge when up-to-date fire safety regulations at building level need to be applied, e.g. fire compartments, escape possibilities, staircases, fire extinction facilities or accessibility for firemen and their equipment. In the case of building block IX only one escape route per fire compartment is present. According to the contemporary fire regulation at least two escape routes should be present. In addition, the escape routes (staircases) are not physically closed off from the collective hall with (fire-resistant) doors.

9.1.2.8 URGE FOR DYNAMIC RENOVATION

The apartments at the Model City built in the first construction phase (building I to III) were characterised by their modern infrastructure and high living standards for the time they were built. Nevertheless, in the buildings of the last construction stage little of these innovative housing concepts is found neither did the building manage to adapt itself to match the present-day context. Architectural and functional trends have altered substantially over the years making the need for renovation apparent.

9.1.3 RENOVATION OF BUILDINGS IX-XII

9.1.3.1 REFERENCE RENOVATION

The winning renovation proposal introduced improvements of the Model City both at urban and building level. At urban level, the renovation works at the Model City aim a better integration of the site with its surrounding urban context by adding new buildings in accordance with the modernist architecture together with social previsions including local shops, a medical centre, collective meeting spaces and offices.
Today, buildings IX to XI are transformed from apartment buildings with 180 living units to 138 living units with high user comfort. An horizontal building extension is made in order to compensate for the lost amount of apartments. The global aims for renovation of building IX to XI described by Bekker (2010) are summarised in Table 9.6.

Table 9.6: Aims of reference renovation of building IX at Model City

	Aims of reference renovation [Bekker 2010]
Building level	*-Homogeneous architecture that refers to the modernist architecture of Braem;* *-Improve the facade insulation, aiming for a K38 level;* *-Provide better acoustic insulation of the building facade and between apartments;* *-Ameliorate the quality of collective access space and the accessibility of the vertical circulation (elevators) of the buildings;* *-Improve the ventilation (integration of ventilation system C);* *-Improve the air and wind tightness of facades and windows.*
Apartment level	*-Enlarge apartments until 90% of the maximal surface area set up by VMSW today;* *-Realise contemporary qualitative apartments that comply with the living standards for the next 50 years.*

During renovation the buildings IX to XII were being stripped down to the load-bearing carcase removing the cantilever balconies to ensure the effectiveness of the high scale interventions today. In addition, a new building facade was provided conform to the initial modernist character of the Model City.

Figure 9.4: Building block IX during and after renovation





Source: A. Paduart

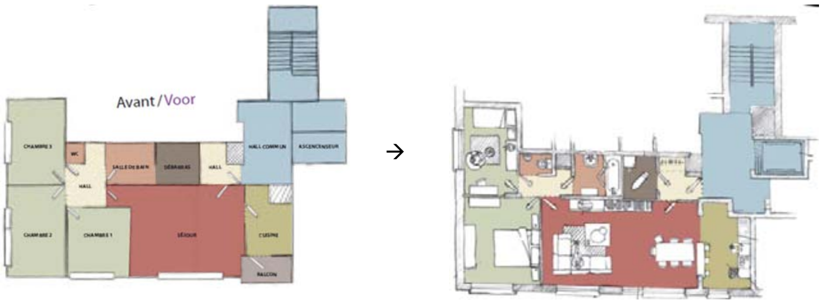
Source: ARCHI + I

Updated plan layouts introduce larger living spaces (living rooms and kitchens) and minimise the surface space of sleeping rooms and sanitary facilities. This is represented in Figure 9.5. This figure also illustrates that although the building structure has been entirely stripped and refitted the new plan organisation is nearly equal to the initial plans.

The new apartment design required an adapted vertical distribution and drain of the technical services. Therefore, new vertical technical shaft were perforated in the floor slabs and existing shafts were closed off. The technical installations are updated including an improved heating system, enlarged elevators and addition of ventilation system C. The heating system on the rooftop was replaced by two central (high efficiency) heating boilers positioned in the lower basement.

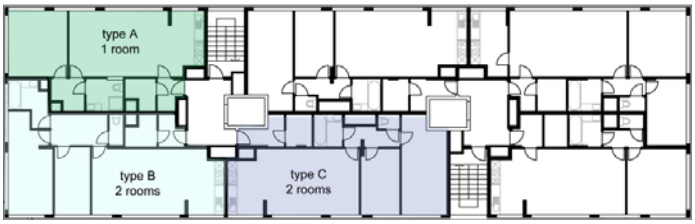
Figure 9.5: Typical floor plan typology before and after renovation (building IX)

before renovation **after renovation**



Source: Toc-Tok n°6 (2007), Foyer Laekenois

Figure 9.6: Plan view of building IX of reference renovation (3 typologies)



To enhance impact sound insulation floating screed subfloors were provided over the separating floors. The airborne sound insulation between apartments is not significantly improved as the partition walls are executed as a single-layered masonry wall. The protection against external noise is strongly depending on presence of local sound leaks of the facade proposal due to the dry connections of the rain screen facades.

9.1.3.2 TOWARDS A DYNAMIC BUILDING STOCK

The thermal insulation level of building IX was upgraded during renovation in order to reach a global K38 level. With upcoming revisions of thermal regulation for new and existing buildings it is expected that these buildings - up-to-date today - will be considered high energy consuming in the light of near-zero energy renovation projects of tomorrow. No future upgrade possibilities have been foreseen in the reference renovation in order to anticipate implications of this scenario.
Besides, one of the main aims of the current renovation project according to A33 architects is, as stated in Table 9.6 'to update and upgrade the quality and the comfort of the current state of the buildings of Model City today, to respond adequately to living comfort standards for the next 50 years'. It is not likely that residential building remains unchanged in the fast-changing society of today with its unpredictable social-cultural, financial and environmental evolving needs. Thus, it is not likely that renovated buildings can withstand 50 years without any major adaptation. The renovation proposal of the building blocks IX-

XI and the applied construction techniques however do not provide flexible features for future reorganisation of the building, neither do they foresee adaptability of building components in order to make alterations possible without participating in labour intensive, material-consuming and waste producing processes. Due to the static organisation of the horizontal plan and due to the massive single-layered masonry walls inserted between adjacent apartments, adaptations in the floor plan are as difficult to be made now as they were in the initial plans.

The aim of the Re-Design for Change proposal formulated in this PhD dissertation is therefore multi-layered. The main goal of the proposal is to provide renovation solutions today that target the initial reduction of the energy consumption but simultaneously integrate long term strategies. To further deal with the use of our natural resources in the future and to avoid further environmental degradation over the building life cycle, a dynamic approach can anticipate evolving requirements and buildings standards. The re-design for change approach for this case study therefore aims to:

A) *Anticipate occurrence of unpredicted building scenarios during the life cycle course of buildings in an environmental and cost-efficient way;*
B) *Anticipate update and update of buildings in the future framework of the European climate plan for the building stock translated in the Belgian 'Renovation 2020';*
C) *Anticipate the future shift related to energy reduction, from energy consumption due to occupation (heating and cooling) towards reduction of embodied energy of the building (including materials);*
D) *Enable flexible reorganisation of residential typologies in the future, in line with future demand of candidate-renters or buyers of (social) housing, future comfort standards and socio-cultural evolution of households;*
E) *Anticipate the end-of-life phase of buildings in which deconstruction with component reuse is a sustainable alternative for demolition of entire building structures.*

In the following paragraphs, Re-Design for Change is developed for building IX at *building level.* After, dynamic building layers (for building facade, wall partitioning, floors, ceilings and roof) are selected that have equivalent properties as the 'reference' renovation in thermal, acoustic and functional terms, whilst anticipating the need for adaptation and reuse of sub components. The detailing of each building layer was extensively discussed in Chapter 6 and financial and environmental impacts of these dynamic building layers were evaluated for comparable functional units in Chapter 8.

9.2 CASE STUDY FOR DYNAMIC RE-DESIGN OF EXISTING BUILDINGS

9.2.1 SOCIAL RE-DESIGN

An important cause of the negative image today of multi-storey blocks of the 50s, 60s and 70s is due to the fact that the use of post-war industrialised construction techniques tended to be repetitive, uniform and often delivered monotone architecture. As a result, large centrally planned mass housing estates give a sense that rules are dictated from above in top-down logic leaving little participation or input from the residents.

Renovation of our post-war building stock can offer opportunities during renovation in this respect. The social differentiation of multi-storey buildings must be embraced simultaneously with functional, thermal and architectural upgrade interventions of today. Instead of introducing equal and repetitive large-scale building characteristics that apply architectural trends of today - which are likely to be re-outdated and out-fashioned in a short period of time - additional attention must be paid to diversity of buildings. A global 'standardised' renovation approach does not necessarily mean a uniform approach. Whilst modular building solutions easily lead to monotone repetitive architecture, a standardised multi-modular approach may still offer a wide range of building solutions.

9.2.2 FUNCTIONAL RE-DESIGN

9.2.2.1 INTRODUCING FRAME AND GENERIC SPACE CONCEPT

To reorganise existing buildings the *frame and generic space concept* of Leupen (2005) can be used as a starting point as discussed in Chapter 3. According to this concept, *permanent* building parts constitute *the frame* within which change can take place. While the frame is specific the space inside is general and its purpose is unspecified: it is *generic space* [Leupen 2005]. In this research the concept was transposed to the context of existing buildings.

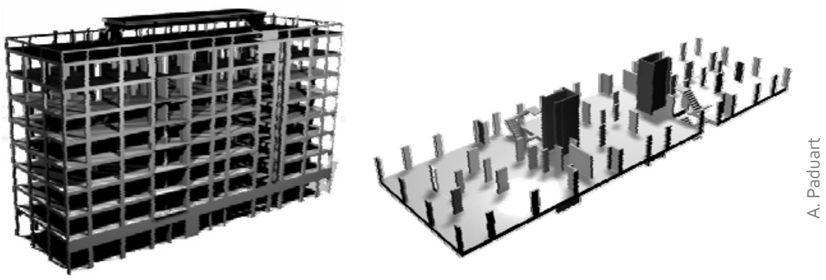
9.2.2.2 DETERMINATION OF THE FRAME

LOAD-BEARING STRUCTURE

First, it was analysed which building parts can be defined as the permanent part(s) in building IX and which building layers are assumed to evolve over time. The analysis in the previous chapter defined that most building layers, i.e. the building envelope, the partitioning and the technical layer, are up to drastic renovation measures. This also becomes clear in the reference renovation, in which the building is entirely stripped until the skeleton structure. Buildings can be released of oppressive building parts and resume a second life after stripping whilst the inherent material value of the load-bearing – incorporating 25% of the initial embodied energy [Cole 1996] - structure is being prolonged. The stripped carcase offers a good starting point to form the permanent frame to re-design buildings of today for a more dynamic building life style tomorrow.

Building IX can be brought back to a challenging blank structure after soft-stripping of the fitting-out[6] and removal of the facade panels. This brings back the building to horizontal plots with as only re-design preconditions two central elevators and staircases and the existing column grid. This load-bearing skeleton structure provides a high degree of building flexibility for re-design for the future.

Figure 9.7: Stripping of the building to the load-bearing skeleton structure



Next is to be defined if more of the main building layers defined by Brand (1995) can be incorporated in the new conceptual frame.

CIRCULATION

The organisation of the building circulation and the technical services is of crucial importance to enhance the future storyboard of the building, as was discussed in Chapter 5. The complexity to adjust these layers in a later stage compared to internal or external fitting-out explains why these layers know little change during the building life cycle.

The analysis of the building structure confirmed the difficulty to make modifications to the vertical circulation (elevators + staircases) due to its bracing function in the building structure. The benefits of reorganising the circulation must weigh up against the significant additional financial investment costs and additional environmental loads of this destructive and material-consuming intervention. Consequently, this is only considered legitimate in case the initial building must face up against a problematic interference of

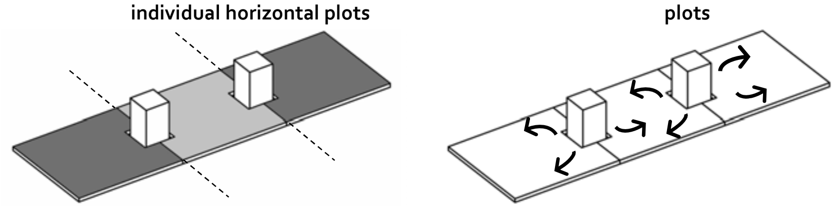
[6] Soft-stripping of the building first enables direct reuse of valuable building products, such as for example plumbing, electrical fixtures, appliances, HVAC equipment, doors, windows, hardwood and floor finishing. Direct reuse of these removed elements should be maximised, and subsequently, material recycling should be stimulated of the damaged components.

the circulation layer with the horizontal flexibility, or for instance, a compulsory building update to stringent fire safety standards is required which cannot be reached with the present circulation.

In building IX, the vertical circulation divides the horizontal floor plan in three individual segments due to its central positioning (Figure 9.8). The central positioning of the circulation offers an important advantage of minimum loss of floor area due to horizontal circulation and maximises the accessibility of the surrounding floor space as was concluded in Chapter 5. Therefore, the circulation was retained in its actual positioning in order to make part of the permanent frame.

Figure 9.8: Influence of vertical circulation

(a) subdivision of the floor plan in individual horizontal plots **(b) good access to the horizontal plots**

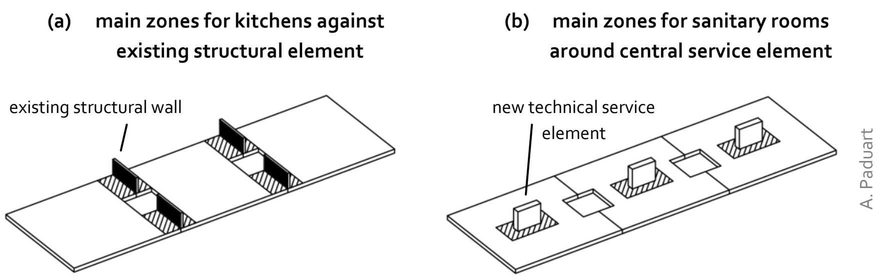


BUILDING SERVICES

When upgrading technical building services in current renovation practice radical changes must generally be applied. This can be explained by the static design: building services are integrated to serve only one resident cycle purpose. The technical organisation in post-war buildings was often not systematised consequently leaving little space for alterations according to new building layouts. Today's reference renovation introduces the same static design approach by replacing all original local shafts and making new dispersed non-systematised perforations in the structure for new local shafts. This can be seen in Figure 9.6. In contrast *clustering* service shafts has proven to offer enhanced building flexibility to stand the test of time. The tower at Boom designed by Braem is one of many projects in which Braem centres the technical core in the heart of the residence. Recent renovation of the tower at Boom proved the effectiveness of this technical clustering: a wide range of new apartment typologies are accommodated in the tower using this initial central service shaft (see Chapter 5). The central positioning enables a wide range of horizontal and vertical subdivisions of the space with access to this technical service shaft for supply and drain of building services.

The benefits of grouping technical functions therefore are explored for the case study of building IX. First, the original set of technical service shafts - which collect the supply of warm water and electricity and the kitchen drain in the collective hall – is retained. Then, a second group of shafts accommodates a functional zone for kitchens, which benefit of the lateral positioning with natural daylight (Figure 9.3 a). In addition, new central service elements are accommodated in each of the three segments of the building floor plan thereby offering a wide range of potential subdivisions of each space segment. The central service element foresees all accommodations in the internal zone for sanitary rooms (Figure 9.3 b). Practical plan implementation taking benefits of this technical re-organisation is represented in Figure 9.12.

Figure 9.9: Organisation and positioning of wet zones in floor plan of building IX



Consequently, the technical clustering is incorporated in the new permanent building *frame*, in which future change of the generic space can be offered.

9.2.2.3 DETERMINATION OF THE GENERIC SPACE

INTERNAL FITTING-OUT

The objective of flexible technical reorganisation is to offer plan layouts that can more easily be transformed to variants suited to the profile of renter-candidates, or, adjusted to evolving minimum standards of functional zones inside living units. Different alterations in the plan layout can take place, e.g. horizontal or vertical conjunction of spaces, break-through of load-carrying walls with extension of the space. Figure 9.10 to Figure 9.13 show a wide range of apartment typologies using the central technical element. The positioning of the technical shaft ensures the grouping of all sanitary and utility rooms in the central zone of the building whilst creating a flexible surrounding space with variable subdivisions. Besides apartments with single orientation also apartments with double orientation are possible with the added value of enhanced natural ventilation and increased residents comfort. In addition, also vertical flexibility attribute to the dynamic concept of a building. A structural analysis was carried out to indicate if additional perforations in the floor slabs were possible [Detemmerman 2010]. By providing perforations in the floor slabs situated on the lateral building sides internal circulation is made possible inside one living unit. The thereby created double-storey living units - so-called duplex apartments – offer high living quality with their double orientation.

Figure 9.10: Clustered technical core offering wide range of apartment typologies

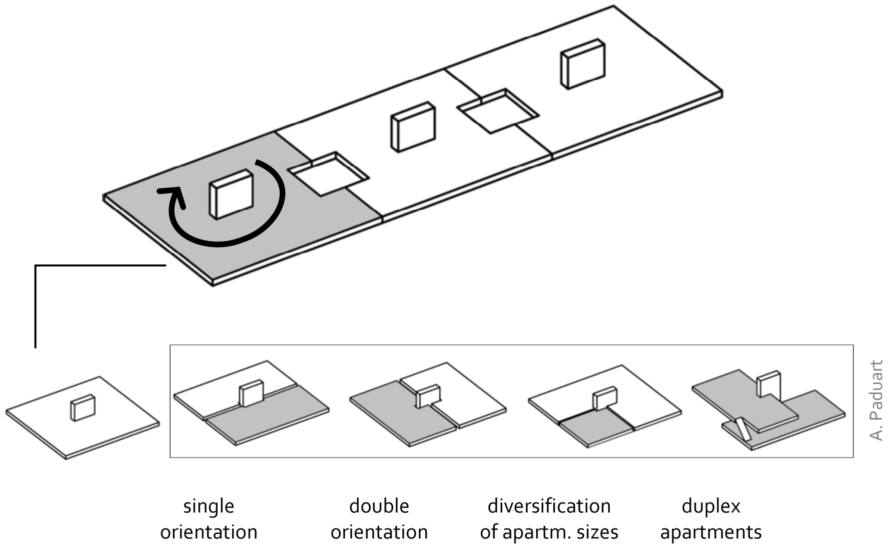
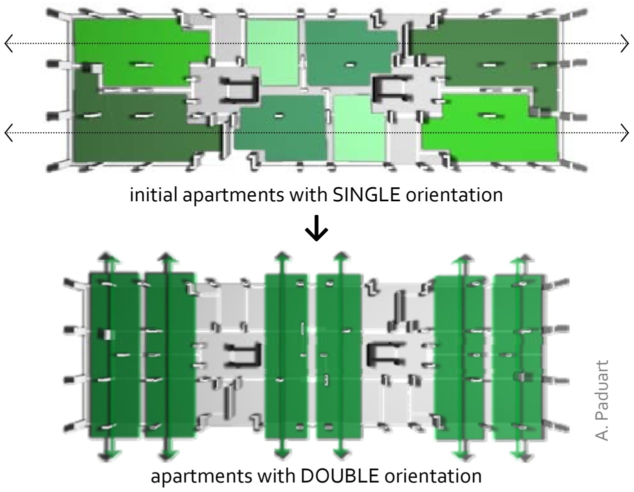


Figure 9.11: Shift from apartment typologies from single towards double orientation



This re-design for change proposal shows that well-thought interventions in the renovation stage allow for a wide range of typologies in the future in comparison with the traditional renovation approach. Examples of seven different apartment typologies are shown in Figure 9.13 showing different variants of the floor plan.

Figure 9.12: Examples of plan layouts after re-design for change

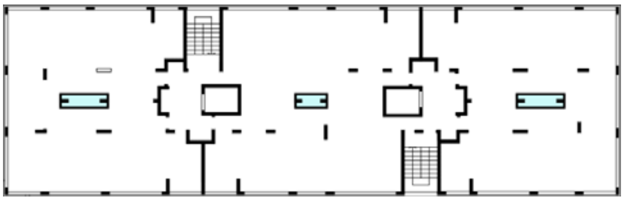
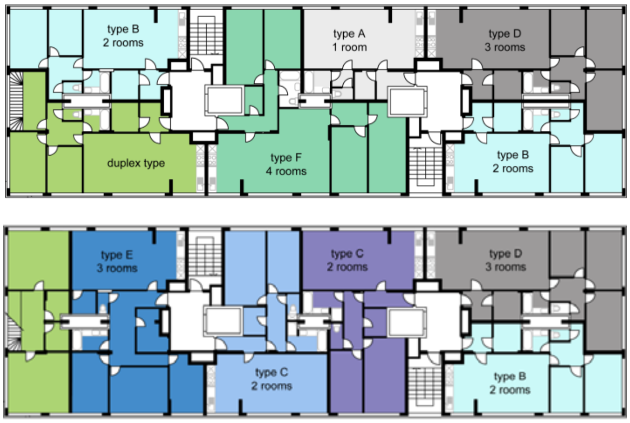


Figure 9.13: Example of plan view of building IX with new typologies (even / uneven floor)



EXTERNAL FITTING-OUT

In analogy, the building facade can similarly be designed as a dynamic building layer. Dynamic design of the facade can be seen as an opportunity to create more building flexibility for the future whilst it can form an expression against monotony of industrialised building. The facade building layer is therefore designed according to dynamic design rules in order to make (thermal) upgrade possible in the future.

The cantilevering balconies of the building block IX form significant thermal bridging in the external facade, which is a well-known problem in post-war buildings. Different approaches can be suggested to deal with this problem, amongst which removal of the balconies together with thermal upgrade of the facade, thermal insulation of the balconies, or replacement of existing balconies with new balconies that introduce a thermal break (Figure 9.14). In order to optimise the thermal performance of the skin this last approach is suggested. In addition, this solution offers new opportunities for external balconies, or other functions as illustrated in Figure 9.15. This figure shows that architecture using standardised generated elements can results in adaptive and non-repetitive architecture as well. The external balconies add to the comfort of inhabitants while they can represent the individuality of the users.

Figure 9.14: Approaches for existing cantilevering balconies

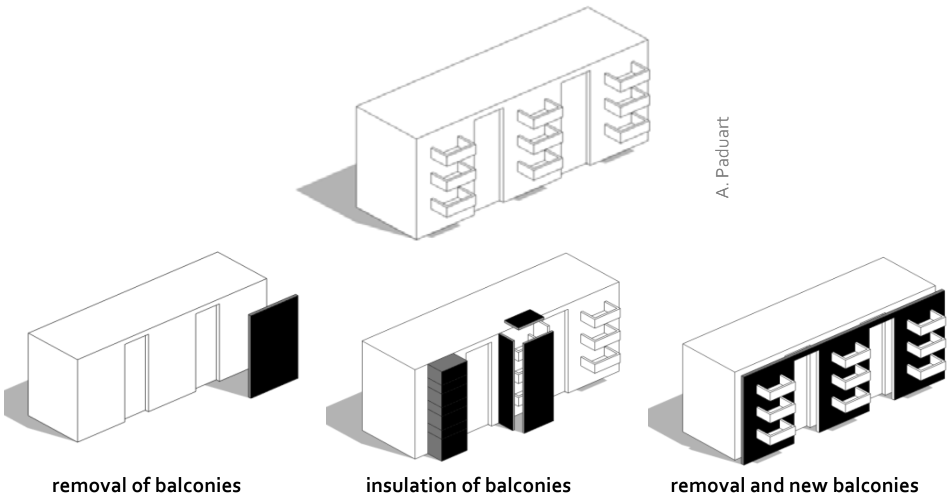
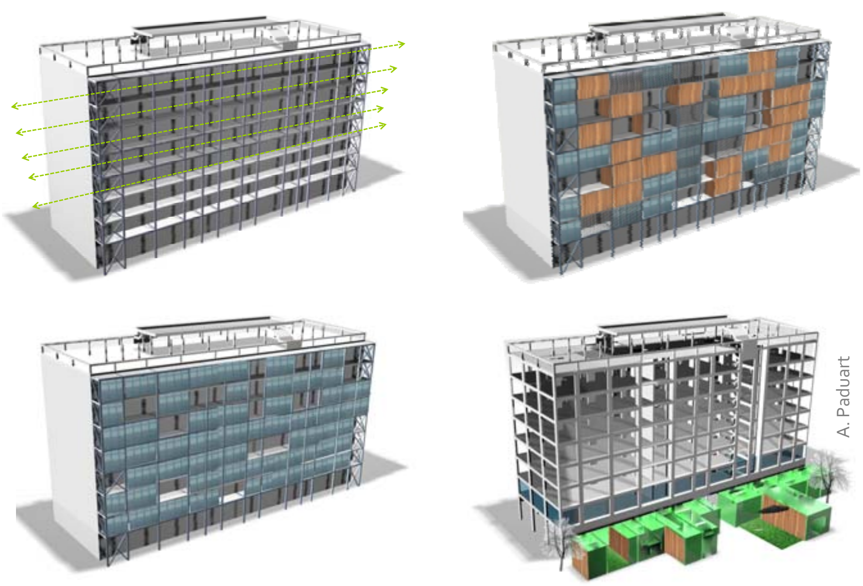


Figure 9.15: Possible configurations of building IX after re-design



9.2.3 PHYSICAL RE-DESIGN

A next crucial design step for dynamic buildings is to integrate a physical separation between the retained building structure and new fitting-out. This ensures that building layers are developed which can be independently modified from each other. Consequently, the design of the building components needs to incorporate Design for Disassembly (DfD) principles which enable deconstruction and reuse of components. A standardisation approach to dimension the basic elements is esteemed crucial for the further reuse of applied elements today. The design of dynamic building layers discussed in Chapter 6, therefore applied the HENDRICKX and VANWALLEGHEM (HV) standardisation approach [Debacker 2007]. According to this approach, the possibilities of component reuse are enlarged by designing the components from a non-specific and non-contextual approach, thereby focusing on systematisation and standardisation of form and dimension.

As a result of the limited storey height of typical post-war buildings - like building IX- a flexible technical supply approach is incorporated in the wall assemblies to distribute the electrical wirings from the technical clustering to surrounding spaces. Therefore, the distribution of services in apartments is organised departing from the central technical service shaft throughout the wall assemblies. The dynamic design of wall assemblies (Chapter 6) offers the advantage that all technical provisions, such as electricity wiring, plugs, or even wall heating stay accessible and can be repositioned or adjusted in case of reorganisation of apartments without having to use destructive methods.

Figure 9.16: Conceptual illustration of plug-in of wall assemblies on central technical service element

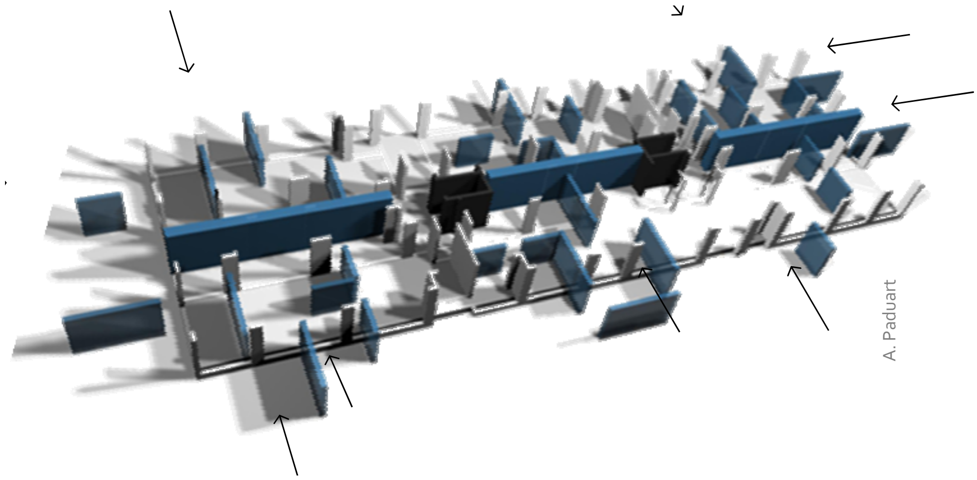
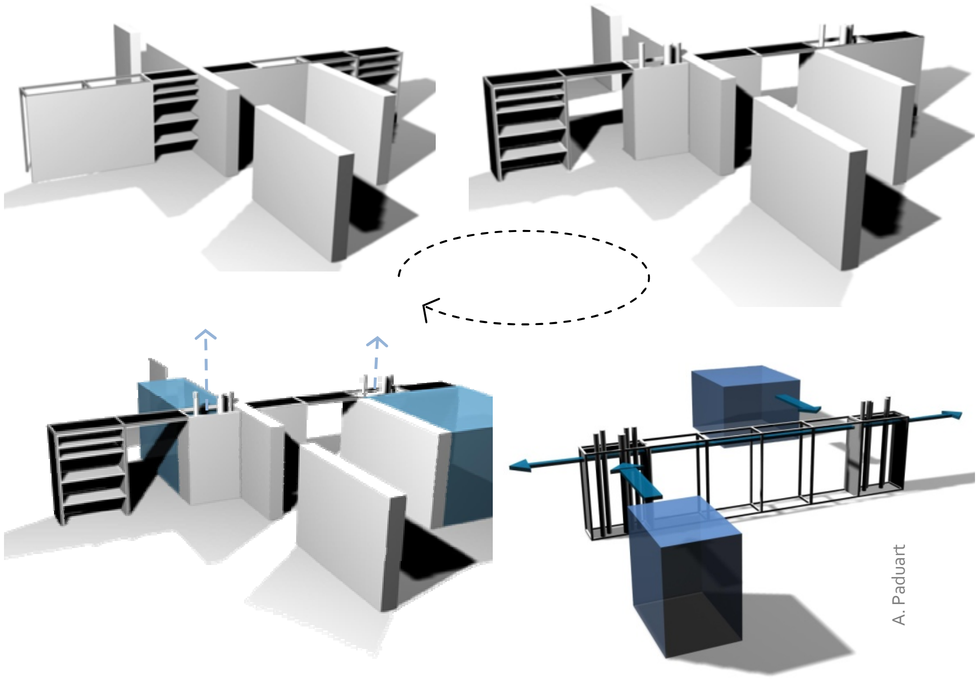


Figure 9.17: Adaptable fitting-out of the internal space



The dynamic wall assemblies enhance repositioning in space, upgrade from internal partitioning walls to partition walls (and vice versa), simple alteration of technical installations (such as wall heating) inside walls and even transformation of walls into functional wall elements (storage elements). At any point, the assembly can be deconstructed to its composing elements for reuse in other applications.

9.3 ENVIRONMENTAL AND FINANCIAL EFFECTS OF RE-DESIGN FOR CHANGE

9.3.1 EVALUATION SCENARIOS

In this paragraph, the reference renovation of building IX (i.e. the renovation taking place today) is compared with the alternative dynamic re-design proposal based on the dynamic design of building layers developed in this PhD. Three scenarios are evaluated (see Chapter 8) to gain more understanding about the benefits a re-design for change approach can offer at building, component and material level.

The scenarios were extensively discussed in Chapter 8. The first hypothetical scenario (**scenario 1**) assumes that due to external motives the renovated building requires early tear-down. The assumed period before tear-down is of 15 years. This scenario analyses if materials with a high initial impact are acceptable if they are only used for a short period, and evaluates the degree of recoverable residual value after the period of analysis as a sustainable strategy.
The second scenario (**scenario 2**) meets the short-terms objectives of renovation today. This scenario either assumes that the renovation can fulfil the minimal comfort standards for the next 45 years, either leaves the renovated building in its future outdated state until final tear-down. The only interventions that occur in this scenario are replacements of components reaching the end of their service life.
The third scenario (**scenario 3**) assumes a dynamic use of buildings renovated today. Buildings are frequently updated to the latest trends to keep up high living quality and update building to the latest building standards. Demographic, cultural and regulatory trends are followed closely by using the transformation capacity of the building as a tool to give rapid feed-back on a fast evolving society.

In this chapter, an additional scenario was evaluated (**scenario 3+)** to take into consideration that not all introduced building layers are being replaced during intervention processes. Therefore, scenario 3+ assumes that 50% of each building layers is updated frequently according to the defined turnover rate (defined in Chapter 8) and the remaining 50% is assumed to stay unchanged (only replacing the outdated/broken components).

9.3.2 ASSESSMENT DATA

It is a difficult but challenging task to estimate all impacts and costs of the design proposals made in the framework of this PhD as detailed and accurate as existing solutions on the market. Due to lack of complete and consistent overall data of all aspects of the building renovation, the assessment of the financial and environmental impact in this paragraph is not performed based on absolute values. Instead, gain or loss in financial and environmental terms is expressed by comparing the DfD designs of this PhD with a *referential solution* for each main building layer. This means that overall cost and impacts related to upgrade of technical services, site preparation or scaffolding has been estimated identical for both alternatives. The plan layout of the apartments and the facade composition are also supposed equal meaning that the only differences between the reference and the DfD proposals relate to *selection of materials*, *assembly of building systems* and *detailing*. Specific data were collected from the technical unit of the Foyer Laekennois and the engineering team of the renovation project. These data were used as a relative basis for the estimation of data for the DfD designed building layers.

The reference renovation offers a balanced mix of rigid and semi-dynamic integrated building solutions. Because of this, it offers a representative case study for current renovation practice that is slowly evolving from static solutions to a higher rate of flexibility.

Table 9.7 and Table 9.8 illustrate the applied renovation solutions for building IX at the Model City and the derived DfD building solutions[7] aiming for equal thermal, acoustic and visual characteristics of the main renovated building layers.

Although the renovation alternatives have similar visual aspects their composition can be divergent: to obtain comparable thermal and/or acoustic performance multi-layered dry connected components differ considerably from the rigid building solutions. This is illustrated with the next example: facade elements with the visual aspect of bricks. Dry connected preassembled brickwork panels as an approximation of traditional facing brick facade have dissimilar physical, functional and technical characteristics than the traditional bricks walls (Figure 9.18).

7 For the ceilings, the same (non DfD) solution was chosen as for the present renovation, i.e. plastering of the ceilings. This enables to make use of the presence of thermal mass in the concrete floor slabs, while maximising the limited storey height of building IX. Improvement of the impact sound insulation is provided by floating dry floors.

Table 9.7: Composition of building layers for reference renovation and dynamic renovation

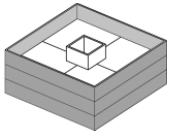
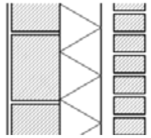
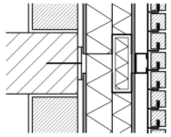
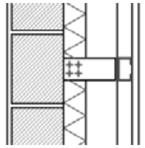
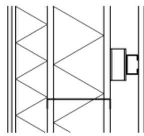
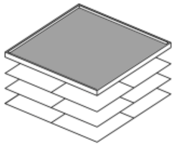
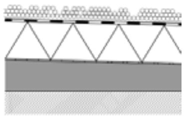
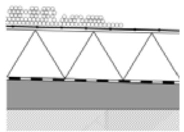
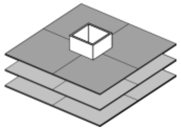
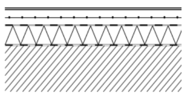
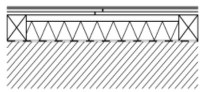
Composition of main building layers				
Building layer	Reference renovation		Re-design for change	
facade  north +south side		**brick wall:** *concrete block (14cm)* *glass wool (12 cm)* *clay bricks (9 cm)*		**brickwork panels:** *concrete block (14cm)* *glass wool (14 cm)* *brickwork panel (4,5 cm)*
east+west side		**ventilated facade with glass panels:** *concrete block (14cm)* *glass wool (14 cm)* *glass panel (15 mm)*		**preassembled facade units + glass panels:** dry wall + glass wool (14 cm) *wooden framework* *glass wool (16 mm)*
roof 		**warm roof with foam glass insulation:** *foam glass (16 mm)* *bitumen (5 mm)* *gravel (5 cm)*		**cold roof with xps insulation:** *xps insulation (18 mm)* *gravel (5 cm)*
floor 		**screed floor with linoleum:** *pur insulation (40mm)* pe-foil (2x3mm) *linoleum (2,5 mm)*		**self-supporting dry floor + linoleum** *glass wool (30 mm)* *battens (50x50mm)* *pb-board(22 mm)* *laminate (12 mm)*

Table 9.8: Composition of building layers for reference renovation and dynamic renovation

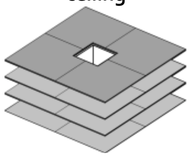
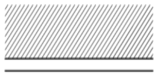
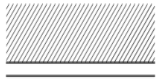
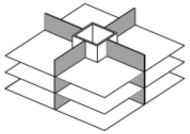
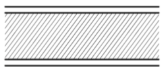
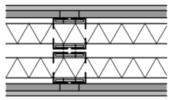
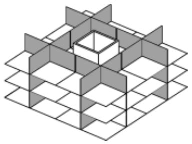
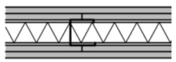
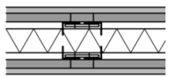
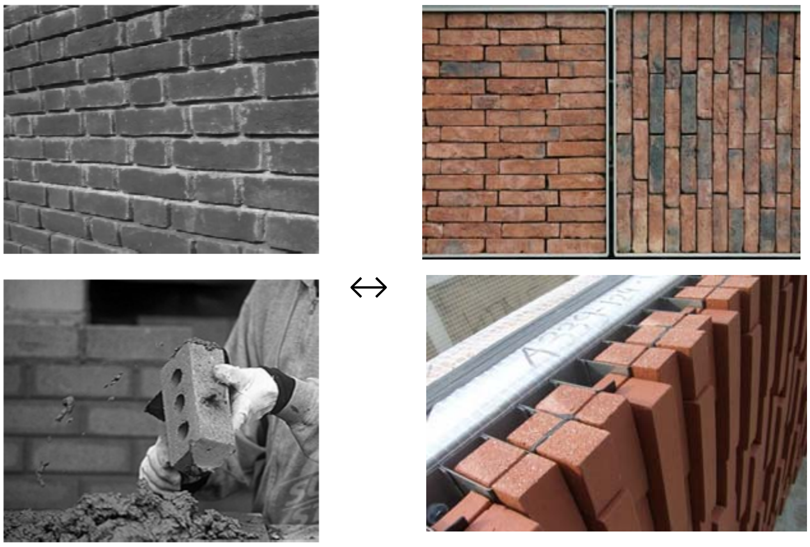
Composition of main building layers				
Building layer	Reference renovation		Re-design for change	
ceiling 		**plastering of ceiling:** *gypsum plaster (20 mm)* *paint*		**plastering of ceiling:** *gypsum plaster (20 mm)*
partition walls 		**brickwork:** *concrete blocks (14 cm)* *paint*		*double metal framework* *glass wool (2 x 40 mm)* *osb board (18 mm)* *gyps fibre board (12,5)*
internal walls 		**dry walls:** *metal studs* *glass wool (40cm)* *plasterboard (25 mm)* *paint*		**preassembled wall unit with finishing on-site:** *metal framework* *glass wool (40 mm)* *osb board (18 mm)* *gyps fibre board (12,5)*

Figure 9.18: Traditional masonry brick wall and preassembled brickwork panels



The brickwork panels function as rain screen facades: air and wind tightness is achieved by the combination of several physically separated layers. Facing bricks in cavity walls on the contrary clusters several functions in one single layer as discussed in Chapter 4. Secondly, bricks - as modular and pre-manufactured building materials - have potential for reuse as long as the applied mortar is not stronger than the brick itself and/or highly adhered to it. Adaptations are difficult to make in standards facing brick walls, due to the irreversible connections. The alternative - using brickwork panels - enables to simplify adaptations when there is an urgent need for change such as for thermal upgrade. The ease for change and potential for reuse of bricks is increased significantly by adopting dry reversible connection methods. This means that when adjustment of the building envelope is needed, the panel solution ensures the bricks to be easily reused, whereas brick walls have to be destructed and reconstructed.

Selection of a dynamic alternative for the solutions applied in the reference renovation was done in analogy for all building layers derived from Chapter 6 – providing dismountable and recoverable technical alternatives to standard building solutions when needed. The results of the analysis in Chapter 8 - indicating that for most building layers dynamic design may lead to significant environmental benefits - were used to choose well-suited dynamic building systems. In addition, the facade and wall assemblies were designed including the option for preassembly to speed up the (de)construction process, decreasing (de)construction labour costs and reducing the production of building waste. As previously discussed, preassembly in dynamic solutions adds financial cost reductions so that these solutions are more able to compete in financial terms with existing solutions on the market, while they increase the quality of construction.

9.3.3 RESULTS OF EVALUATION SCENARIOS

9.3.3.1 CONTRIBUTION OF THE BUILDING LAYERS

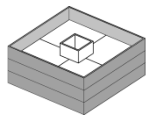
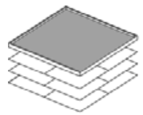
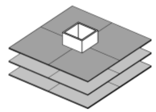
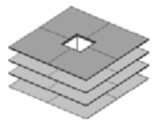
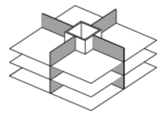
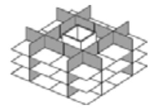
Table 9.9 shows the renovated surface area of each building layer assessed for the two renovation approaches for building IX. For this type of longitudinal multi-storey building the largest surface to be renovated is the floor layer (27%) and subsequently, the facade (20%) and internal wall partitioning (21%). The roof and dividing walls account for respectively 4% and 2% [8].

Based on the life cycle analysis result, a representation of the relative contribution of each building layer to the initial and life cycle environmental impacts and financial costs is given in Table 9.9. The table shows that during the initial construction phase the facade causes high environmental impacts and financial costs in comparison with other layers, contributing for respectively 50% and 57-59% of the overall environmental impacts and financial costs. This is due to the 'radical' facade upgrade in which the original outdated facade is entirely replaced by a new one.

Secondly, separating floors and internal wall partitioning account for 26% and 10% of respectively the overall environmental impact and financial cost. The ceiling upgrade (plastering) does not contribute to a high extent because the improvement of the impact insulation was integrated on the upper floors to maximise the storey height.

[8] The small contribution of the dividing walls can be explained by the presence of structural walls which physically divide the horizontal plan in three parts and already act as dividing partitions.

Table 9.9: Contribution of each building layer to environmental and financial life impacts in renovation approach (REF and DfC) of building IX

		Building layers											
		Building skin				Space partitioning							
		facade		roof		floor		ceiling		partition wall		internal wall	
													
renovated surface (% of total)		*2100 m² (1) + 550 m² (2)* 20%		*550 m²* 4 %		*3825 m²* 27 %		*3825 m²* 27 %		*250 m²* 2 %		*3050 m²* 21 %	
		REF	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**
contribution to environmental assessment (% of total)	**IE**	50%	50%	4%	4%	26%	22%	3%	3%	3%	2%	15%	19%
	LCE Scen 1	50%	52%	4%	3%	26%	21%	3%	3%	3%	2%	15%	18%
	LCE Scen 2	44%	50%	3%	3%	22%	19%	4%	4%	3%	2%	23%	21%
	LCE Scen 3	46 %	45%	3%	3%	20%	14%	3%	6%	5%	2%	23%	20%
contribution to financial assessment (% of total)	**IF**	57%	59%	7%	7%	10%	10%	4%	4%	13%	12%	9%	9%
	LCF Scen 1	47%	49%	2%	2%	22%	21%	10%	9%	2%	2%	17%	18%
	LCF Scen 2	45%	46%	2%	2%	20%	19%	12%	11%	2%	2%	19%	20%
	LCF Scen 3	48%	48%	5%	5%	8%	7%	5%	5%	21%	16%	14%	18%

(1) longitudinal facade
(2) transversal facade

Scenario 1: period of analysis = 15y ; turnover = 15y
Scenario 2: period of analysis = 45y ; turnover = 45y
Scenario 3: period of analysis = 45y ; turnover = 10y (internal wall)-15y (partition wall + facade)-20y (roof + floor+ceiling)

REF Reference renovation
DfC Design for Change

Contribution of dividing walls was revealed more significant in financial terms than in environmental terms. The initial investment contribution accounts on average for 13% whereas in environmental terms it only stands for 3% of the total interventions.

The difference between the relative contribution of each layer to the overall result is on average equal, regardless of the reference renovation or the DfC renovation.

9.3.3.2 ENVIRONMENTAL ASSESSMENT

Table 9.10 shows the results of the environmental life cycle assessment for the four defined building scenarios. It gives the loss or gain percentages for the environmental impact as a result of DfC renovation compared to the reference case.

A first result of the analysis is the observed initial increase in environmental impact (+9%) related to alternative DfC design. The main contribution comes from the internal wall partitioning (+ 46%). A reduction is perceived in terms of the partition walls due to the lower initial impact of dry dynamic walls, compared to brickwork walls.
This relatively small overall addition of initial environmental impacts shows to be effective on the long-term in two ways. First, in case of a dynamic life cycle (scenarios 3 and 3+) there is a reduction of the overall life cycle environmental impacts when compared to the reference renovation of 44% and 28%, respectively for scenario 3 and scenario 3+.
In the scenario in which no updates, upgrades or changes occur in the internal and external building layers (scenario 2) the environmental opportunities of the DfC proposal remain unused. Consequently, this leads to higher total environmental impacts compared to the reference case due to the initial higher impact of the DfC proposal. Nevertheless, the overall additional impact is only of 5% compared to the reference case. Benefits of reuse of sub components and fast deconstruction yet are additional benefits compared to conventional design approach.

Secondly, an important aspect that is not included in the result of the life cycle environmental impacts is the residual (environmental) value of DfD designed building component that is left after the demolition of buildings. This value is shown in Table 9.6 for both renovation approaches. The remaining residual value is depending on the period between initial renovation and time of demolition and on other preconditions discussed in Chapter 7 (e.g. connection types and remaining life span). The table shows that residual value after the scenario of early building tear-down (scenario 1) is of 58% in case of DfD design. For the reference renovation the residual value only mounts up to 18% since little building materials can be recuperated for reuse.

Table 9.10: Environmental gains/losses of Design for Change (DfC) compared to reference renovation of building IX

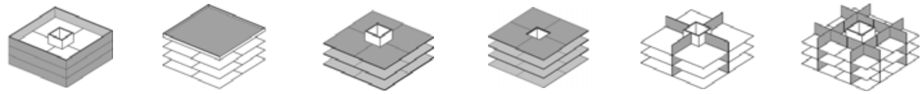
			Building skin			Space partitioning			
			facade	roof	floor	ceiling	partition wall	internal wall	
									**global**
environ-mental gain (-) / loss (+)	**IE**		+9%	+3%	-7%	0%	-23%	+46%	+ 9%
	LCE	scen 1	+9%	+3%	-7%	0%	-23%	+46%	+ 9%
		scen 2	+9%	+3%	-7%	0%	-19%	-10%	+5%
		scen 3	-32%	-49%	- 60%	0%	-78%	-51%	-44%
		scen 3+	-20%	-31%	-42%	0%	-65%	-35%	-28%

Table 9.11: Financial gains / losses of dynamic re-design compared to reference renovation of building IX

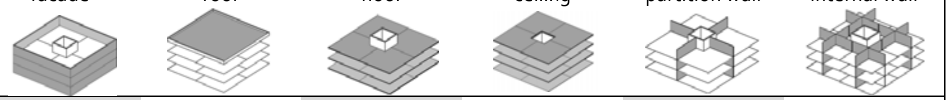
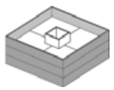
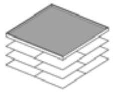
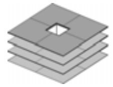
			Building skin			Space partitioning			
			facade	roof	floor	ceiling	partition wall	internal wall	
									**global**
financial gain (-) / loss (+)	**IF**		+12%	+ 5%	+ 13%	+0%	+ 2%	+ 10%	+ 9%
	LCF	scen 1	+9%	+ 3%	+10%	+0%	-2%	+ 11%	+ 6%
		scen 2	+9%	+ 1%	+10 %	+0%	0%	+ 9%	+6%
		scen 3	-11%	- 35%	-7%	+0%	-30%	+12%	- 5%
		scen 3+	-8%	- 24%	-1%	+0%	- 23%	+11%	-1%

Table 9.12: (Environmental) residual value of main building layers for reference renovation and dynamic re-design

			Building skin						**Space partitioning**							
			facade		roof		floor		ceiling		partition wall		internal wall			
															**global**	
			REF	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**	**REF**	**DfC**
residual value	**LCRV**	scen 1	27%	65%	0%	88%	17%	49%	0%	0%	0%	68%	0%	66%	18%	58%
		scen 2	15%	36%	0%	50%	32%	26%	0%	0%	0%	33%	0%	36%	13%	31%
(% of EI)		scen 3	7%	25%	0%	50%	8%	25%	0%	0%	0%	33%	0%	36%	5%	26%
		scen 3+	9%	30%	0%	50%	16%	25%	0%	0%	0%	33%	0%	36%	8%	28%

9.3.3.3 FINANCIAL ASSESSMENT

It was expected that alternative construction techniques - not (yet) competitive with traditional large scale building methods - would not lead to excessive gains in terms of life cycle costs. The main objective was to provide alternative solution that did not add significant investment and financial costs, compared to standards solutions. Table 9.11 shows that the goals in this matter were reached. In the worst scenario, i.e. scenario 1, the added life cycle costs amount up to 9% whereas for the most relevant scenario in this research, i.e. the dynamic scenario 3+, a status quo (-1%) can be reached compared to the reference renovation. In addition to the environmental life cycle benefits, this makes the dynamic re-design approach proposed in this PhD research viable for this case study.

9.3.3.4 LONGEVITY OF THE SERVICE LIFE OF COMPONENTS

Sensitivity on the component service life expectancy shows the importance of the finishing of walls and floors. Wall and floor finishing with a short life expectancy need replacement every 5 years. This significantly contributes to the total life cycle environmental impacts and financial costs. The following graphs show the relative addition of total life cycle impacts/cost or residual values to the initial situation for the two renovation alternatives applying four building scenarios, respectively for long and short estimated service life of the components (ESLC). Figure 9.20 shows that a short estimated service life of components can cause the total life cycle environmental impacts to add up till 311% of the initial environmental impact. The importance of a good execution, good detailing and a good maintenance of the building layers are therefore essential.

In this matter, preassembly has the advantages that the quality level (and thus service life) of components can better be ensured, since the preassembly takes place off-site. When this long service life expectancy is assumed (Figure 9.19) the benefits of dynamic building layers can fully be taken advantage of. The total environmental impacts for all scenarios never exceed 50% of the initial impacts in this case, whereas for the reference case total life cycle impacts may add up 150% of initial impacts.
In financial terms, the overall life cycle costs can add up to 324% of the initial investment costs if a short estimated service life of components is assumed (Figure 9.22). Again, improved design, construction and maintenance circumstances lead to a reduction of the total financial costs to a maximum increase of 163% for DfC renovation and 170% for the reference case (in scenario 3).

Figure 9.19: Total environmental impacts for renovation building IX – LONG ESLC

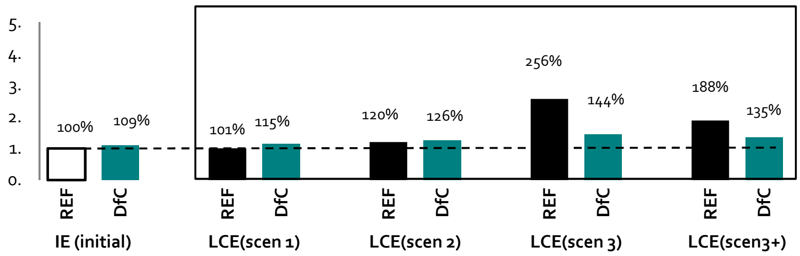


Figure 9.20: Total environmental impacts for renovation building IX – SHORT ESLC

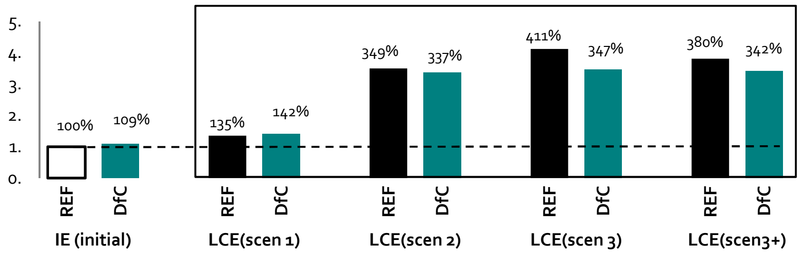


Figure 9.21: Total financial costs for renovation of building IX – LONG ESLC

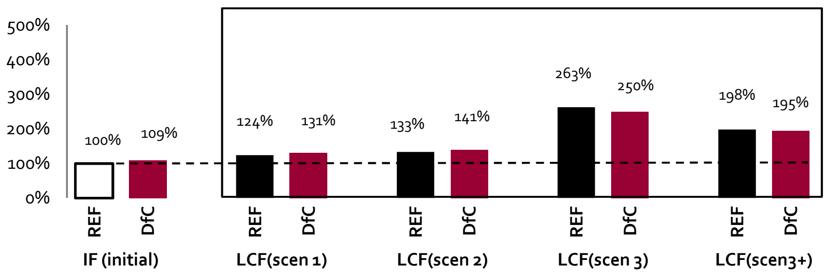
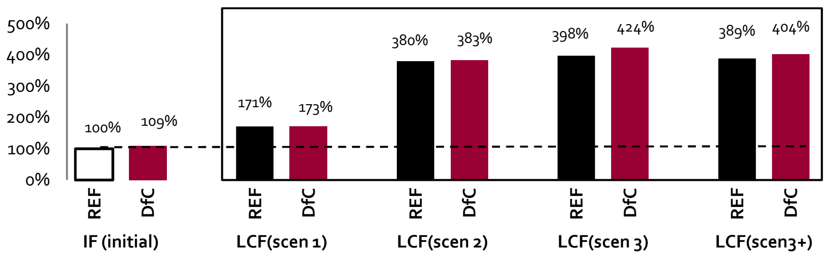


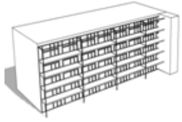
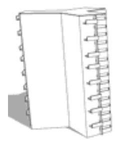
Figure 9.22: Total financial costs for renovation of building IX – SHORT ESLC



The building's dimensional system, the organisation of the circulation, available technical provisions and the type of load-bearing structure all have an important influence on the opportunities for a re-design of buildings for change. The case study for the Model City aims to give an example of a possible Re-Design for Change approach, by defining a new frame for generic space to evolve during the years [Leupen 2005].

The surface of each building layer submitted to renovation differs to a certain extent depending on the building typology as represented in Table 9.13. Three typical post-war building typologies, i.e. a medium-rise low building block, a high-rise building block and a tower block are compared in this table according to the surface of each present building layer.

Table 9.13: Examples of contribution of the building layers in building typologies

	Relative contribution of building layer according to building typology		
	Building IX at Model City (Brussels)	**High-rise building I at Model City** (Brussels)	**Tower at St. Maartensdal** (Leuven)
Building typology			
Number of floors	7	16	16
Facade	19%	22%	16%
Roof	4%	2%	2%
Floors	27%	26%	29%
Ceilings	27%	26%	29%
Partition walls[9]	2%	0%	2%
Internal walls	21%	25%	22%

The table shows that the differences between the presence of each building layer according to the building typology does not differ for more than 3 to 4%. It can therefore be assumed that for other building typologies the results of this chapter would not differ to a large extent. However, the re-design approach discussed in the first part of this chapter is still depending on the specifications of each building context.

[9] Only partition walls were included which are not formed by load-bearing walls, like is the case for cross wall structures.

The analysis at building level showed that building layers in the reference renovation in which no reuse of disassembly design strategies were applied have a high degree of improvement in environmental terms, when the scenario of periodic update (scenario 3 and 3+) is being applied.

A dynamic building re-design generally looks the same as traditional renovation, but the design departs from a fundamentally different conceptual view. Although the materials used in dynamic designed building solutions do not differ in great extent from traditional building products, the detailing of the components and their (inter)connection activate a dynamic dimension in buildings and their life cycle use.

It is difficult or even impossible to predict which are most appropriate building solutions to face up all energetic, environmental, financial and social challenges of tomorrow and the future. Research of today can only guess about the efficiency of new developed products on the market and their long-term effects. Therefore, during renovation one can only make a supposition of what is best for the evaluated context of today; the only certainty for the future is that further development will take place and that our socio-environmental context evolves at high pace.

It can be concluded that static designed buildings that require destructive measures for each adaptation that is needed, will become a burden for the future building stock. By introducing dynamic solutions an appropriate respond is given by anticipating the uncertainty of buildings' life cycles and challenges of the future in a reversible way.

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CONCLUSIONS

This research project intended to verify if a *Re-Design for Change* approach is generally suitable for the renovation of social post-war buildings and, also, how a decision-making methodology for this renovation strategy can be developed. Building solutions frequently applied in the renovation of post-war buildings were therefore analysed. Based on the revealed shortcomings an improved strategy was developed for the renovation of the referred buildings. This dynamic re-design strategy has been applied to the design and detailing of dynamic building solutions for the most customarily upgraded solutions during renovation of post-war buildings. Furthermore, the environmental and financial life cycle assessment of these dynamic solutions showed some promising benefits in the current renovation practice.

This last chapter highlights the most important findings of the research and recommends areas of further investigation. The first part answers the main research questions by describing the findings during the different research stages and discussing the methodology developed in the dissertation which can be applied by designers to evaluate analogous research topics. Following, the influence of this work for practical application is being shortly discussed and finally, the last section gives recommendations for further fields of research and an outlook onto future development of a dynamic approach in the field of renovation and Design fof Disassembly (DfD) practice.

10.1 DISCUSSION OF RESEARCH QUESTIONS

10.1.1 PROMISING BUILDINGS FOR DYNAMIC RE-DESIGN APPROACH

At present, the residential building stock constructed in the post-war era is undergoing a wide-scale renovation action all over Europe in order to deal with environmental concerns we are facing today. This research dealing with the question how to not only reduce *current* impacts but also *future* impacts related to these buildings, imposed an analysis of the existing (social) post-war building typologies and their problems.

First, the construction of these post-war buildings took place during an era in which thermal and sound insulation was unheard explaining why these buildings are most promising in terms of thermal and acoustic building upgrade. In addition, typical internal problems in buildings from the 1970s relate to monotony of apartment layouts, outdated living comfort, small floor area surfaces and low flexibility of apartments, revealing why a high-scale renovation of these building types offers the most appropriate approach to tackle the overall problems of these building types.

Following, it was analysed how buildings with a high spatial and technical building flexibility – determined in relation to *the load-bearing structure*, organisation of the *circulation* and *technical clustering* - offered opportunities for an overall Re-Design for Change approach. Skeleton structures with non load-bearing facades were determined to show most potential in order to radically transform outdated buildings to 'renewed' buildings catching up with contemporary trends and new energetic standards, whilst showing potential for further transformations in the future. Consequently, the approach to strip these buildings to the load-bearing carcase offers the best perspectives according to Leupen's *frame and generic space* concept.

10.1.2 FACILITATING DECISION-MAKING FOR DESIGN FOR CHANGE APPROACH

This PhD dissertation was aimed to verify if the developed Re-Design for Change concept was viable within the scope of *renovation* of *social apartment buildings* of the *1970s*. The methodological steps taken in order to respond the research questions are represented in the flowchart in Figure 10.1. By answering several sub questions, methodological steps can be followed in order to reveal if the re-design approach developed in this research study was successful for the defined *research scope*.

In addition, this methodological framework is also applicable for variants of renovation, such as residential buildings from an earlier or later *construction period*, *building typologies* such as urban terraced houses or even buildings with non-residential functions such as offices or schools. In this case, again, analysis - based on literature study and surveys -

must establish insights and identification of problems related to the new research scope in order to define if a dynamic re-design approach is required.
Moreover, this methodology can also be used for *new construction* if the determination of the *frame and generic space* concept is introduced according to a 4Dimensional Design approach.

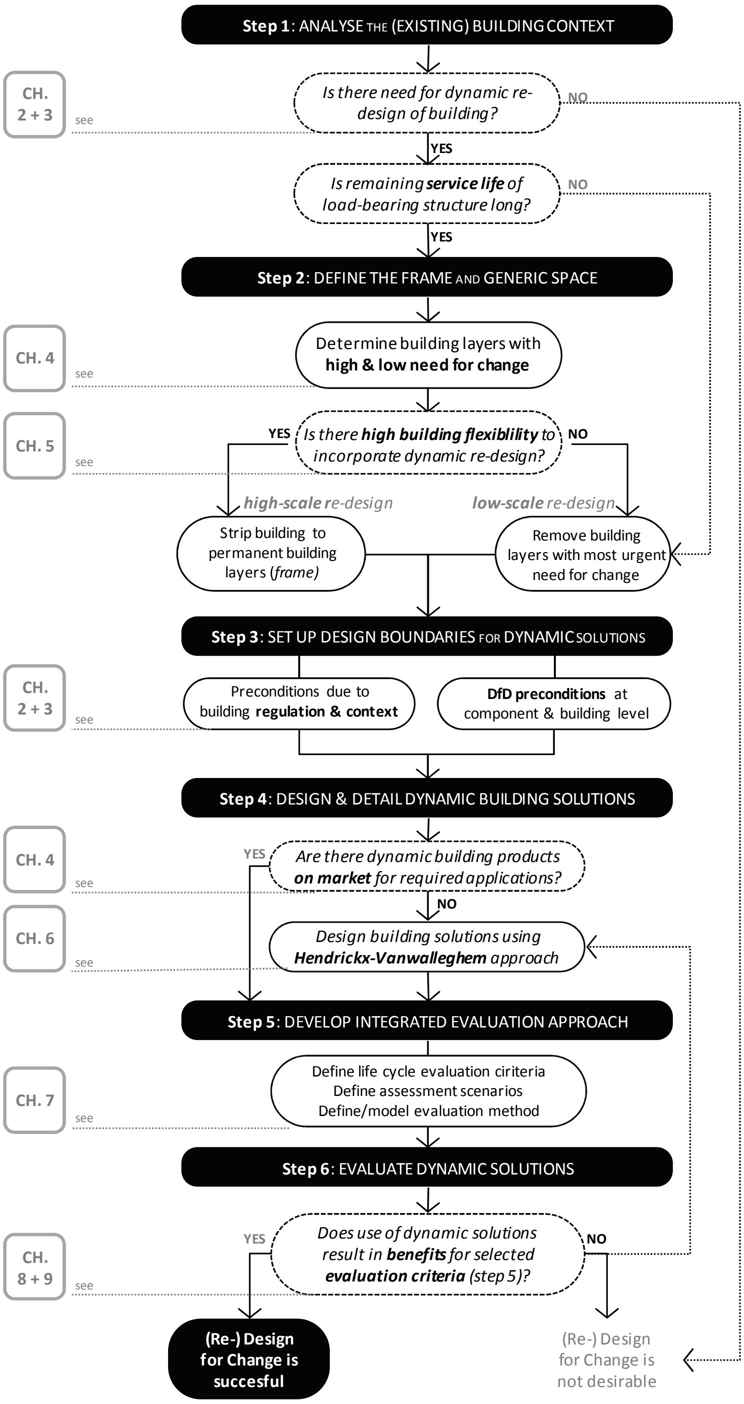
The use of the flowchart (Figure 10.1) is illustrated with the example of the Re-Design for Change approach developed in Chapter 9 for the case study of **building IX** at **Model City** in Brussels. This case study portrays a typical multi-storey apartment building constructed in the beginning of the 1970s of which the outdated architecture and poor thermal performance calls for urgent renovation measures.

Step 1: Analyse the (existing) building context

In order to evaluate if a Re-Design for Change approach is worthwhile, in a first stage, analysis of the **building context** must reveal the actual **need for a dynamic approach** in order to guarantee its feasibility. The analysis of building IX's residential and social background led to the identification of problems in relation to spatial, functional and technical building properties. It was identified that this social apartment building type has problems keeping up to standard with variable spatial requirements due to unpredictable occupation by a wide range of household compositions and sizes – typical for the social housing context. In addition, a renovation process taking place today with contemporary energetic standards in mind is based on energy policies which will be outdated soon since the Belgian EPBD (Energy Performance of Buildings Directive) policies are predicted to be revised in upcoming years. In order to avoid that this building - expected to withstand for more fifty years – becomes obsolete in the near future due to rapidly evolving trends, the incorporation of a dynamic approach to the new fitting-out of the building was esteemed relevant, in order to give a quick future response to evolving comfort standards, developing energetic performance directives or further social diversification of the resident population.

Since preliminary study of the load-bearing structure of building IX confirmed its good condition and structural integrity, a transition can be made to the next methodological step. In case the structural analysis would reveal a short remaining service life of the load-bearing structure, a high-scale renovation intervention is not found appropriate since benefits related to radical building transformation do not weight up against the introduction of high initial environmental and financial loads if the remaining building life cycle is short.

Figure 10.1: Representation of flowchart with methodological research steps



Step 2: Define the Frame and Generic Space

In order to establish a successful dynamic approach to buildings we need to identify which **building layers** (e.g. facade, roof, partitioning and floors) have a *permanent* character (the **frame**) or a *periodical* need for *upgrade/alteration* (the **generic space**). The permanent building layers - usually determined as the load-bearing frame with the circulation - act as the frame which creates freedom and enables various adjustments to building layers subject to frequent update (the generic space) without requiring such adjustments to be precisely determined in advance.

For the case of building IX, a survey was developed in this research amongst principal stakeholders of social housing, namely architects, social housing societies and the Flemish organisation for social housing. This survey was set up in order to define the need for change of the building layers typically upgraded during current renovation like the building facade, the roof, partitioning and separating floors. The existing load-bearing framework of the building (Structure) and its circulation (Circulation) were kept back as the permanent *frame* in which the external fitting-out (Skin) and internal fitting-out (Space) are characterised by periodical alteration processes. The survey revealed a high periodical turnover for *partitioning*, the *roof* and the building *facade* in the context of renovation of social apartments.

Next, the following logically sub question deals with the **flexibility of the building** itself in order to incorporate dynamic features. In Chapter 5, an analysis of the post-war typologies for multi-storey residential buildings revealed that skeleton structures - especially in combination with non load-bearing facades - enhance the opportunities for a radical transformation. Consequently, building IX - a skeleton frame construction - could be considered appropriate for a high-scale Re-Design for Change intervention. This would include stripping of the load-bearing structure to the carcase increasing the effectiveness of the building transformation in order to anticipate both contemporary and future developments. Adding *technical clustering* - which was introduced as a new feature inside the existing structure of building IX - as a complementary part of the permanent frame supports future opportunities in order to include a wide range of scenarios without having to radically adapt the technical plan organisation for each alteration.

Step 3: Set up design boundaries for dynamic building solutions

Dependent on the building's *function* (e.g. residential, offices or schools) and the *policy framework* in force, a broad set of **preconditions** exist whereby renovation of a given building has to comply. In addition, each building is confronted with complementary contextual boundaries such as requested speed of renovation, limited access at the construction site by tower cranes, low storey-height building properties, or unevenness of the existing structure. On the other hand, *designing for change* also calls for building

systems to comply with *Design for Deconstruction* (DfD) principles in order to ensure adaptability and component reuse in development of dynamic construction systems. Consequently, discrepancies must be revealed between all requirements so that dynamic building systems can be developed optimising both properties according to **compulsory building regulations** and the **opportunities for change**.
This inventory of design boundaries set up for the case study - dealing with renovation of social post-war buildings - can be found back in Chapter 2 and 3. Subsequently, in Chapter 6 the discrepancies with *dry construction* design rules were pointed out in order to comply with thermal, acoustic and fire safety requirements, and *DfD principles* in order to maximise component reuse.

Step 4: Design and detail dynamic building solutions

In the following step - with the design boundaries in mind - dynamic building solutions can be designed according to the Hendrickx - Vanwalleghem approach (HV), that is, a strategy to design building systems using widely standardised and compatible basic elements in analogy with kit-of-parts systems like *Meccano* or *Lego*. While the morphology of basic elements is systematised in order to obtain simplified building kit-of-parts with a wide field of application, the use of reversible connections allows these building systems to be altered or reconfigured using non-destructive methods - hence maximising reuse profits. If building products are already developed on the market with the use of disassembly and reuse strategies while complying with the contextual requirements, clearly, these do not need to be re-invented.

In order to evaluate the existing building solutions applied in renovation of post-war buildings, standard building products were analysed in Chapter 4 - through *Multi-Criteria Assessment* (MCA). This analysis revealed that these solutions are mainly developed to optimise the instant (re)construction phase. For instance, in new subdivision of buildings in apartment layouts, dry systems are widely applied due to advantages relating to short construction times, low weight, good economics, good overall performance and large availability. The general idea is that these walls can be configured in order to enhance the initial user comfort, however, when alterations are required for the internal organisation of apartments, the only possibility is to demolish the walls, dispose them and replace them entirely with new dry walls. In order to encounter the lacking opportunities of component reuse, an alternative partitioning wall proposal was developed in Chapter 6, based on the HV-approach and including preassembly of semi-finished wall units. In analogy with flexible universal shelf systems, the design proposal of this dynamic wall partitioning intended to conceive multi-layered and multi-functional, customised but ever transformable building assemblies which maximise the opportunities for component reuse.

Step 5: Develop integrated evaluation approach

The research question addressed in the beginning of each research study must be complemented with a definition of the proposed objectives regarding the **evaluation criteria**. The determination of evaluation criteria in *sustainable building design* is often based on a selection or a combination of one of the three interdependent pillars of sustainable development, i.e., *environmental, financial* and *social* factors. According to the availability of data, assessment models, modelling software, stakeholders' perspectives and/or accessible knowledge, one can select the appropriate evaluation criteria and can agree on whether or not an integrated evaluation approach is appropriate to investigate the defined research topic. Subsequently, the assessment methodology must be refined in order to give response to the aims and scope of the research question.

In this dissertation, *environmental* and *financial* criteria were esteemed relevant in order to comprise an overview of the long-term effects of a dynamic renovation approach when compared to the current way of building. To calculate benefits related to a dynamic design approach the evaluation boundaries were enlarged from initial construction concerns to life cycle construction concerns in order to include all processes buildings are confronted with, i.e. from *construction* phase to *end-of-life* phase including all intermediary building processes. Consequently, *life cycle assessment* (LCA) and *life cycle costing* (LCC) methods were selected in order to investigate if the extension of the useful service life of components - as the result of implementation of reuse strategies - could result in environmental or financial life cycle benefits in buildings with periodical replacement and alteration processes. To include the reuse potential of components an additional service life was included in the assessment methodology, namely the *functional service life* of each building layer. Instead of calculating the number of replacements of components relating to the total period of analysis (e.g. determined by the technical service life of the load-bearing structure) it is proposed to calculate the number of replacements of components according to the number of periodical changes suffered by the building layer in which the component is used and according to the use of reversible connections. Hence, a more nuanced estimation of the reuse potential of sub components can be given.

Step 6: Evaluate dynamic solutions

Once the evaluation methodology has been established, the relevance of the research question can be checked. On one side, the research question - namely the feasibility of a (Re)-Design for Change approach in a selected research scope - can be answered **confirmatory** based on *positive results* according to the selected evaluation criteria. In the other case - when the outcome is *negative* - an additional attempt with alternative dynamic design / detailing / materialisation of building system can be made in order to enhance the previous results. However, when the results remain negative one may conclude that the application of a dynamic renovation approach in the defined field of research is not esteemed feasible.

The results for the case study at the Model City for building IX in Chapter 8 and 9 revealed that the viability of a dynamic design approach depends on the *building layer*, the *execution level* of the building products and the *evaluation criteria*. First, for building layers with a *high need for periodical changes,* benefits of the service life extension of components through multiple reuse can be optimised. The better the execution level of the components, the more the benefits can be optimised in environmental terms. In financial terms, the high contribution of labour costs to the overall life cycle costs of building products is responsible for lower financial benefits. Indeed, reuse of components still includes disassembly and re-assembly labour costs adding up to the overall life cycle costs. Nevertheless, as techniques for deconstruction improve and subsequently productivity improves labour costs should see a reduction in the near future. With these improvements, in time, deconstruction techniques will become more competitive with current demolition practice. In addition, *preassembly* was assessed as a powerful tool to diminish labour costs and enhance the benefits of reuse, while speeding up the renovation process - crucial in the context of renovation of social housing.
For building IX - as for similar multi-storey apartment building from this construction period - it can be concluded that the principal building layers to incorporate a dynamic design approach are the *facade*, and the *internal partitioning* since they both contribute for about 20% of the total surface area considered for renovation. The floors and ceilings - although they each contribute for about 25-30% of the total renovated surface - are less viable to introduce a dynamic approach since the limited storey-height of post-war buildings constrains the adaptation opportunities.

10.2 EXPECTED BENEFITS

10.2.1 REDUCE IMPACT OF BUILDING PRACTICE

The threat of limited landfill space in the future, rising tipping fees and increased environmental awareness of the impacts of building products we use in construction today call for alternative material and (re-)design approaches. Implementing reuse and disassembly strategies in existing buildings in order to transform, reuse of deconstruct our buildings to their individual substituting parts at the end-of-life stage of buildings offers a better alternative to demolition, primarily in its consistency with recent trends in environmental life-cycle awareness.

The use of a systematised (fractal) grid in the HV design approach of building components ensures that all basic elements are simple and straightforward in order to have a high applicability in building practice while enhancing a future second life in a wide range of applications after deconstruction. Hence, materials can be used in a more sustainable way, while at the same time a response can be given to the rising amount of demolition waste. This approach is in strong contrast with the throwaway culture that many building companies promote today in a merely profit-based reasoning.

Moreover, too many outdated apartment buildings are demolished due to ignorance or prejudice. This Re-Design for Change approach illustrates that old-fashioned buildings may still include various possibilities for a sustainable and qualitative renovation. For each building that is renovated - and thus reused - the extraction of raw materials and the manufacturing processes and energy involved with new construction can be partially avoided to the benefit of the environment.

10.2.2 REGULAR UPGRADE AND ADAPTATION

Our daily lives are subjected to constant change. New buildings, as well as the buildings renovated today, will have to cope with changing living patterns and socio-economic-ecologic evolutions in the future. The general perception on *the way we live and build* is changing much faster than the actual service life offered by the buildings we (re-)design today. This leads to the fact that 'new' construction is esteemed obsolete only after a short while since the design is not perceived up to date. For that reason, design tools that enable a fast adaptation can offer buildings a quick response to urgent changing requirements, improved performance or even a better social representation.

In the context of the evolving EPBD policies, a dynamic renovation approach shows important benefits. Social housing societies - aware of the expected further evolution of these directives - postpone the renovation of their social building stock in order to comply with the latest energy policy version towards the European 20-20-20 objectives. By shifting away the concept of renovation from an *end-state building intervention*, which can no longer be upgraded in a further stage to a *intermediary building state*, an answer can be given to this current adjournment.

10.2.3 SPEEDING UP THE RENOVATION PROCESS

Measures which speed up the renovation process of social housing apartments are highly desirable for a number of reasons. First, since many post-war apartment buildings in an urgent need for renovation are densely-populated with social renters, speeding up the renovation process diminishes the conveniences for inhabitants. Besides, social housing in Belgium is characterised by a long waiting-lists for renter-candidates meaning that each second counts during renovation of social housing. In addition, for social housing societies the faster apartments can be in use the less bank loans will be determinant. Depending on the building typology and the scale of renovation, interventions can be a combination of manual labour on the construction site and off-site preassembly. For instance, post-war building typologies with load-bearing panel walls can often be renovated without interferences with the inhabitants. Prefabricated facades on the other hand, can be best renovated by replacing the old modular facade units with new prefabricated/preassembled units. The preassembly of facade units proposed in this dissertation enables to save production time on site while speeding up the renovation process to keep the disturbance time for residents minimised. Moreover, (semi-finished) preassembly of internal partitioning is also a crucial proposal in this study to accelerate the internal works, while it also results in faster layout adaptations in the future.

10.3 FUTURE PERSPECTIVES

10.3.1 DEVELOPMENT OF DYNAMIC BUILDING SOLUTIONS

Since this research study complements a substantial base of knowledge of DfD strategies that already exist, a proactive approach in turning the developed strategies into actual constructions does seem an obvious next step. The results of this PhD dissertation can be used as a first step in order to activate an alternative way of designing in the building products we currently apply by sensibilising the different stakeholders in the built environment, i.e. policy makers, building material fabricants, practisioners in the demolition of buildings, and engineers, architects and designers.

Initiatives like building challenge design competitions for students and professionals as *Solar Decathlon 2011* in which the E-Cube was developed by the university of Gent show a promising attempt to stimulate design of building components in order to optimise material resource efficiency in the whole life cycle of buildings. In the case of Ghent University's E-Cube, it was proposed an affordable, do-it-yourself building kit for a solar-powered house that is pre-engineered, produced off-site and easily assembled without professional labour skills.

As a result, a next step to take is to contact building product fabricants in order to identify the barriers they perceive for incorporation of reuse and design strategies in their building product design. Hence, collaboration can be established, and is also desirable, between the research and professional building market in order to develop building products with wider opportunities than merely finished once-off products. Building products that keep requiring destructive measures for each adaptation will become a burden for the future building stock. By introducing dynamic solutions, an appropriate respond is given to anticipate the uncertainty of the future in an environmentally responsible way.

10.3.2 LEGAL FRAMEWORK FOR DFD DESIGN

The overwhelming focus on regulating energy performance as the driver for sustainable building standards has relegated the building's life cycle into design considerations as just a good practice. This situation leaves designers and government authorities with a lack of legal power to introduce 'dynamic design' in the current built environment. This reality presents conscious designer/architect/engineer the challenge of embodying dynamic strategies within their personal re-design philosophy. It can be expected that no extensive integration of a dynamic design approach will become common practice as long as the financial and legislative constraints are designed to support short-term financial profit rather than sustainability over the life cycle of buildings [Nordby 2010].

Nevertheless, a first feasible strategy may lead to a greater motivation for designers and investors to incorporate DfD strategies. Design approaches that simplify the deconstruction at the end-of-life phase of buildings will become economically a more interesting option when governments set higher taxes for landfill sites and incinerators. Such landfill taxes could make these forms of disposal expensive and thereby encouraging reuse and recycling of reclaimed building components from the deconstruction site. A second suggested alternative could be the introduction of an *eco tax* for each new development in building design. This could motivate all stakeholders involved in renovation to search for other ways of answering the described challenges in this PhD research.

10.3.3 MARKET FOR REUSE

At present, the lack of financial markets for used building materials forms a possible barrier for the incorporation of reuse and disassembly strategies. The economic structure of the demolition/deconstruction industry requires the recovered materials to be sold at a significant price in order to achieve any level of profitability. However, the perception of the *low value* of reclaimed building materials remains a problem in the construction industry today.

Nevertheless, architect offices like Rotor show that there is a market for reuse of building elements for alternative applications such as interior architecture after a first use in the built environment. Although the current applications relate mainly to furniture and finishing, reuse in the building environment is also possible if building elements have been standardised in form and dimensioning in order to be compatible with other construction systems. A good example that could be transferred to the built environment is the *OpenStructures* project established by Thomas Lommée in which an online databank of second-hand items for basic elements for interior furniture and appliances is offered; all based on the same fractal model thereby all compatible with each other [Lommée 2010].

In other words, the sink of a kitchen can be easily replaced by another (compatible) second-hand item to catch up with individual taste and preferences. The same concept could be transferred to non load-bearing building elements present in building assemblies like walls, floors, etc. The case of load-bearing elements clearly is more difficult since the structural properties of reused building elements need to be guaranteed. In this context, a system of labelling could offer some solutions in the future.

It is my personal conviction that with the knowledge of reuse and disassembly strategies available today, new building product design can evolve towards more sustainable design of global construction kits - in analogy with Meccano kit-of-parts - enabling to extend the service life of components through *multiple component reuse*. Whether we are *re-designing* existing buildings or *designing* new buildings, a holistic dynamic design approach should be equally applied since the new buildings of today are the buildings we will renovate tomorrow.

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GLOSSARY

Adaptability

Adaptability of buildings is related to the definition given by Schmidt (2010) as the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life.

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems [ISO 14044 2006].

Basic element

A basic element is a single element with a neutral meaning, processed out of a (building/construction) material through formal and dimensional standardisation rules (cf. formal and dimensional generating system in the Hendrickx-Vanwalleghem design approach). It is conceptually the smallest entity of a (building/construction) system. Further processing is permitted so long no specific purposes are given to the element. [Debacker 2007a, Henrotay 2007]

Component/sub component

A (construction/building) *component* is an element which has one or different functions. If the HENDRICKX-VANWALLEGHEM design approach is considered, it is made of one or several basic elements. Once these basic elements are assembled into a component, they become *sub-components* since they receive a meaning.

The prefixes 'sub' and 'super' are used to define the level of the system under study. A thermal insulation layer is, for example, a sub component of a panel. Multiple panels can be assembled into a wall. Taking the panel (or the thermal insulation layer) as reference, the wall is a super component. Henrotay et al. (2007) use the same prefixes to differentiate the level of processing of (basic) elements.

Cradle-to-cradle

Cradle-to-cradle is a design paradigm popularised by W. McDonough and M. Braungart, through their book "Cradle to Cradle: Remaking the Way We Make Things". Cradle-to-cradle design is inspired by nature, where there is no place for waste, since waste equals food for other product systems. In this line of thinking life cycles do not end (cf. cradle-to-grave paradigm) but succeed each other (cf. reinvestment). McDonough and Braungart make a distinction between technical and biodegradable (organic and polymeric) materials. Technical nutrients can be recycled or reused with no loss of quality (read: minimum) and biodegradable nutrients composted or consumed. [McDonough 2002]

Embodied energy (EE)

EE of a (product) system is characterised as the energy consumed in all activities necessary to support the (manufacturing) process of that (product) system. Depending on the building (product) system under study, different definitions can be made.

Deconstruction

A process of carefully taking apart a building with the intention to maximise reuse or recycling of components and materials and to minimise landfill [Nordby 2009].

Discount Rate

Factor reflecting the time value of money that is used to convert cash flows occurring at different times to a common time.

Down-cycling

Recycling for a purpose with lower performance requirements than original.

Dry construction

Dry construction systems make use of light-weight materials, light-weight structures and light-weight systems. A typical example of is dry wall, which uses dry materials such as gypsum board, plywood or wallboard in construction, without the application of plaster or mortar.

Environmental impact

Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g. emissions, resource extraction, land use).

Flexibility

Flexible buildings corresponds to "buildings that can easily adapt to the changing needs of users" [Schneider and Till 2005]

Floor-through apartment

An apartment that runs from front to back of a building, while sharing the same floor with another unit across from it.

Functional lifetime

The time in which a component or a building is usable, or in actual use, for one purpose.

Functional unit

The functional unit is a quantified performance of a product system for use as a reference unit. [ISO 2006a, ISO 2006b]

Industrialisation

This term has two different meanings in this research:

1. It is used to describe all three aspects of offsite construction work: modularisation, prefabrication, and preassembly [Haas 2000]. The industrialisation process can be defined as an investment in equipment, facilities, and technology with the intent of increasing output, decreasing manual labor, and improving quality [Warszawski 1999].

2. Industrialisation is also a term that was in common use in the 1970s to describe mass production of housing aiming at construction of low cost and improvements of construction process through enlarging of component size, prefabrication and repetition. Mass production was linked with large-scale components what had direct consequences for the architectural expression of industrialised building [Durmisevic].

Industrialised building has built its reputation in Europe in a first half of twentieth century through. Its reputation was especially based on the trend from 50's and 60's which.

Nominal Discount Rate

Rate used to relate present and future money values in comparable terms taking into account the general inflation/ deflation rate.

Preassembly

A common definition for preassembly is "a process by which various materials, prefabricated components, and/or equipment are joined together at a remote location for subsequent installation as a unit" [Tatum 1987]. The preassembly may be completed at the job site in a location other than the place of final installation. The preassembly process can involve adapting sequential activities into ones that are parallel. A preassembly often contains only portions of systems, and work from a variety of crafts is typically necessary.
Preassembly is generally considered to be a combination of prefabrication and modularisation. It may use fabricated components made offsite and then assembled near the site. These units can then be installed at the site, similar to modules. [Haas 2000]

Prefabrication

Prefabrication can be defined as "a manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a component part of a final installation" [Tatum, 1987]. Any component that is manufactured offsite and is not a complete system can be considered to be prefabricated.

Real Discount Rate
Rate used to relate present and future money values in comparable terms, not taking into account the general or specific inflation in the cost of a particular asset under consideration.

Re-design
Re-design for change covers design strategies for renovation with the objective to create buildings that can be more easily adapt tomorrow

Refurbishment
Renewal of an entire building or component to a condition comparable with the original when new.

Residual Value
Value assigned to an asset at the end of the period of analysis.

Renovation
The transformation process of the physical, functional, financial, architectural and ecological characteristics of a building product or project to realise a comprehensive and useful extension of the life span [Thomsen 2001].

Salvage
Retrieve or preserve building materials from destruction, for utilisation through reuse or recycling.

Sensitivity Analysis
Test of the outcome of an analysis by altering one or more parameters from initial value(s).

Service life
Expected or actual lifetime of a component or a building, may be confined by functional, technical, economic or esthetic reasons.

Soft- stripping
Soft-stripping refers to the removal of specific building components or equipment prior to demolition of the structure. Examples of items that may be of value include: plumbing or electrical fixtures, appliances, HVAC equipment, doors, windows, hardwood, tile flooring, etc.

Technical lifetime
Lifetime of a component or a building related to technical durability.

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