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EXPANDABLE HOUSES

Exploring the potential of anticipated extensions in terms of changing lifestyles, material efficiency and life cycle costs

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Master thesis submitted under the supervision of
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A WORD OF THANKS

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ABSTRACT

This dissertation explored the potential of anticipated extensions of expandable houses in terms of changing lifestyles, material efficiency and life cycle costs

First, a **reflection on current phenomena** such as material efficiency, affordability and non-planned expansions of conventional housing is made to illustrate why the concept of expandable housing is relevant today.

The **research** is conducted in three steps. In the first place, different case studies of expandable houses applied in different contexts are analysed. Accordingly, several design strategies for expandable houses are outlined. Second, as changing lifestyles contain an uncertainty about the future, scenario planning is used to develop plausible evolutions regarding household types. These are used to design an expandable house with the developed design strategies. Third, the expandable house is compared to conventional housing in terms of changing lifestyles, material efficiency and life cycle costs.

The last part of the master thesis contains **guidelines** that are developed to introduce the possibilities of expandable housing.

The obtained **results** derived from the research part indicate that expandable houses need less materials to be accomplished than conventional housing. If the total weight of both housing types is compared, one can also **conclude** that expandable houses are beneficial in terms of total weight. This is a consequence of using alternative building elements instead of conventional building elements and having a smaller floor area. Nevertheless, regarding recyclability, the materials used in the conventional house have a higher recycle percentage. Another key point is the life cycle cost. The main results indicate that expandable houses are profitable if initial cost is an issue. Additionally, also the life cycle costs of building an expandable house are lower. When the building element compositions are compared, it can be observed that in terms of cost efficiency there is no difference between both element compositions for accomplishing expansions.

KEY WORDS Expandable houses, Changing lifestyles, Material efficiency, Cost efficiency, Life Cycle Design, Adaptable architecture

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CHAPTER 1: INTRODUCTION

WHY IS EXPANDABLE HOUSING RELEVANT TODAY?

Sustainable architecture is often understood amongst the building community as buildings equipped with green technologies (Laudy 2015). Green technologies have as a common goal to minimize energy and water expenditure through the reduction of energy demand of buildings, combined with renewable energy supply that preserve both climate and resources (Laudy 2015). Green technologies are a progress towards a more sustainable architecture but green technologies alone cannot make a dwelling sustainable. Sustainable buildings unite green technologies with a high comfort level for the user, while simultaneously taking into account socioeconomic aspects (Bauer, Mösle, and Schwarz 2010). Socioeconomic realities with direct effects on sustainable living need to be considered from the initial design stage since people strive for optimal comfort and economic benefits (Bauer, Mösle and Schwarz 2010).

On the one hand, today's desired housing model takes up too much space, is built on expensive land, has high initial construction costs and wastes energy (Demil and Bellens, 2017). On the other hand, there is a high demand for affordable dwellings, but at the same time it was found that people, in particular young first-time buyers, were looking for dignified homes and not for small houses that would feel cramped in the near future (DeBeCo&Aranth, 2016). The question is thus: how can we utilize the available land and resources as efficiently as possible, ensure cost-efficient construction and living, and provide dwellings that fit the residents' lifestyles over the years? Rethinking spacial use of dwellings and introducing **design concepts in response** to changing lifestyles and demographic trends are, therefore, significant if sustainable buildings are the target.

Hereunder, the focus is placed on the problem of affordability of housing today and the economic benefits adaptability offers. Furthermore, the different changes in lifestyles are considered and the reasons why the need for adaptability occurs. Then the benefits adaptable design has to offer in terms of material efficiency is shortly explained. In these three topics, the concept of adaptable houses is narrowed towards expandable houses. Lastly, the problem of non-planned expansions is discussed. Expanding houses is not a new concept. Therefore, it is explained why the conventional methods should be addressed (*Figure 1*).

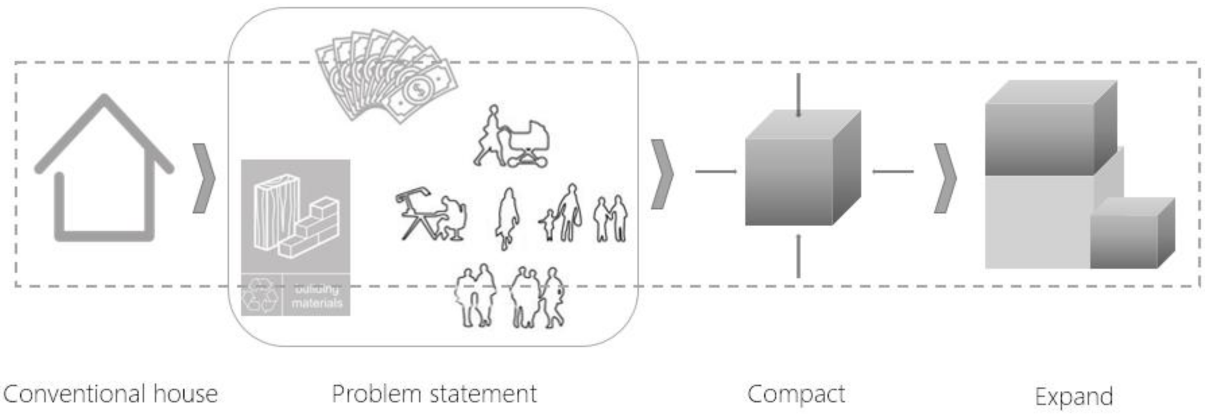


Figure 1: Scheme of the problem statement

Affordable housing

Architecture is not only confronted with the natural resources scarcity, which is the main concern of green technologies, but also with a crisis of economic resources. Currently affordable housing is one of the **priorities** in Belgian housing ("Social Housing in Europe Belgium" 2010). Moreover, the Brussels Region is facing major challenges in terms of high land prices and affordable housing as a result of close packed land and strong demographic growth (Observatorium voor Gezondheid en Welzijn van Brussel-Hoofdstad 2015). The price per square meter of new building plots increases since the mid-90s onwards.

As stated before, the choice must often be made either by price or by level of comfort, instead of both simultaneously. This is because buying or building a conventional dwelling is accompanied by high initial costs. For the development of affordable housing, financial resources are typically limited (Bach et al). As buying a house is often one of the largest investments in peoples' lives, maintaining the same level of comfort required. This demands **creativity from developers.** Therefore, reassessing how spaces are used and challenging traditional thinking regarding housing are a key factor (Bach et al).

Furthermore, if the needs or the financial status change during peoples' lives, households often consider to relocate. The main reason is to avoid costly maintenance, while relocation results in significant transaction costs, such as fees, additional resources, expenditures of moving companies, cost of fitting the new home, etc. Adaptability and expandability of the original dwelling may outweigh relocation costs (Friedman, 2002).

Changing lifestyles

Often the perspective of cost reduction is the only determinant in a new affordable housing project. **Other critical determinants** such as taking into account the different lifestyles of the targeted public and their evolving needs is absent or superficially illustrated (Salama and Alshuwaikhat 2006). This results partly out of the fact that affordable housing usually deals with the problem of mass housing (Ruffa 2013), where they tend to ignore those determinants. Taking into account the changing lifestyles of people introduces uncommon design challenges (A. Friedman 2002). The most crucial **challenge** for the design and the construction of the future home is how it will be able to adapt to those constantly changing lifestyles.

The need for expanding dwellings can have different reasons. They depend on the users' lifestyle. Changing lifestyles are partly due to **more social diversity** (Ruffa 2013), but also the transformation of a **traditional family** drives the need for adaptable houses. Getting a partner and children requires different spatial arrangements living alone. Moreover, less traditional family compositions emerge increasingly. The incidence of divorce enables single-parents households and remarrying creates new composed families (A. Friedman 2012). Besides this, peoples' live extend and many of the **seniors** want to spend the rest of their lives in their own homes. This creates the need for design that enable occupants to age comfortably at home (De Zilveren Sleutel, 2016). All these household are potential home buyers, and designs should respond to their needs.

Material efficiency

Growing **environmental awareness** lead to the creation of green technologies, that sustain valuable resources, but at the same time also another facet of adaptability: material efficiency. Material production is energy intensive. Therefore, in the first place, **reducing the demand for material** would lead to reducing extraction of natural resources, reduced energy demand and other environmental harms (Allwood et al., 2013). Secondly, prolonging the **building's lifespan** diminishes resource consumption and thus also the aggravation of environment pollution.

Taking adaptability into account in the initial design process promotes less material and less demolition waste, as buildings are reformed instead of destroyed and rebuild. Dwellings can be designed and constructed to become life-cycle houses where changes are supported (A. Friedman 2002).

Non-planned expansions

A house has often to accommodate several households over its life span. Each household has its unique lifestyle and living habits (Friedman, 2002). Once occupants move into their new home, a **life-cycle process** begins. Typically, this process requires **adaptation** to fit the house to the needs of the new household. Expanding the kitchen or adding new walls are examples of these adapting processes. When larger adaptations are needed, in terms of expansion outside the perimeter of the house and when the design cannot anticipate on the future uses, applying larger changes to a dwelling layout become complex and costly. An example of such a task is demolishing and rebuilding building components.

In Chapter 2 it is shown through case studies and design strategies for expandable houses how project developers and architects were confronted with similar problems and solved these problems through the concept of expandable housing. The different examined cases are carefully chosen to show that this concept is applicable in different contexts and can occur in a variety of forms. Nevertheless, they all have the common goal to adapt to the needs of the occupants.

OBJECTIVE OF THE MASTER THESIS

The overall objective is to explore the potential of anticipated extensions in terms of changing lifestyles, cost efficiency and material efficiency.

To be precise, the definitions of those terms are expressed.

Expandable house	Expandable houses are a segment of adaptable houses, where the adaptations are realised through expansions. Expansions are one of the most frequent building alterations and they have an important special impact. The aim of expandable houses is to provide occupants with possible extensions that facilitate the fit between their space needs and the constraints of their homes (A. Friedman, 2002).
Cost efficiency	Cost efficiency has as aim to present suitable results for minimal financial expenditures. In this thesis, the cost efficiency should be treated as an indicator of the total cost efficiency. Foundations and techniques are not included in the calculations. Moreover, also taxes, designer fees, neither the advantages of mass production and prefabrication are not considered. Because this study is a first exploration of its kind, the financial impacts that are examined are only the life cycle costs of the main building elements. These elements are the ground floor, the intermediate floor, the roof, the exterior wall, the partitioning wall and windows and doors. The costs are thus in the first place a consequence of the design choice made in the Research by Design part.
Material efficiency	Material efficiency is significant in terms of environmental impact. Material production is energy intensive and has consequently a large environmental impact. Therefore, in first place, reducing the demand for material leads to reducing extraction of natural resources, reduced energy demand and other environmental harms. Secondly, prolonging the building's lifespan diminishes resource consumption and thus also the aggravation of environment pollution. Thirdly, reusing or recycling building elements is promoted to reduce the waste of materials (Allwood et al., 2013). To investigate the full-scale environmental impact of expandable houses is beyond the scope of the thesis. Therefore, material efficiency can be used as an indicator of the environmental impact. This will be monitored by modelling the materials consumed and wasted over building's service life, and comparting those quantities for alternative design strategies and choices.

OUTLINE OF THE MASTER THESIS

This dissertation is divided in four chapters. The first chapter contains the problem statement, which is a reflection on current phenomena, and illustrates why the concept of expandable housing is relevant today.

The second chapter explores several cases of expandable houses in different given contexts. In the next section, several design strategies for expandable housing are outlined. These design strategies are based on the analyse of expandable housing projects, concepts and systems. Moreover, they are compared to conventional housing and the way conventional housing expands during its life cycle. These obtained strategies are used in the continuation of the master thesis to develop an expandable house in the given context of the applied case study.

The third chapter examines the defined **design strategies**. To test these design strategies, a suitable project was pursued to apply them to. The master plan for the site '*De Molens*' in Vilvoorde was selected in the in the framework of future densification and the call of the Flemish government for stimulating pilot projects for common and innovative living. Designing for changing lifestyles includes future uncertainties, and therefore, these are anticipated through evaluating demographic data and by using **scenario planning** to be able to develop plausible evolutions.

In architectural design, scenario planning is helpful to demonstrate that the designed buildings can endure time. This is realized by the potential the building has to adapt to each scenario alternative (Galle, 2016). In the case of expandable houses, future **expansions can be anticipated** through scenario planning to discover what the benefits of expandable buildings are in terms of changing lifestyles. Four different scenario narratives are worked out: Work at home, Children, Kangaroo dwelling and Co-housing.

With the defined scenarios, the design strategies and the scenarios are used to design an expandable house. This is established by a **research by design** approach. The designed expandable house, which contains a core and several possible extensions, is compared to a conventional row house. To become dignified comparisons in terms of material efficiency and cost efficiency, the conventional house is also expanded according to the alternative scenarios.

Forthwith, **the material efficiency** is determined by the with the aid of four indicators: estimated service life, total materials used, total of materials that can be re-used and recycling per total generated waste. The life cycle cost analysis is established by considering all relevant costs throughout the lifetime of a building. The financial impacts are calculated by taking into account the main building elements. For both material efficiency and cost efficiency, comparisons are made between the conventional house and the expandable house.

The fourth and last chapter contains **guidelines** that are developed to introduce the possibilities of expandable housing to designers, developers, occupants and governmental authorities. The guidelines are structured by the objectives of the thesis which are: changing lifestyles, material efficiency and cost efficiency.

CHAPTER 2: STATE OF THE ART

EXPANDABLE HOUSES: PROJECTS, CONCEPTS AND SYSTEMS

In the problem statement examined why it is alluring to explore the concept of expandable housing. In this chapter, several existing cases of expandable houses are analysed and discussed. The cases are examined through their valuable concepts but also through their limitations and constraints.

In selecting case studies for investigation of expandable housing, following criteria were important:

- A spread of **different methods** used to expand a dwelling to demonstrate the implementation of design approaches;
- A spread of **different contexts** likely to affect design approaches, such as housing markets, locations and occupants.

In all case studies the expansions were planned in the initial design phase. These case studies show the opportunities expandable houses can offer and that there is an international interest in this concept.

The most valuable case studies were Quinta Monroy by ELEMENTAL, Skilpod by UAU Architects, Jan Vrijs and Filip Temmerman and Nakagin Capsule Tower by Kurokawa. Firstly, Quinta Monroy is a social housing project for slum neighborhoods and where people start with a basic core house. The intention is that the users build the expansions themselves when needed and when financially possible. Secondly, Skilpod is a Belgian project which works with modular volumes of different sizes that can function on their own, that can be connected to other modules or that can serve as a new extension to an existing building. Lastly, the Nakagin Capsule tower is an example of a project where the architect had the intention from the initial design phase to design an expandable building, but where the expansions never took place.

Furthermore, six more case studies are explained shortly.

Major cases

QUINTA MONROY

Figure 2: Core housing (“Quinta Monroy / ELEMENTAL”, 2008)

Figure 3: Expanded constructions (“Quinta Monroy / ELEMENTAL”, 2008)

CONCEPT

The project Quinta Monroy is constructed on a site that was originally a **slum neighbourhood** in the city centre of Iquique, Chile. The authorities wanted to overcome the poverty these families endured for years (Wade, 2009). Elemental was asked to revive slums, but the budget was rather small for such a project. Elemental solved this by **providing what the residents do not** have the capacity to construct themselves, such as the structure, vertical circulation and infrastructure as a kitchen unit and a bathroom (Dostoglu, 2011).

The **housing typology** Elemental defined is a three storey condition, which accommodates one house on the ground floor and another duplex house occupying the second and the third floor (Dostoglu, 2011). The **interior** of the houses is bare, as no finishing is present. This is also a result of the concessions.

The expansions are not provided and are for the **residents to build** it. Nevertheless, precautions are made in the initial stage. Structural bays are left open for the future self-build completion. The bays ensure that expansions can be made as effortless as possible. They were dimensioned to fit standardised fabricated material, as they have a width of three metres. This way, the residents can find cheaper materials which need less adjustments (Wade, 2009). The extensions can expand each 36 m^2 house to a 72 m^2 house, and each 25 m^2 duplex to a 72 m^2 duplex. The **main objective** of extensions is to improve housing conditions.

WHY DID THEY CHOOSE FOR EXPANDABLE HOUSING?

The **funds were insufficient** to build a dignified house for every family (Vale et al. 2014). It allowed to build bad quality housing. Elemental preferred to design half a house of proper quality instead. The strategy was to provide housing with a solid structure that is wind- and waterproof with the **essential utilities** like a bathroom, clean water supply and a kitchen unit (Vale et al. 2014) (Figure 2).

The construction of the second half must be **done by the residents** (Figure 3). This way public funding is used to activate capital accumulation through half houses (Vale et al. 2014). The necessities are foreseen, and they build additions they can afford (Boano and Perucich, 2016). Affordable housing often loses its value from the moment it is built. However, Quinta Monroy has gained value since it's completion. This type of housing should be seen as an investment and not as a mere social expense (Aravena, 2010).

SKILPOD

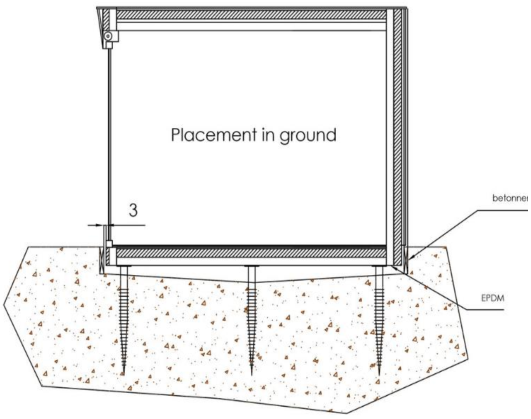


Figure 4: Skilpod Light #15 (Deckmyn, 2015)

CONCEPT

Skilpod is made by the Belgian design office UAU Collectiv, in collaboration with Filip Temmermans and Jan Vrijs (Galle, Paduart, and De Temmerman 2016). Skilpod is a project which works with **modular volumes** of different sizes that can function on their own (*Figure 4*), that can be connected to other modules or that can serve as a new extension to an existing building.

On the one hand, a Skilpod is an easily **replaceable** modular volume. It can be removed without destruction of the pod. On the other hand, it is not the intention to demount the pods themselves (Deckmyn, 2015). Therefore, several modular volumes are developed. The pods range from 30m^2 up to 150m^2. The difference between the smaller modules and the bigger ones is that the smaller ones are meant to be mobile units, while the bigger ones are meant to be permanent quality expansions. Currently an entire building is built out of Skilpod modules (Deckmyn ,2015).

Skilpod offers solutions for **all types of living**. Therefore it is possible to merge different pods to become dwellings that are suitable for single parent families, disabled people, first time buyers and group living projects (Archdaily, 2017).

WHY DID THEY CHOOSE FOR EXPANDABLE HOUSING?

The main motivation of the designers to develop Skilpod was a personal case concerning **family care**. Flanders' Care is investigating the use of modules in taking care of people at home. Certainly with the shortages of places in care centers, Skilpods can offer an answer to this demand (Van Cauwelaert, 2015).

The designers wanted to offer a commodity that can be added to an existing building, but what has a certain living quality (Deckmyn, 2015). Hence, Skilpods **are small but complete housing units**. This way the designers wanted to lower costs of expanding buildings and to be able to accomplish it more easily. Especially for enterprises that grow temporarily and sometimes need more or less capacity, this concept of modular expansions can serve as an answer.

NAKAGIN CAPSULE TOWER

Figure 5: The Nakagin Capsule Tower by Kisho Kurokawa, Tokyo, Japan (Varinsky, 2015)

Figure 6: Inside one of the capsules (Soares and Magalhaes, 2014)

CONCEPT

The Nakagin Capsule Tower is a design of the architect Kisho Kurokawa. He had the intention to start a new movement of expandable buildings. The Nakagin Capsule Tower consist of two central shafts and small capsules that can be added to the shaft as Lego blocks (*Figure 5*). These **capsules** of 10m^2 contain a place for sleeping and a small bath room (*Figure 6*). The capsules are prefabricated and it is possible to assemble them quickly. The project has the potential to add more capsules to the shaft whenever more rooms are needed. The capsules themselves cannot be changed in terms of transformation nor in terms of changing function (Varinsky, 2015).

WHY DID THEY CHOOSE FOR EXPANDABLE HOUSING?

The architect wanted to provide rooms for business man who came to Tokyo to work (Varinsky 2015). The intention was to make a building that was able to change in order to keep up with **demographic evolutions** and the growth of the cities. It was an outcome of the Metabolist movement in Japan[1] (Varinsky, 2015). Kurokawa had a picture in his head of the building growing like a tree, and that the shape would grow when the number of occupants increased (Soares and Magalhaes, 2014).

Even though the idea was admirable and the extensions were obviously planned in the initial design phase, it never worked out this way. Not one expansion is added after completion in 1972 (Soares and Magalhaes ,2014). There is no clear reason why it did not work. Only Soares and Magalhaes came with a theory that the capsules were not adaptable to the requirements of the occupants and that the indoor climate is not ideal (Soares and Magalhaes, 2014).

Minor cases

THE NEXT HOME BY AVI FRIEDMAN, MONTREAL, CANADA

Includes concepts Affordability, terraced houses, expand on the inside

Limitations Fixed outer shell, cannot expand anytime

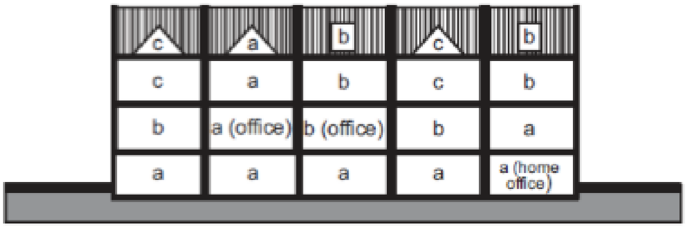


Figure 7: Scheme of the Next Home (Friedman, 2015)

The Next Home is a three-story row house. The concept is to provide a dwelling that can be converted into two or more independent units by manipulating entrances and vertical arrangements.

In the Next Home, a household can start by buying one story. If a household wants to expand and a story adjacent to theirs is free, they can buy it and connect it to their home (*Figure 7*). Savings (in building costs) were made through efficient use of materials and using standardized building parts. Alternative arrangements include using one of the levels as a home office (A. Friedman 2015).

IBBN (IK BOUW BETAALBAAR), KOOS VAN LITH, NIJMEGEN, THE NETHERLANDS

Includes concepts Affordability, Kit-of-parts, rapid construction

Limitations Single families only

[1] Metabolism is a post-war Japanese architectural movement that fused ideas about architectural megastructures with those of organic biological growth.

Figure 8: Project IbbN (Hofmans 2013)

The project of Koos van Lith focuses on first-time buyers. It is a two-story house designed to be cost-efficient (*Figure 8*). The house is assembled from a prefab kit, to ease and speed up the building process. The architect chose for durable materials with low maintenance to reduce life cycle costs. After completion of the house, more rooms or even a third story can be added (Hofmans, 2013).

ME:LU by AB Design studio, inc., Los Angeles, USA

Includes concepts Modularity, reuse of containers

Limitations Module itself not adaptable

Figure 9: ME:LU (Architizer, 2017)

ME:LU stands for Modular Expandable: Living Unit and is based in a concept of providing a housing module that can work for different typologies. The expandability is realized by connecting containers with identical openings to each other (Architizer, 2017). This allows for reconfiguration in various ways when the needs of the residents change.

Aquitanis by Tetrarc Architects, Bordeaux, France

Includes Concepts Modularity, core house, prefabrication

Limitations Module itself not adaptable

Figure 10: Assembly of different modules of Aquitanis (Aquitanis, n.d.)

The project consists of a system of modules. The base is four modules that are assemblable in different ways. All modules have a floor area of 11,56 m^2. One module contains the entrance the bathroom, the second one the kitchen, the third one a bedroom and the fourth one is an empty module. The assembly can be done in different ways, it is not an ordinary repetition of modules. At the end there are more than 50 solutions (Aquitanis, n.d.).

SLIDING HOUSE BY dRMM ARCHITECTS, SUFFOLK, UK

Includes concepts Manipulation of volumes

Limitations High-tech solution

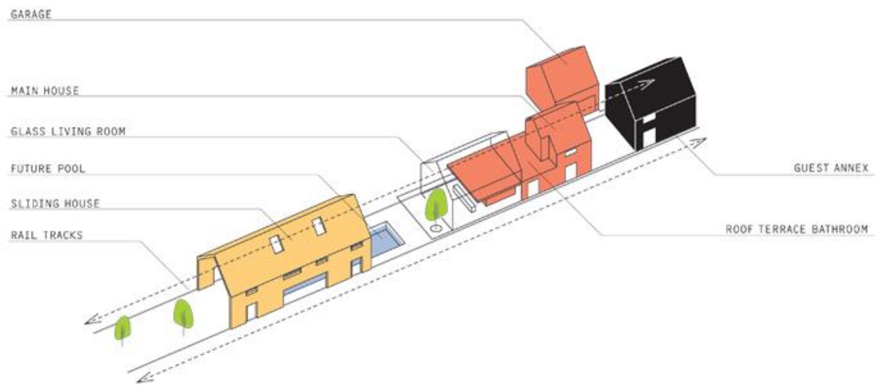


Figure 11: Scheme of the Sliding house (DRMM Architects, n.d.)

A linear house is sliced into three programmes. The garage is pulled off axis to create a courtyard between the three units. The separated units are transformed by a mobile roof/wall enclosure which traverses the site, creating combinations of enclosure, open-air living and framing of views. The tracks can be extended in the future if other structures are added, which may need occasional shelter (DRMM Architects, n.d.).

SHARIFI-HA HOUSE BY NEXT OFFICE, TEHRAN, IRAN

Includes concepts Manipulation of volumes, box-in-box principle, sun-oriented

Limitations High-tech solution, no further expansions

Figure 12: Sharifi-Ha House (Archdaily, 2014)

The Sharifi-Ha house is a family house in Tehran, Iran. The exceptional element is that the bedrooms can turn around their axis. This way they can gain extra space and sunlight. It adapts to the needs of the users (Archdaily 2014). When the rooms fold out, extra terrace space is made available.

Comparison of the different cases

The concept of expandable housing is already applied **in several countries** in different continents. This reveals that the idea of expandable housing is not only locally applicable, but that the concept of expandable housing fits in **different contexts**. A first example is IbbN, located in the Netherlands, focusing on young-first time buyers. A second example, the case where context is most decisive, is Quinta Monroy, located in Chile. Here, the expandable house offers a solution for reviving a slum area, with the residents being able to contribute partly to the project. The extensions are made entirely by the residents, which benefits the pride of the neighbourhood. Notwithstanding that Elemental has taken some precautions to make these extensions as simple as possible, fully predesigned extensions would not fit in this context. The project would even lose a part of its context.

Other projects were not bound by context, but rather **a concept project**. This is the case with the project ME:LU. The expansions have been pre-designed so that they fit perfectly with the initial structure. In this manner, the modules can be placed anywhere. **One goal** is common to all projects: to offer the opportunity to adapt to the lifestyle of the inhabitants.

The extent of growth is manifested in a **variety of forms**. An extension can vary from a simple addition, such as adding a module, to an addition of a large and complex volume, such as an adjacent dwelling.

Expandable houses can be designed for different **typologies of users**. Although all expandable house projects allow changing of lifestyles, the main household typology is the single-family household. Examples of cases that focused on single families were Quinta Monroy, Sharifi-Ha House and IbbN. Skilpod and The Next Home also focused on multigenerational living or cohousing.

Modular volumes are frequently used in the design of expandable houses. Four cases (Skilpod, Nakagin Capsule Tower, ME:LU and Aquitanis) used **modular** expansions. This is due to the simplicity of the prefabricated modular volumes, which induces rapid construction and thus cost efficiency (Gunawerdena et al., n.d.). The cases Sliding House and Sharifi-Ha House use rather sophisticated solutions by using massive rails to cover up spaces or a turning mechanism to rotate rooms. In terms of **cost-efficiency**, these solutions are not ideal.

The case of the Nakagin Capsule Tower is an evidence that even if expandability is strictly set out from the initial design stage, it is still not a guarantee that occupants will use the possibilities of expanding. The real reason for the lack of success is never clarified (Soares and Magalhaes, 2014).

In the next section, several design strategies for expandable housing are outlined. These design strategies are based on the analyse of expandable housing projects, concepts and systems. Moreover, they are compared to conventional housing and the way conventional housing expands during its life cycle. These obtained strategies are used in the continuation of the master thesis to develop an expandable house in the given context of the applied case study.

DESIGN STRATEGIES FOR EXPANDABLE HOUSING

The reason why people expand their house is because the extension would add quality to the house. This quality can be the use of space or its appearance. The likelihood to add value is larger when the extensions are contemplated in advance (Schoenmaker, 2015). Therefore, the different case studies were analysed by means of used design strategies to expand a house. This resulted in three main design strategies. To be complete, the design strategies for expandable housing are compared to non-planned expansions that are added to conventional housing (*Figure 13*).

The strategies are set up to be applied in the initial design stage, where the designer can employ the strategies during the concept phase. The strategies all have the aim to facilitate expanding a house in the occupancy stage. The difference is that the three different design strategies for expandable houses each start with a different core and, as a consequence of the different cores, the extensions also differ one from another.

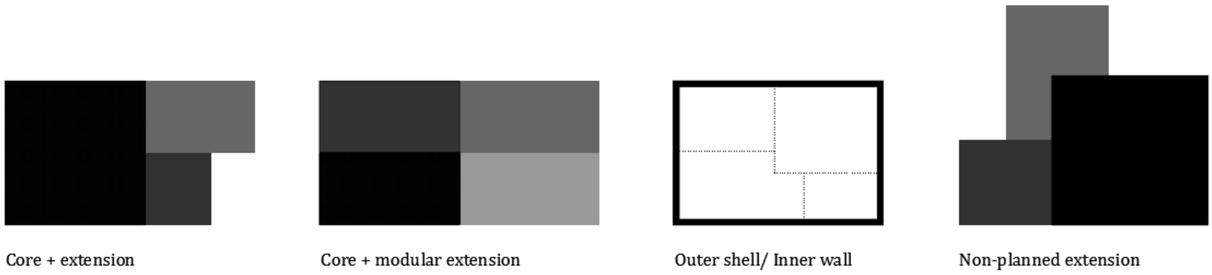


Figure 13: Scheme of design strategies for expandable houses

The different expansion strategies are discussed individually hereunder. Each strategy contains a description and how it is executed. First, the strategies '**Core + extension**' and '**Core + modular extension**' are discussed. These strategies are add-on strategies, which mean that the expansions are realised outside the perimeter of the building. An **add-on** extension may include a horizontal extension or a vertical extension. A vertical extension is also called 'on-topping'. For on-topping to be possible, structural framing must be designed from the beginning to support future additional loads.

The main difference between both strategies is the aspect modularity. In the strategy 'Core + extension' the extensions are custom-made while in the strategy 'Core + modular extension' the extension take form of modular volumes. Both custom-made and modular expansions have their advantages and disadvantages, which are explained later in this chapter.

Secondly, the strategy '**Outer shell/Inner wall**' is explained. This strategy is an **add-in** strategy, which means that the internal division of spaces change, but the outer shell remains the same. In other words, the built floor area stays the same. It can be seen as the reversed process of the 'Core + extension' strategy.

Furthermore, other expansion strategies, such as sliding and folding, are explained. These design strategies are not further analysed in this master thesis. Such strategies are often only specifically applicable and not easily adaptable to accommodate housing.

Lastly, consequences of expanding a house are discussed, as extensions have an influence on the initial dwellings' daylight, natural ventilation, circulation, etc. Often expanding a house is related to its context, but there are main considerations that should always be taken into account, for every strategy and every context.

Core + extension

The initial phase of the design strategy is a core house. This **core house** should minimally should include all necessary functions, such as a minimal living space, a kitchenette, a toilet, a bathroom, storage and a bedroom. Not every function should be placed in a different room, but they should all be present in some way. For example, storage can be placed underneath the stairs and living room and bedroom can happen in the same space.

If it is the intention to become a multi-story dwelling, then it is preferred to plan in the **stairs** from the outset. The most desirable solution is to place the stairs already in the core house. If this is not possible, then it is recommended to frame the floor in advance in such a way as to facilitate the future placement of stairs (Friedman, 2002).

The extensions are placed **adjacent** to the core house. This implies that an extension is added next to or onto the main house. The extensions in this strategy are custom-made. It is forthwith possible to design them according to the specific needs of the users, the environment and the context of the house. The extensions may vary in shape and size. The size can vary from a porch to a new level on top of the house.

The bigger the planned expansions are, the more must be considered in the initial design stage. For example, by adding larger extensions, such as new level, attention needs to be paid to the initial bearing structure. Hence, while designing the initial foundations and structure, future extensions need to be taken into account. When expanding horizontally, the boundaries of the property have to be respected.

Examples of cases where the design strategy 'Core + extension' is applied, is Quinta Monroy by Elemental (*Figure 14*) and IbbN by Koos van Lith. These cases are explained in the section 'Expandable houses: projects, concepts and systems'.

Figure 14: Different expansions after 5 years ("Chile Quinta Monroy" 2008)

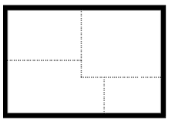
Core + modular extension

This strategy is similar to the strategy 'Core + extension' except for the use of **modular volumes**[2] instead of custom-made volumes. Nevertheless, the same advices are valid concerning the initial necessary functions and the stairs in the core house.

Reasons to choose modular structures over custom-made structures are often to achieve cost effective and rapid construction (Gunawerdena et al., n.d.). This is because modules are typically assembled off-site and put together on-site (Doran and Giannakis, 2011). This shortens construction time. Secondly, modules are repeated and thus often consist of standardized components, which lowers the price. Due to this repetition of units, a modular system often uses a grid structure, that can be divided into several subsystems, which makes it easy to replace one of the subsystems (Nakib, 2010). Furthermore, modular designs and approaches are useful for managing complexity (Gunawerdena et al., n.d.). Modularity is, and especially in transformable design, used to facilitate reconfiguration.

An example of using a module to expand a house is **Skilpod**. The Skilpod can be a unit on its own but it is also possible to connect different modules with each other (*Figure 15*). A Skilpod is an easily replaceable module, and can be replaced or removed without destruction (Deckmyn, 2015).

Figure 15: A compilation of Skilpod modules (Archdaily, 2017)



Inner wall partition

The strategy 'Inner wall partition' exists of a static frame structure and is designed in terms of **volumes to be subdivided** and rearranged in this frame. The difference with the previous design strategies is that the **outer shell** does not expand. In other words, the expandability is limited with the outer shell structure and the built floor area remains the same. Therefore, the outer shell should be large enough from the initial design stage to be able to be subdivided in different volumes in a next stage.

For example, this design strategy is used nowadays in dwellings where inhabitants leave the upper floor or the attic **open and unfinished** and subdivide and finish it in a later stage. The design strategy can also be applied to larger projects, where a large house is subdivided in different apartments (*Figure 16*). On a smaller scale, taking advantages of unused spaces and turning it into a room by enclosing it is also a form of expansion.

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[2] A module is an essential and self-contained functional unit relative to the product of which it is part (Miller 1998).

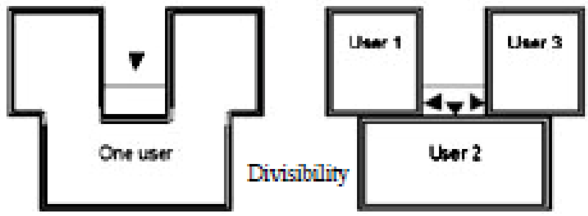


Figure 16: Divisibility by adding inner walls (Nakib, 2010)

To apply the 'Inner wall partition' strategy, an **open plan** is indispensable. Therefore, internal columns and bearing walls should be avoided. The bearing structure should be positioned in the outer structure as much as possible. The partitions can be designed in this manner that they accommodate maximal choice of transformation with minimal disruption and cost. The most thoughtful solution is to create distances in between the bearing elements that match standard sizes of materials.

Furthermore, easily removable, adaptable or re-usable **inner walls** are preferred to facilitate transformation. For this reason, the use of dry connections in the inner walls is promoted (OVAM, 2015). The reversibility of connections determines the feasibility to demount the inner walls or its components without damaging them. Only then they can be reused or sorted and recycled (OVAM, 2015).

This strategy is compelling if only a **small parcel** is available and expanding is not a possibility. Additionally, the 'Inner wall partition' strategy is also intriguing if occupants would like to have the spatial or financial assurance that the outer shell is built, but are not sure what the future will bring. In this manner, the 'Inner wall partition' strategy is a transition between the conventional house and the expandable house 'Core + extension'.

An example of a case that used this design strategy is the case **The Next Home by Avi Friedman**. The interior is liberated from load bearing partitions. The adaptable interior walls combined with the efficient design for transformability reduces the life cycle cost of a house. The dimensions of the units are chosen to have modular sizes in order to reduce the waste of materials. As can be seen in the figure, each dwelling part can have another function (*Figure 17*). Those functions can change when needed (Friedman and Krawitz, 1998).

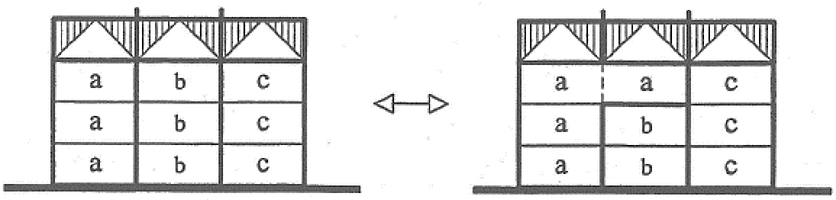


Figure 17: The Next Home by Avi Friedman: subdivision in a multistory attached structure (Friedman, 2002)

Manipulation of volumes

Manipulation of volumes means that existing volumes and spaces expand or shrimp in form and volume. Examples of design strategies that manipulate volumes are sliding and folding of structures. These design strategies are shortly explained, but are not further analysed in this master thesis. Such strategies are often only specifically applicable and not easily adaptable to accommodate housing. This is due to limited thermal and acoustical insulation and water tightness complications (Valcarcel, Dominiguez, and Lamas, 2002). The choice of using such structure structures is usually determined by properties as compactness during transportation and storage and the relative ease of construction.

Sliding

A series of volumes slide into each other or out of each other gaining higher or lower compactness. Sliding is achieved by using rails. A consequence is that the structure should not weigh too much. Lightweight materials are therefore preferred (Da Sousa Cruz, 2013).

An example of this strategy is 'Fill in your own Form' by Nikos Asimakis and Vaggelis Maistralis (*Figure 18*). Their expandable house is made of a steel structure and lightweight materials, such as wood and polymers. When it is not used, it enters a storage state within a minimal volume (Marianthi and Kostas, 2017).

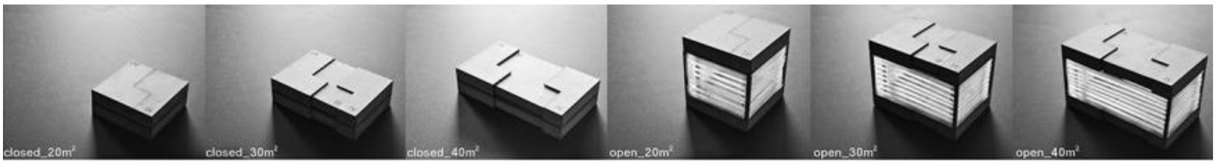


Figure 18: Different states of the sliding house 'Fill in your Form' (Marianthi and Kostas, 2017)

Folding

In conjunction with the sliding strategy, the folding (or deployable) strategy also manipulates the volume but with other techniques. Deployable structures can expand and contract due to their geometrical, material and mechanical properties. Deployable structures can be classified according to their structural system. Four main groups can be distinguished: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, tensegrity structures and membrane structures (De Temmerman, 2007). The minimum component of spatial bar structures is the scissor-like element. The scissor-like element consists of two bars connected to each other with a revolute joint, which is also used to obtain the structure in *Figure 19* (Friedman, 2011).

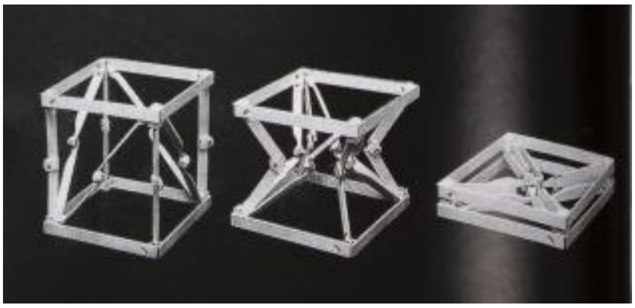


Figure 19: a deployable system containing scissor-like elements (N. Friedman, 2011)

Deployable structures used in housing projects are often to obtain temporary dwellings. More common structural applications are: hangars, tents, storage buildings or protective coverings.

Non-planned extension

A house has often to accommodate several households over its life span. Each household has its unique lifestyle and living habits. Typically, this process of relocation requires **adaptation** to fit the house to the needs of the new household. But even when a household stays in the same dwelling during their entire lives, the needs of the household change continuously. This needs causes the demand to modify the conventional house. Therefore, even in conventional housing, applying changes in the occupancy phase are common (A. Friedman 2002).

Non-planned extensions are **renovations** of a house. As the extensions are not planned, complications can occur more efficiently. The division of the interior spaces and the parcel of the house are not foreseen on extensions. Sometimes, a solution is to add an **ancillary expansion** instead of an adjacent extension. An ancillary expansion is a freestanding structure which belongs to a main building. This strategy is nowadays used when households need a carport or a shed (Archdaily, 2017). The major limit for ancillary extensions is the plot size. An advantage is that the ancillary expansion does not have to consider the structure of the initial dwelling.

The case of a conventional house expanded with non-planned extensions will be compared to expandable housing in Chapter 4 in the data development. This way the expandable housing strategies can be compared properly to each other and to the conventional house in terms of changing lifestyle, material efficiency and cost efficiency.

Consequences of expanding

Each expandable housing project should have the aim to design a house that can be extended without hampering the original dwellings' functioning or its coherence (Nakib, 2010). Therefore, when designing expansions, one should be aware of daylight distribution, natural ventilation, fluent circulation, etc. in any stage of the occupancy.

Firstly, expansions can cause implication in circulation routes. For a **fluent circulation**, short and logic routes are mandatory (AIA 2001). This applies to horizontal circulation as well as vertical circulation. When adding a vertical extension and new stairs are required, the designer needs to be aware that the placement of stairs have a large influence on the circulation on both connected floors. This is important when functions change. Often a stair is static. Therefore, the location of the stairs should be planned in advance (Friedman, 2002). In general, horizontal expansions have fewer complications, especially when it is at ground floor level (AIA 2001).

Secondly, expansions can cause a barrier for **daylight and natural ventilation** regarding the core (A. Friedman 2002). Therefore, the consequences of the expansions need to be taken into account from the initial design stage. This way designers can anticipate to such inconveniences. An example is shown in *Figure 20*, where the expansion is adjusted to obtain enough daylight in an office space.

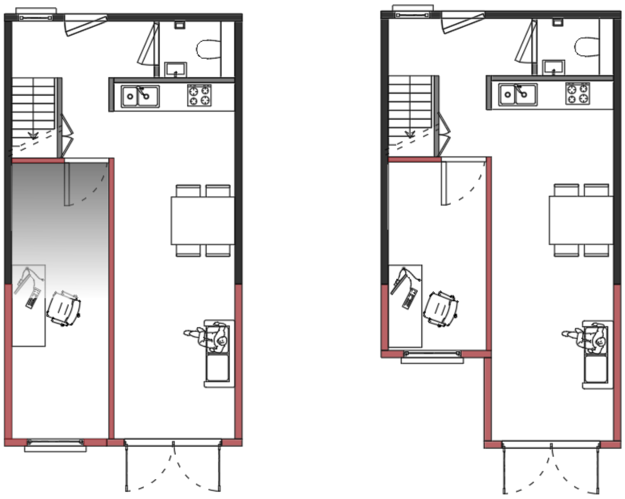


Figure 20: Example of daylighting issues when expanding

Furthermore, not only the internal inconveniences should be considered, but also the external inconveniences. When expanding vertically, one should consider the **view** of the environment when adding a large extension on top of the building. It should not hinder the sight of the neighbours (A. Friedman 2012). When expanding horizontally, the degree of horizontal expansion depends on the **lot size** and the zoning regulation (A. Friedman 2002).

Additionally, there are also consequences concerning **material efficiency**. When expanding, several building elements must be demolished or deconstructed and new building elements constructed or assembled. One of the aims of planning expansions in advance is to limit material waste. Limiting material waste is possible when using reusable building elements or components. The difference in material efficiency of the three expansion strategies and of the conventional house is further discussed in Chapter 3.

CHAPTER 3: EXPLORATIVE STRATEGY ASSESSMENT

DESIGNING FROM PLACE

The study of expandable housing is applied on the site **'*De Molens*'**, situated in Vilvoorde. The site is a brownfield and is part of a large urban renewal project along the canal, which is the extension of the harbour of Brussels. The master plan is developed by Xaveer De Geyter Architects (*Figure 21*). The relationship with the water is a key factor in the project. Space for living and working, but as well community infrastructure and public places are provided in the new district (Stad Vilvoorde, 2011).

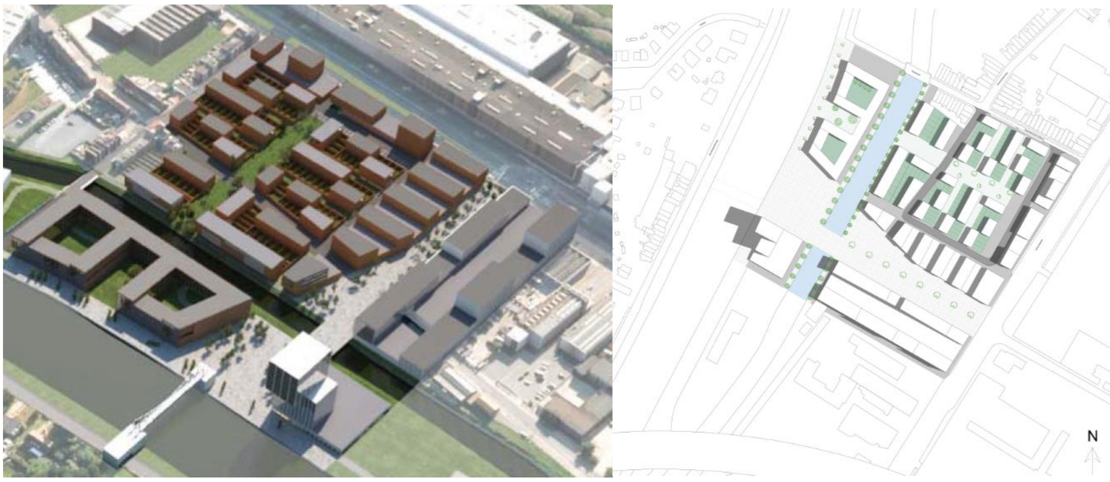


Figure 21: Master Plan of 'De Molens', developed by Xaveer De Geyter Architects (Stad Vilvoorde, 2011)

The site '*De Molens*' is selected for **several reasons**. The first reason is that, considering the Flemish policy on urban planning, brownfields should be used to expand the cities and to leave the remaining space open (Van den Bossche, 2012). Secondly, the demand for space increases continuously and future densification, mainly in and around cities, might be necessary (Van den Bossche, 2012). Thirdly, the Flemish government calls for stimulating pilot projects for common and innovative living (Homans, 2016).

At the same time, if it is known that the site will densify, it is tempting to build with a higher density in short-term. But, as districts evolve continually, there is a growing awareness of the long-term consequences of design choices. Therefore, the design has to **anticipate** on current and future uses (amount of inhabitants, use of spaces, newly composed families) and on the evolution of the neighbourhood (new zoning, transport networks, transformations of offices in dwellings). Therefore, and within the framework of the call of the Flemish government for "Experimental housing projects" and new forms of living (Homans, 2016), it is valuable for the site to be the context of the design of expandable houses that are expected to offer long-term gains.

ANTICIPATING FUTURE UNCERTAINTIES

The next step is to define which households will plausibly live on the site. Scenario planning is used to develop different plausible evolutions for a design. This way the adaptability of the design alternatives is tested through several scenario alternatives.

Before discussing different household scenarios, it may be helpful to present some trends in the household changes in Flanders. The results of the household projections should consider assumptions on the long-term population evolution and population structure. Pronging household changes makes it possible to prepare for future housing demands (Alders and Manting, 1999).

The main **household type** in Flanders is the *Single-person household*. They represent 31,8% of all households today. A large proportion of young people at ages between 20 and 30 tend to live alone for some time. Other examples are divorced persons or elderly persons that are living alone. *Couples with children* and *Couples* (without children) are the second and third main typologies of household types. Those three types together represent 90,3% of all households (*Figure 22*). The proportion of persons living as a *Couple* generally increases rapidly between the ages of 20 and 30. At later ages, between 50 and 70 years, the proportion of persons living with a partner declines relatively slowly, followed by a more rapid decline after about age 70 (VMSW ,2016). The other household types include for example collective households.

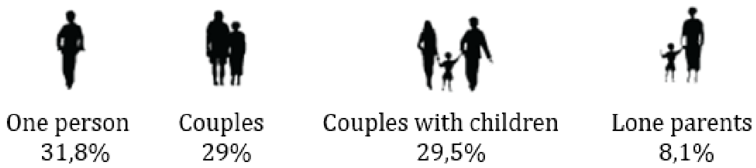


Figure 22: Amount of household types in Flanders in 2016 (VMSW, 2016)

Because current demographic situation has a distinct link with that of the next generation future, it is possible to project the household type percentages. VMSW did this prognosis for the year 2060. The S*ingle-person household* group will have grown and represent 49,7% of the households. In contrast, the *Couples* typology will reduce to only 8,4%. The percentage of the other two household typologies, *Couples with children* and *Lone parents*, remains similar to the current situation (VMSW, 2016) (*Figure 23*). Due to this dilution of households, an increase of 20,6% of the amount of households in Belgium will occur in the coming 45 years (FOD Economie, 2016).

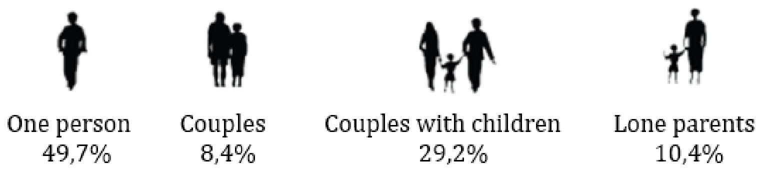


Figure 23: Estimation of the amount of household types in Flanders in 2060 (VMSW 2016)

From demographic data, other useful information can be retrieved. It is apparent that population is continuously ageing and that diversification is increasing in society (VMSW, 2016).

Decision making is assumed to be based on data and analysis. Even though demographic studies rely on large surveys, the obtained figures are never definite. They can be used as an indicator for the future. To complement this data, especially concerning lifestyle changes discussed in the problem statement, **scenario planning** is used to develop plausible evolutions (*Figure 24*).

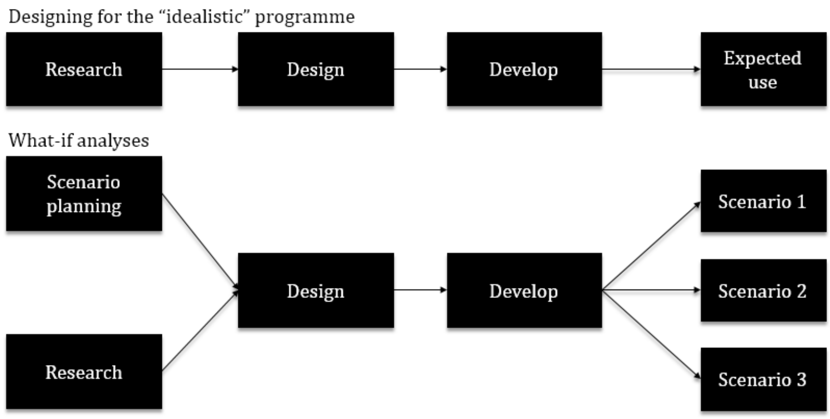


Figure 24: Difference between conventional planning and scenario planning

In this master thesis, scenario planning is used to demonstrate that the designed alternative houses can **endure time**. This is realized by the potential the building has to adapt to each alternative scenario (Galle, 2016). In the case of expandable houses, future **expansions can be anticipated** through scenario planning to discover what the benefits of expandable buildings are in terms of changing lifestyles.

While creating scenarios, it is useful to establish boundary conditions. The main boundary condition is the time horizon. In this thesis, the time horizon is set on a building life time of 60 years. Expansions occur at building years 15, 30 and/or 45. This time horizon is further explained in the section 'Life cycle cost'.

Definite and indefinite elements

To become relevant scenarios, a specific set of predetermined elements and a set of uncertainties must be identified. By including uncertainties, scenario planning considers the uncertainty about the future. Although it was not possible to do so in the context of this thesis, the relevant uncertainties should be developed and discussed with stakeholders and future users. In this research, the uncertainties are relied on literature and previous studies. The downside is that scenarios provide little insight in the aspects that were not set as variables (Galle, 2016).

Scenario planning aims to define predetermined elements and uncertainties of a project. **Predetermined elements** change slowly, for example changes in demography. Demographic data is based on collected survey data. From those observations, reliable projections can be made about the populations near future. These projections are for example the population's continued ageing, the declining family sizes and the growing diversification (Galle, 2016).

Uncertainties relate to non-deterministic evolutions. Especially individual choices are subjected to them. Therefore, uncertainties focus on identification of drivers and trends rather than data (Galle, 2016). It is a complex coherency of different personal experiences, economic circumstances and trends that depend the individual's housing ideal. Moreover, this complex coherency drives people to change their lifestyle. Changes in, for example, partnership and parenthood result in diverse housing needs (A. Friedman 2002).

Predetermined elements in the context of the site '*De Molens*' are:

- Population is continuously ageing (VMSW, 2016)
- Expensive land for building (FOD Economie, 2014)

- Individualization (VMSW 2016)
- An increasingly diverse society (VMSW, 2016)
- A constant demand for affordable housing (Belgian Federal Government 2016)

Uncertainties are in the context of the site '*De Molens*' are:

- Requirements of users
- Speed of change
- Extent of change
- User behavior

Driving forces of change

The driving forces for developing scenarios in the case of expandable houses are mainly **social drivers**, for example: household types, dwelling types and requirements people set. **Economic drivers** are also a significant factor. Examples of economic drivers are life cycle costs of the project, location of the plot or comparing the building with other alternatives. The social drivers are fixed and the economic drivers are the variable. People's requirements and the extent of change are dependent on the economic driver. In the scenario matrix, the household type is fixed and the changing lifestyles depend on the economic driver. (*Figure 25*)

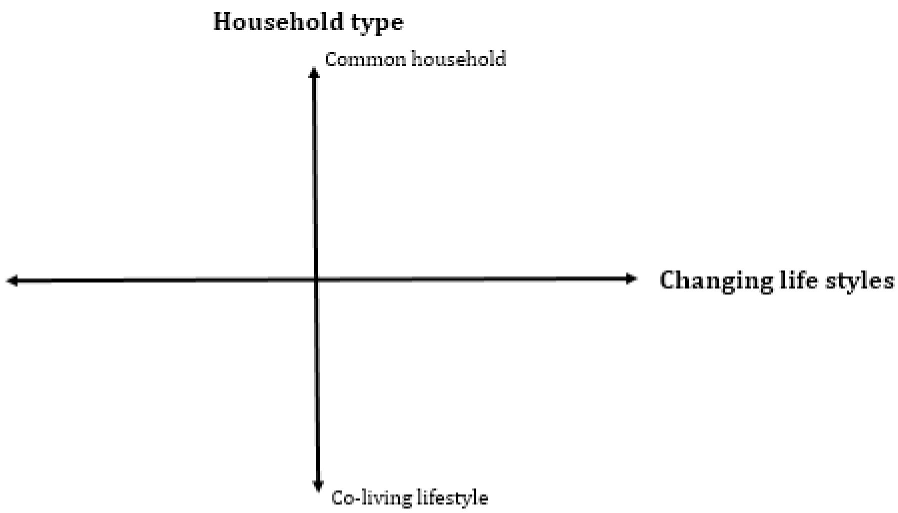


Figure 25: Scenario Matrix

HOUSEHOLD TYPE

Household types are classified according to the number of family nuclei they contain and the relationship, if any, between the family nuclei and the other members of the household (United Nations, 2017).

The **types of household** that can be distinguished are:

- one–person household
- nuclear household (couple family or single-parent family with or without children)
- extended household (household consisted of relatives);
- composite household (household composed of non-relatives with or without relatives)
- other

The demographical data shows that the *One-person* and *Nuclear households* are the main household types. Beside those two dominating household types, the *Extended households* and *Composite households* are becoming increasingly important (VMSW, 2016).

STRESS TESTING THE ALTERNATIVE DESIGN STRATEGIES

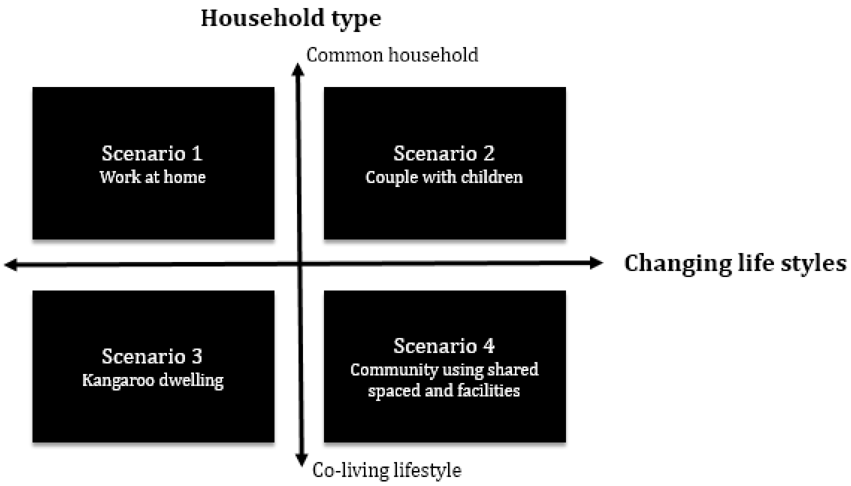


Figure 26: Scenario matrix

Now the demographic data, uncertainties and key drivers are identified, scenarios can be developed (*Figure 26*). In every scenario, the first phase is the '*One person*' household, since this is the smallest form of a household that can occur. It is a limit of the household size. Furthermore, the main household type is single-person households, as derived from the demographic data (VMSW, 2016). At the same time the scenario can start at every phase, as different starting points are needed in the site's development. For example, a family with three children can come in in an expanded house.

Scenario 1: Work at home

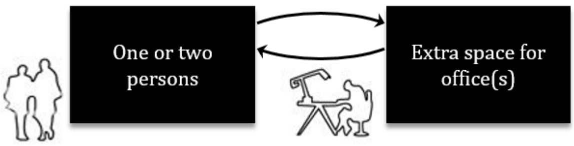


Figure 27: Work at home scenario

The 'Work at home' scenario does not imply changes of the household type or size, but the household demands extra space. The uncertainty in this scenario is thus the requirements of the occupants. In a design view, the 'Work at home' scenario implies at least an extra, secluded room that serves as an office.

Scenario 2: Couple with children

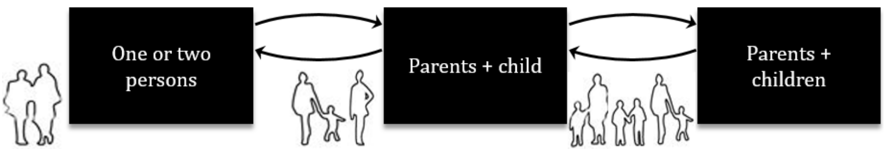


Figure 28: Couple with children scenario

The most probable scenario in Flanders is still the **"common" household development**. This indicates that in the initial phase, a single person lives alone. Later, he or she finds a partner and subsequently the family grows. After the children have grown up (*Figure 29*), they leave the house and the couple remains (De Zilveren Sleutel, 2016). Most parents (82% in Flanders in 2014) have one or two children. Only 4% have more than three children (Peters, Van Den Driesschie and Bauwens, 2014). To evolve from 'One person' towards 'Parents + children', additional rooms need to be created and more space need to be made for living so that the dwelling can support this larger household. The uncertainty considered in this scenario is the extent of change. The expansions are made according to the number of persons that join the household.

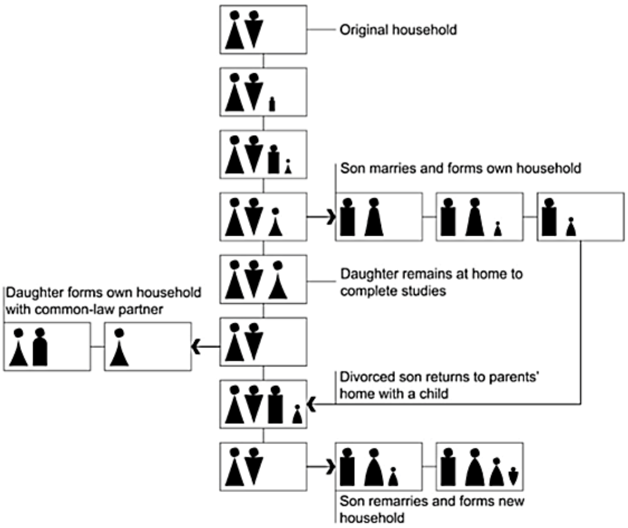


Figure 29: Example of an evolution of a "common" household (A. Friedman 2002)

Scenario 3: Kangaroo dwelling

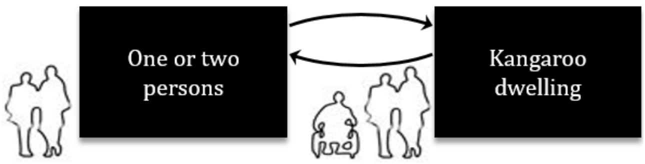


Figure 30: Kangaroo dwelling scenario

The population is continuously ageing (VMSW, 2016). This **ageing population** compels to seek housing solutions outside amenities, such as nursing homes. The Flemish policy on housing and care strives to **more independent living at home**. Meanwhile the search for affordable housing, as for young people, is becoming increasingly difficult (De Zilveren Sleutel, 2016). All this ensures that we should find alternative solutions to fulfil our needs.

A possible solution is creating **kangaroo dwellings**. In this concept, older people, who would otherwise live alone or in a nursing home, live together with their children or other relatives (*Figure 31*). This is an example of nuclear household transforming into an extended household. Of course, with the change of the household type also the requirements change (uncertainty), affecting the preferred number of spaces, the size of the rooms, the level of privacy etc. (Galle, 2016).

The Flemish government set up regulations on kangaroo dwellings. The dwelling unit of the older person is subordinated to the main dwelling and should have smaller volume than the main dwelling (Ruimte Vlaanderen, 2017). When the older person moves out, it is conceivable that the extra space will be reused for other purposes, such as housing for multiple families. However, in this thesis it is assumed that the expansion will be removed again.

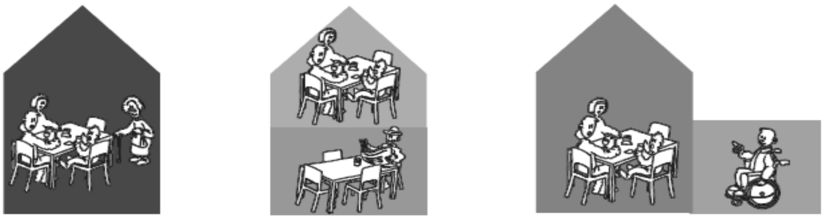


Figure 31: Kangaroo dwellings, 'Kangoeroewonen, een woonconcept voor nu en later, voor jong en oud' (De Zilveren Sleutel, 2016)

Scenario 4: Co-housing

Figure 32: Co-housing scenario

Co-housing is a type of residential projects where several housing units are joined and where private units are combined with common functions (Vlaamse overheid, 2017). The residents are jointly in charge of the management of the project. Therefore;, it is recommended that the architecture of a co-housing project should offer an increased opportunity for social interaction (YM, 2013). At least the space where families can eat together is shared. The kitchens, dining rooms or other common areas can, in some cases, also be accessible for non-residents (Vlaamse overheid, 2017). Considering co-housing as one of the four scenarios in the financial life cycle assessments could be a way to identify more precisely some strengths and weaknesses of this household type.

DATA DEVELOPMENT

Previously, three design strategies for expandable houses are defined and four different scenario narratives are outlined. The next step is to apply these design strategies and scenarios in a design. Ultimately, it is intended to test which design is the most beneficial in terms of cost efficiency and material efficiency.

Three methods are used to develop data: research by design, life cycle cost analysis and material efficiency.

Research by design

Research by design is used to fine-tune the problem formulation and project definition. It is an instrument to explore and test expandable houses in different contexts. The focus lays on floor plans, to have an overview of environment, context and design strategies. Research by design is not an abstract knowledge but a method used to envision how we want to live in the future. The research by design focuses on the different developed scenarios, to be able to discuss them the obtained floor plans.

As discussed in chapter 2 in the section 'Design strategies for expandable houses', the first expandable house consists of a compact core in its initial phase. The second expandable house project consists of volumetric modules and the third expandable house starts from an over-dimensioned outer shell (*Figure 33*).

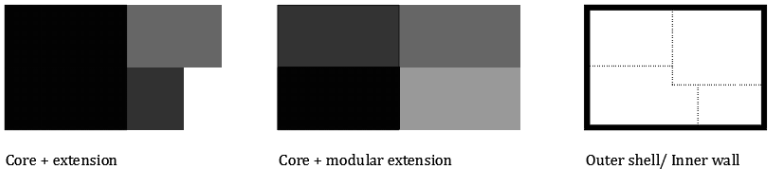


Figure 33: Design strategies for expandable houses

The first and the second core will be expanded with add-on extensions and the third one with add-in extensions.

The purpose is to compare the different expandable houses in terms of floor plans, material efficiency and cost efficiency. To become a dignified comparison, it is required to compare the designed expandable houses with **conventional housing** (*Figure 34*). To do so, conventional housing must be defined and characterized. Another study, made by Van der Veken, Creylman and Lenaert, *kenniscentrum Energie*, 2015, defined reference dwellings which are considered representative for the Flemish housing stock. These dwellings will be used as conventional housing in this master thesis.

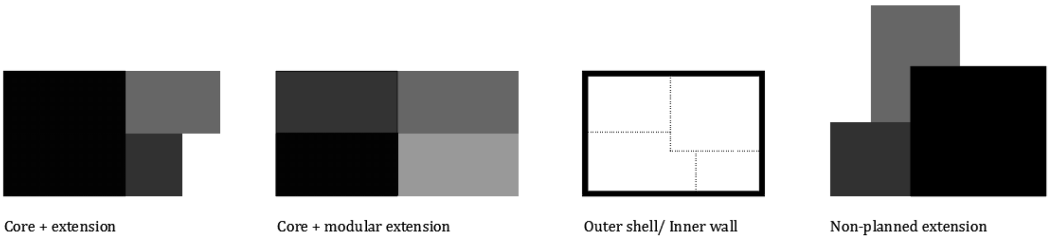


Figure 34: Conventional house and expandable house concepts

Furthermore, the different scenarios are applied on the expansions of each so that the expansions can be tested on their reliability (*Figure 35*).

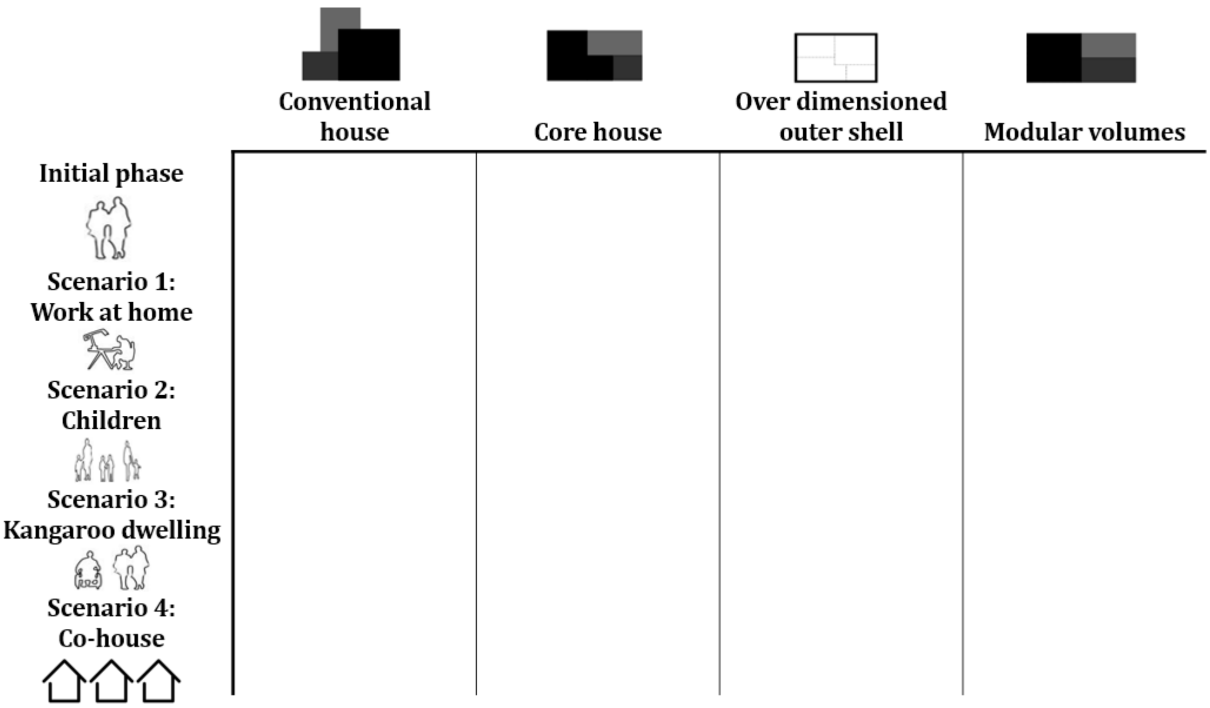


Figure 35: Scheme of the four scenarios applied to the different design strategies for expandable housing

In the housing stock, there is wide range of **housing types**, ranging from large houses to quasi dorm formulas with little more than an individual bedroom. The research continues with the housing type **'row house'** because of its available data and its representativeness in Flanders (Van der Veken, Creylman, and Lenaerts, 2015).

First, the conventional house and its expansions are tested by applying the different scenarios to it. Second, the design strategy 'Core +extensions' is applied to a row house typology. For the design strategies 'Core + modular extensions' and 'Inner wall/ Outer shell' the initial phase is worked out. In the framework of the temporal length of the master thesis, it was not possible to work them out in detail. After all, the aim is to have a comparison between the expandable house and the conventional house.

CONVENTIONAL HOUSE

The conventional row house is fictional and designed so the parameters correspond to average values in the real Flemish housing stock.[3] The compiled row house consists of three floors. It has four bedrooms and two bathrooms (*Figure 36*). The supporting structure consists of bearing walls, made up of concrete blocks. The floors consist of concrete slab floors. The façade material is brickwork. The roof is a pitched roof covered with roof tiles. The maximum number of persons living in the house is 6.

Hereunder a table with the properties of the conventional house is given (*Table 1*: Properties of the conventional house (Van der Veken, Creylman, and Lenaerts, 2015) . These properties apply to the original stage of the house, but also to all expanded stages. Only the floor area changes.

Table 1: Properties of the conventional house (Van der Veken, Creylman, and Lenaerts, 2015)

Properties conventional house	
Floor area	175,58 m^2
Compactness[4]	2,20 m
U-value outside walls	0,24 W/m^2K
U-value windows	1,5 W/m^2K U_g = 1,1 W/m^2K
U-value wall in between two dwellings	1,0 W/m^2K
K-peil	K40 (thermal insulation)
E-peil	E50 (energy performance)

[3] U-values of 2016, Flanders and EPB requirements since 01/03/2017, Flanders

[4] Compactness = Volume of the house / floor area. To limit the amount of material used, the building should have a compact design with rational forms.

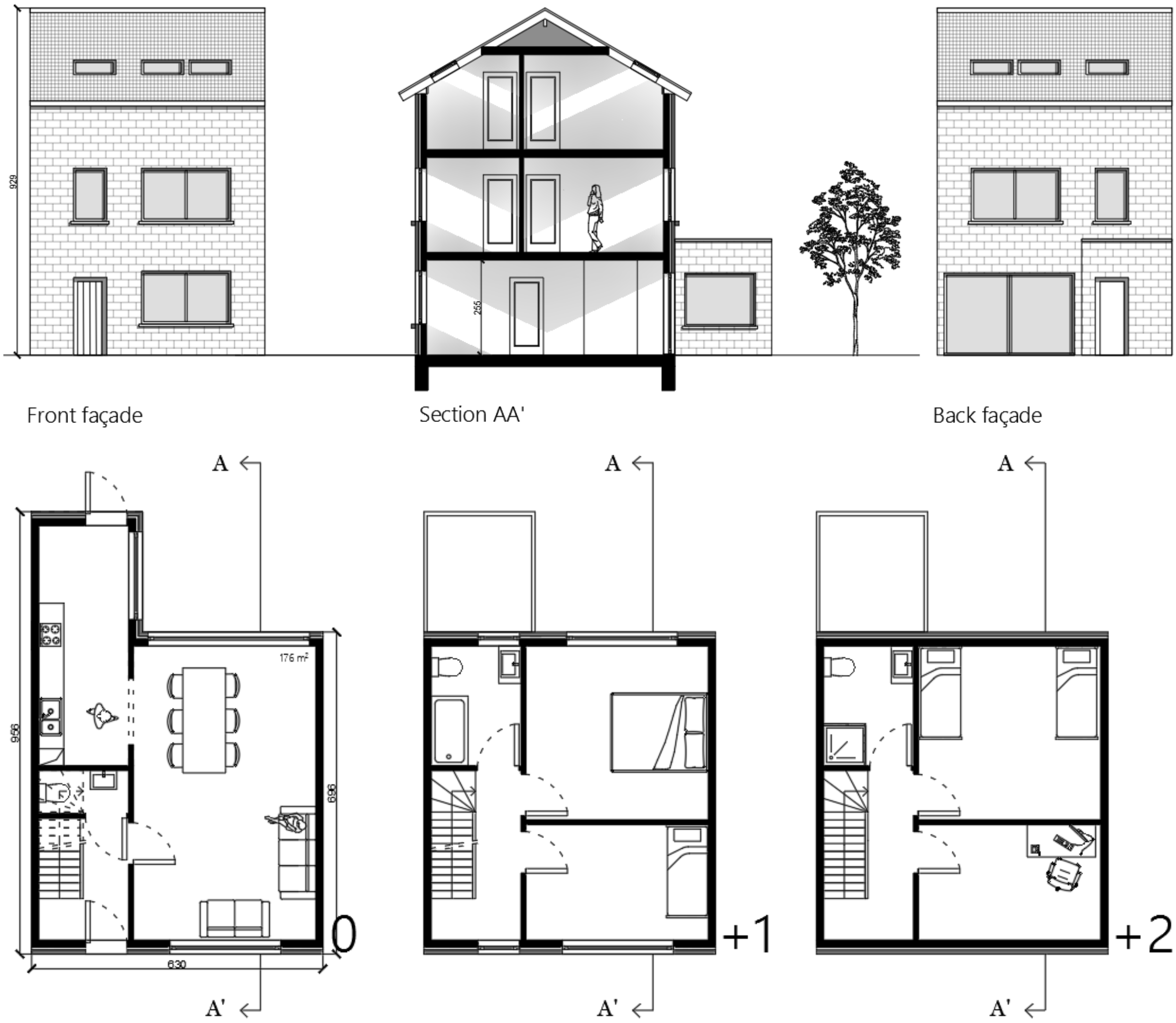


Figure 36: Floor plans, façades and section of the conventional house in original stage

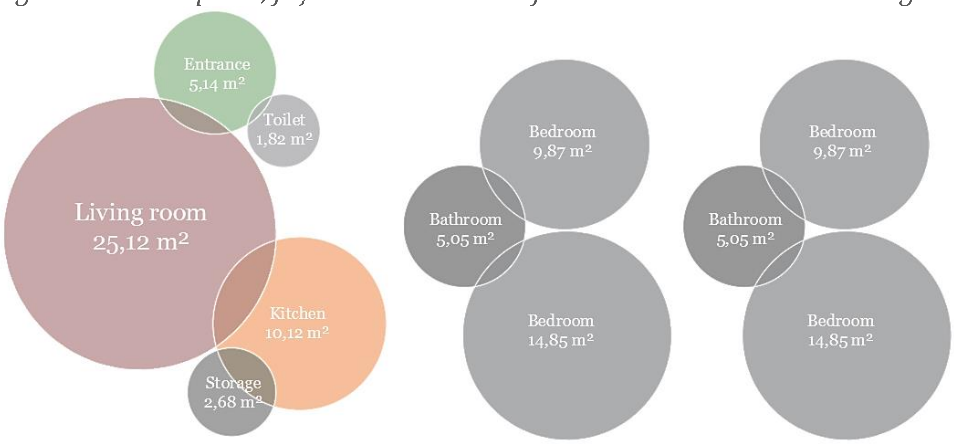


Figure 37: Different functions and corresponding floor areas of the original conventional house

<u>SCENARIO ALTERNATIVE 1: WORK AT HOME</u>

To be able to work quietly, to welcome clients or colleagues, the office is placed at the front of the house, on the ground floor. Preferably separated from the private part of the house, so connected to the corridor of the entrance door. If possible, on the north side to not have direct sun light entering. Because the office takes in some space at the ground floor, extra space is added in the living room of the house. The extensions add 10 m^2 to the original ground floor.

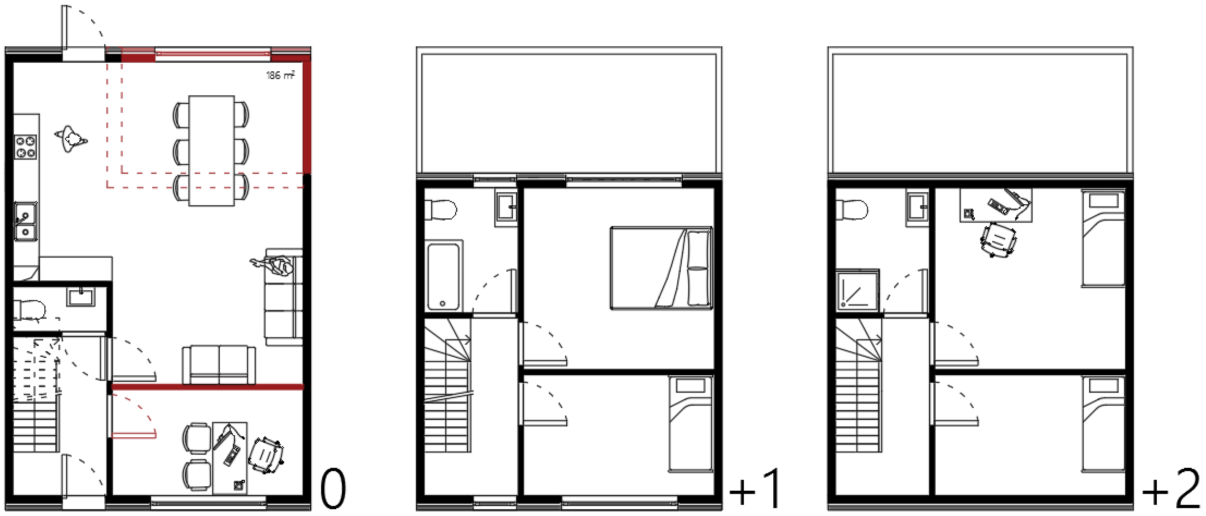


Figure 38: Floor plans of the 'Work at home' conventionale house

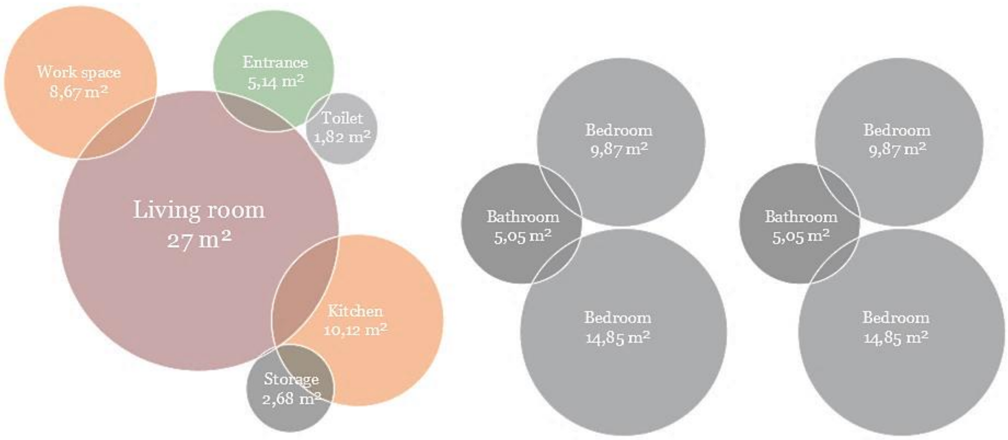


Figure 39: Different functions and corresponding floor areas of the 'Work at home' conventional house

<u>Scenario alternative 2: Children</u>

The conventional house is designed for an "average" family with children, as described in the scenario 'Children'. Therefore, no changes need to be done to the conventional house in order to obtain a house that fits the needs of a family with children. It contains enough bedrooms and enough space.

<u>Scenario alternative 3: Kangaroo dwelling</u>

Because a lift is technically and financially unjustifiable, the dwelling for the older or the disabled person is located on the ground floor. This way less mobile residents can relate on a private space in the kangaroo dwelling. All spaces on the ground floor are wheelchair accessible. It is preferred that the entrance of the dwelling on the ground floor is near the front door, so that privacy can be obtained for all occupants. Therefore, no functions for the family are placed on the ground floor. The toilet has transformed in a bathroom and the new kitchens are placed so that all wet functions are clustered. To realize enough space for the unit on the ground floor, an extension is added.

Hence, a bedroom is added on the ground floor. This is a bedroom for one person. The area of extension is the same as for the 'Work at home' scenario, which is 10m².

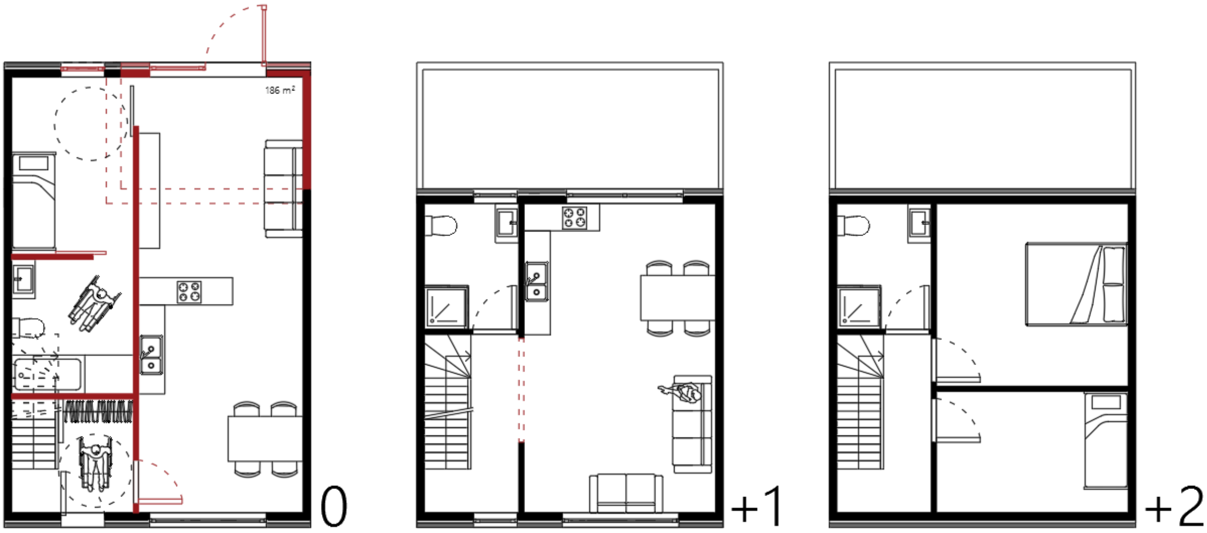


Figure 40: Floor plans of the 'Kangaroo dwelling' conventional house

Figure 41: Different functions and corresponding floor areas of the 'Kangaroo dwelling' conventional house

<u>SCENARIO ALTERNATIVE 4: CO-HOUSE</u>

The co-house is an assembly of five row houses. Three of them are merged and the other two are a kangaroo dwelling and a conventional house. On the ground floor in the middle, the shared community part is located. This space contains a large kitchen with a bar, a dining room, a living room, a workshop, a laundry room, storage and toilets. At the end, the co-house is meant for the same number of persons as 5 row houses together, which is maximum of 16 persons. Above the central part, studios are placed, which have a small bathroom and kitchen and a bedroom/ living room. The three gardens are put together, so a large garden occurs where there is room for bike storage and trash storage.

The concept of a co-house in this case is not where the occupants sleep in dorms, but where they each have their own dwelling unit. This is because the starting point is already existing row houses. The row houses transform because of function change, but the transformation is accomplished it with as less changes needed as possible. It is still reaching the intention of the new function and comfortable dimension requirements set by VMSW.

Figure 42: Floor plans of the 'Co-housing' conventional house

Figure 43: Different functions and corresponding floor areas of the 'Co-housing' reference house

CORE + EXTENSION

As cost efficiency is one of the objectives of this master thesis, to be able to provide an economic beneficial option for potential buyers, the core house is made as compact as possible. To maintain a comfortable home, **the minimum areas** for dwellings of the VMSW (Flemish Society for Social Housing) are used as guidance (VMSW, 2014).

Hence, the design of the core house **is based on three givens**. The first given is the site '*De Molens*', which is the location of the design. The expandable house is located in a neighbourhood with multiple terraced houses and in a green environment. Secondly it is based on the conventional conventional row house. This is significant for the expandable house to be comparable with the conventional house. Thirdly, the minimum floor areas determined by VMSW, to be sure to obtain a comfortable dwelling at any time.

The core house has an entrance with a toilet, a living room and a kitchenette on the ground floor. The living space is smaller than the minimum floor area of the VMSW. Still, it fulfils the legal norms. To compensate the compact feeling, the backside is opened towards the garden. On the first floor, there is a bedroom, a bathroom and storage space.

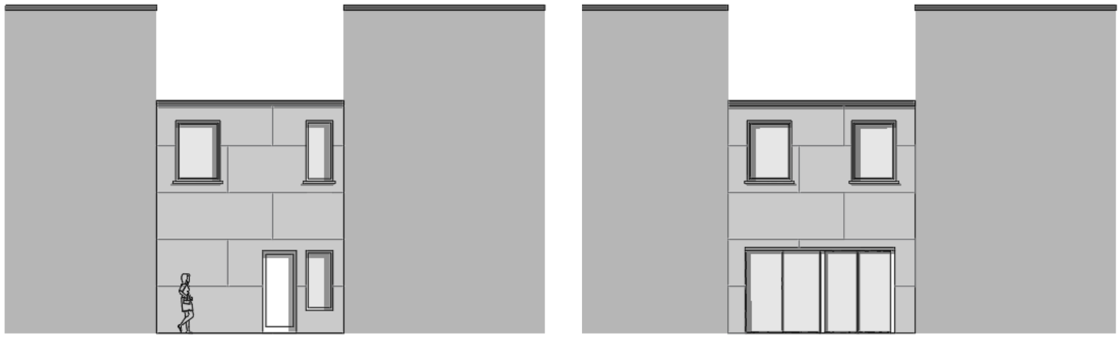


Figure 44: Front and back façade of the core house

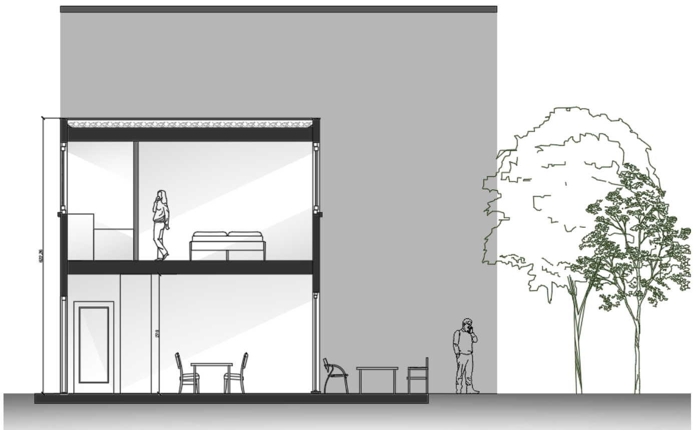


Figure 45: Section AA' of the core house

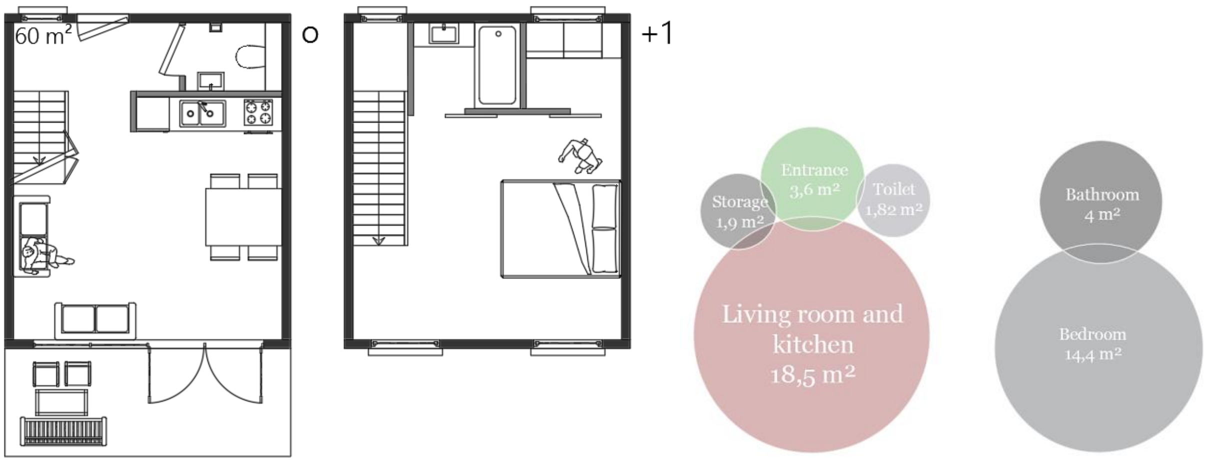


Figure 46: Floor plans and corresponding floor areas of the core house

<u>SCENARIO ALTERNATIVE 1: WORK AT HOME</u>

In the 'Work at home' scenario, an extra space is added to include an office. It is extended with similar demands as in the conventional house, e.g. at the ground floor, near the front door. Because the office takes in some space at the ground floor, the living area must be expanded too. In this context, it was not possible to expand towards the left or right sides, which results a living room with a larger length. Still, it is opened towards the garden. If desired, the living room can be closed off by placing a door in between the corridor and the living room.

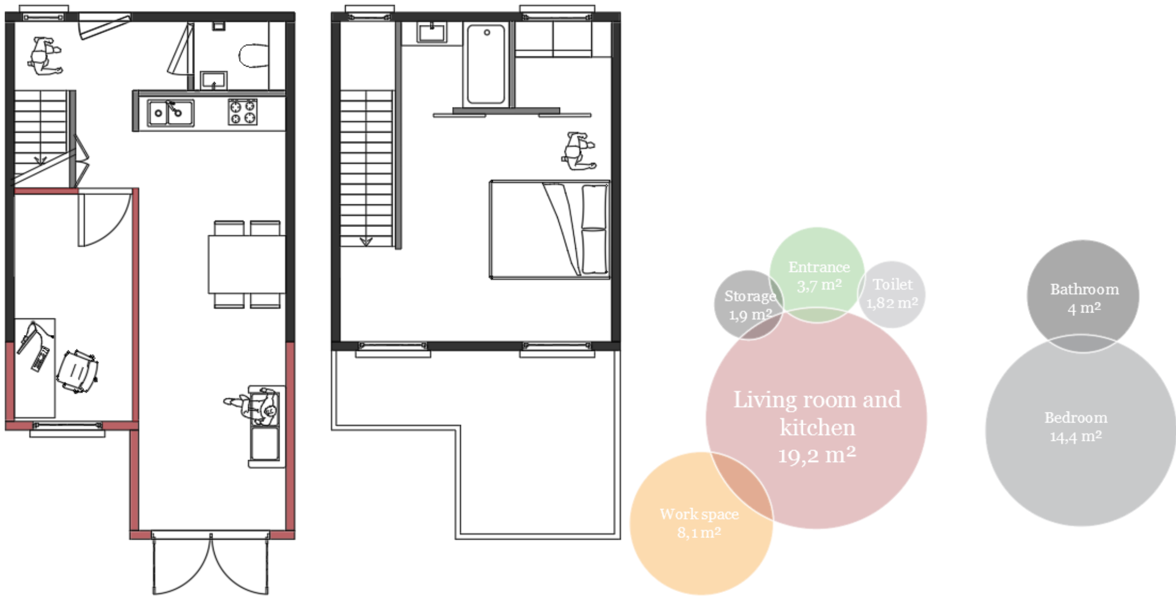


Figure 47: Floor plans and corresponding floor areas of the expandable house in the 'Work at home' scenario

<u>SCENARIO ALTERNATIVE 2: CHILDREN</u>

In the scenario alternative 'Children', two expansions are set out. The first expansion is for when the family grows and have one child, the second expansion is for when the family grows even more, with a maximum of four children.

In the first expansion, expansions are realised at the back of the house because it is enclosed at the left and the right side. The kitchen and the living rooms expand. Furthermore, one bedroom is added on the first level.

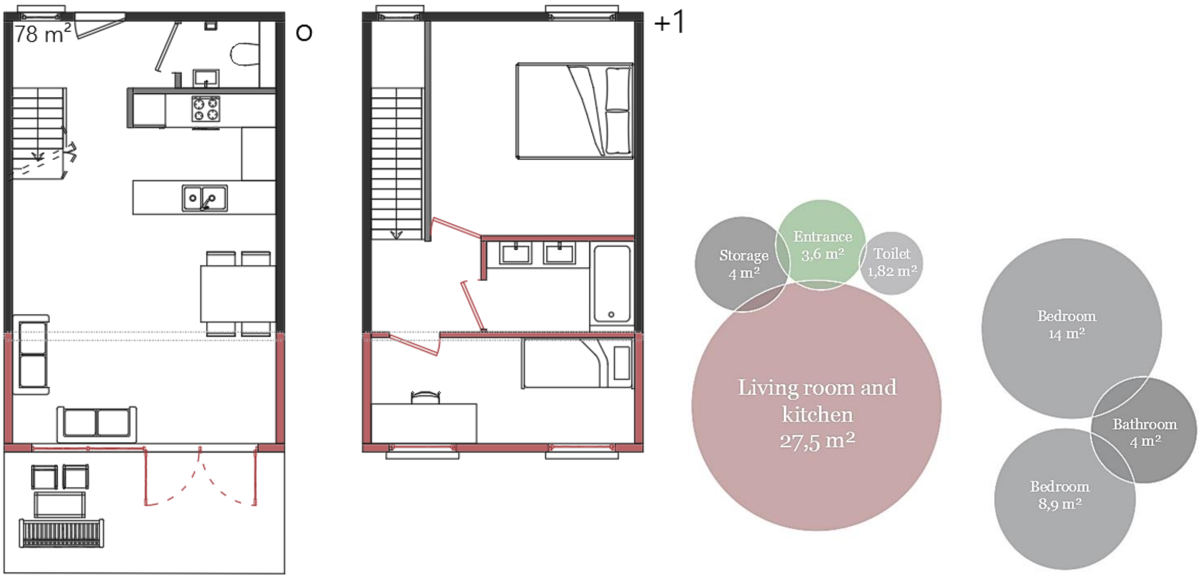


Figure 48: Floor plans and corresponding floor areas of the expandable house in the 'Children' scenario

In the second expansion, a new level is added on top. In the section 'Material efficiency', it is demonstrated that expanding with lightweight materials has an advantage to make it possible to add a new level. The foundations and the bearing structure should be dimensioned to be able to bear the new level. In this new level, 2 bedrooms and one bathroom are added.

Figure 49: Floor plans and corresponding floor areas of the expandable house in the 'Children (2)' scenario

<u>SCENARIO ALTERNATIVE 3: KANGAROO DWELLING</u>

Because a lift is technically and financially unjustifiable, the dwelling for the older or the disabled person is located on the ground floor. This way less mobile residents can relate on a private space in the kangaroo dwelling. All spaces on the ground floor are wheelchair accessible. It is preferred that the entrance of the dwelling on the ground floor is near the front door, so that privacy can be obtained for all occupants. To realise enough space for the unit on the ground floor, an extension is added at the backside of the dwelling. Hence, a bedroom and a bathroom are added on the ground floor. On the first floor, the same area of extension is added. This area contains a new living area and a kitchen. A balcony is provided for the occupants to have an outdoor private space.

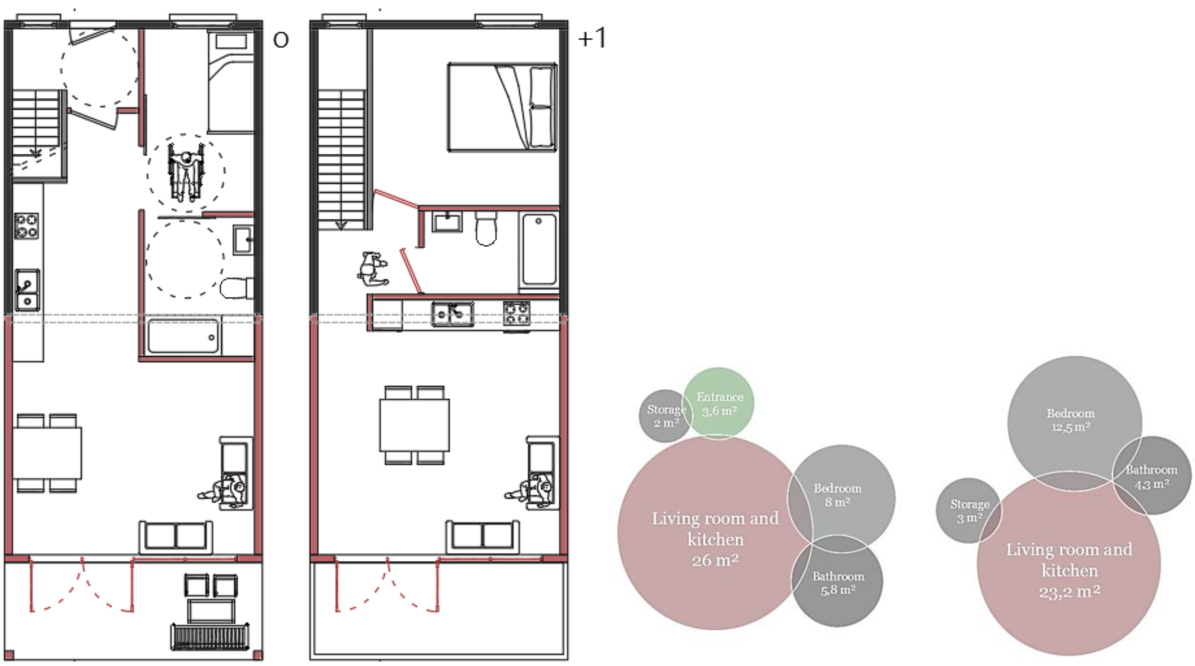
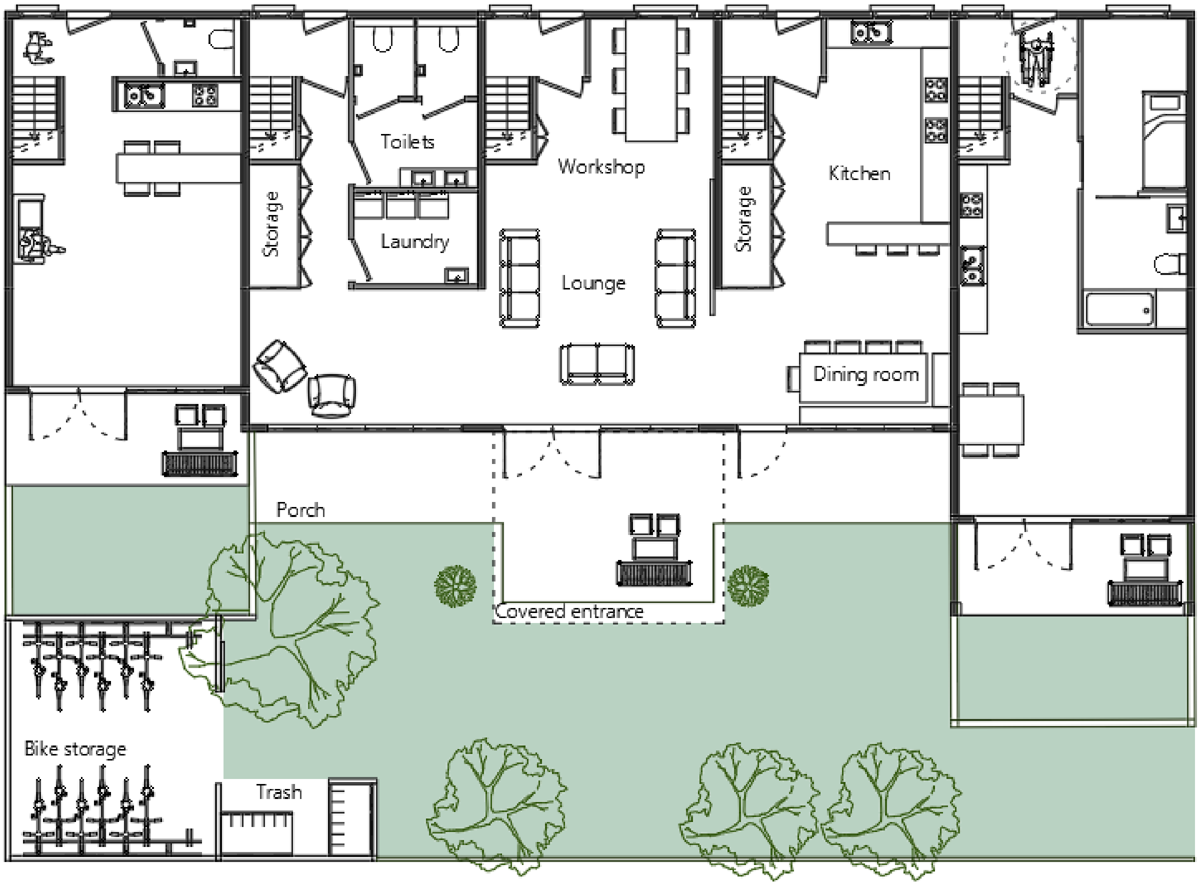


Figure 50: Floor plans and corresponding floor areas of the expandable house in the 'Kangaroo dwelling' scenario

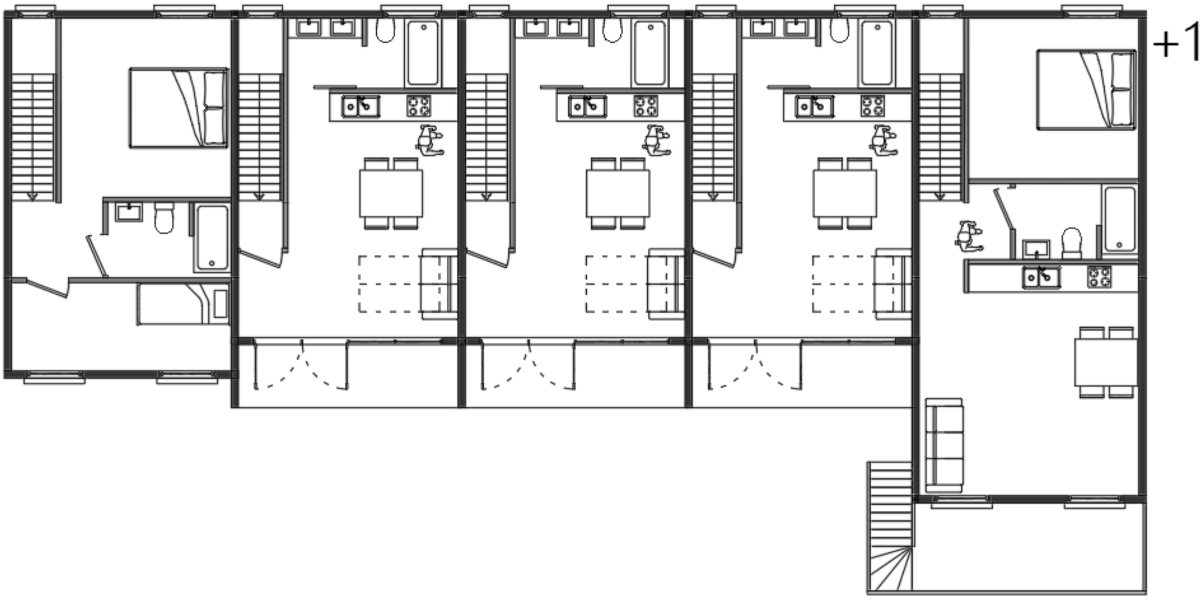
<u>Scenario alternative 4: Co-house</u>

The co-house is an assembly of five row houses. Three of them are assembled and the other two are a kangaroo dwelling and a 'Children' dwelling. On the ground floor, in the middle, the shared community spaces are located. These spaces contain a large kitchen with a bar, a dining room, a living room, a workshop, a laundry room, storage and toilets. At the end, the co-house is meant for the same number of persons as 5 row houses together, which is maximum 12 persons. Above the central part, studios are placed which have a small bathroom and kitchen and a bedroom/ living room. The three gardens are merged together, so a large garden occurs where there is room for bike storage and trash storage.

The concept of a co-house in this case is not where the occupants sleep in dorms, but where they each have their own dwelling unit. This is because the starting point is five existing row houses. The row houses transform because of function change, but the transformation is accomplished it with as less changes needed as possible. It is still reaching the intention of the new function and comfortable dimension requirements set by VMSW.



Toilets
Workshop
Kitchen
Storage
Laundry
Storage
Lounge
Dining room
Porch
Covered entrance
Bike storage
Trash



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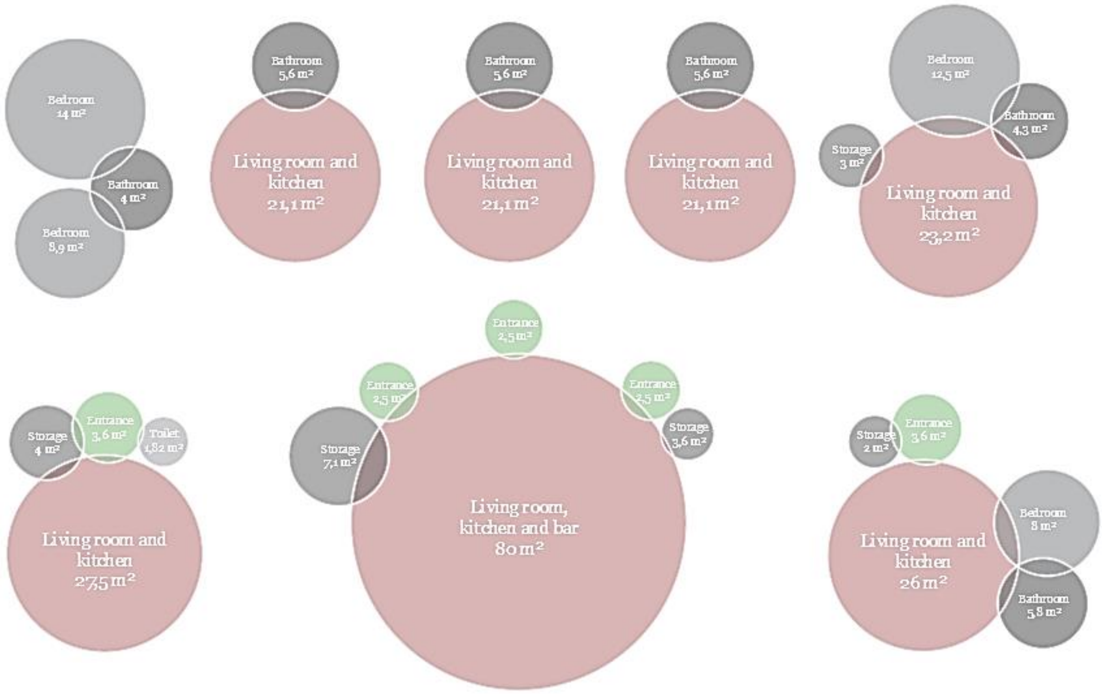


CORE + MODULAR EXTENSION

For the design strategy containing modular volumes, different base modules are drawn. As in the 'Core + extensions' design strategy, the minimal dimensions of VMSW are used as a guideline. It is the intention to build up different alternatives by combining several modules. For example, in Figure 51, a core house is made of a combination of such modules.

Figure 51: Floor plans of four base modular volumes and a core house resulting from a combination of such modules

INNER WALL/OUTER SHELL

In the design strategy 'Inner wall/ outer shell', it is not about starting from a compact core house. On the contrary, in the initial phase the house consists of three building levels. The outer shell has this form because it follows the form of the largest volume of the design strategy 'Core +

extension'. As can be seen in Figure 52, the inside of the house is empty compared to the previous floor plans. It is the intention to divide the internal space in different compartments according to the needs of the occupants in a later stage.

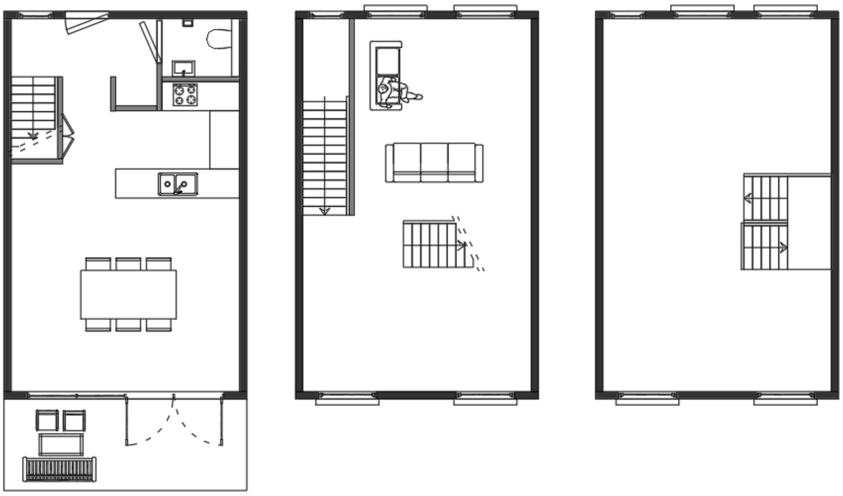


Figure 52: Floor plans of the initial phase of the 'Inner wall/ outer shell' design strategy.

Material efficiency

Material efficiency is significant in terms of environmental awareness. Material production is energy intensive. Therefore, in first place, **reducing the demand for material** would lead to reducing extraction of natural resources, reduced energy demand and other environmental harms (Allwood et al., 2013). Secondly, prolonging the **building's lifespan** diminishes resource consumption and thus also the aggravation of environment pollution. Thirdly, reusing or recycling building elements is promoted to reduce the waste of materials. A strategy to recycle and re-use more is to build with modular construction elements and with dry connection methods (Allwood et al., 2011). The aim is to work with a circular cradle-to-cradle approach and set up closed-loop service life models (*Figure 53*) (Galle, 2016).

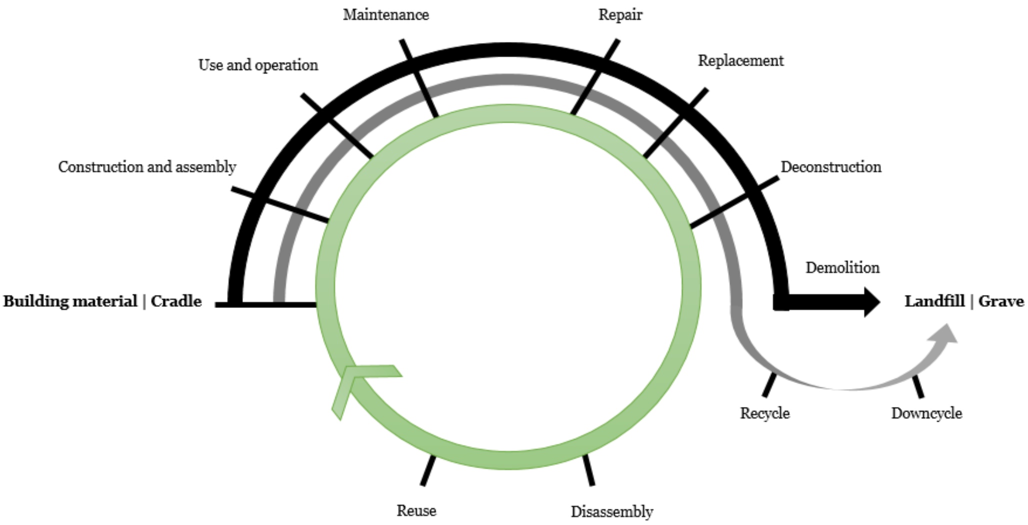


Figure 53: Graphical representation of the phases a building undergoes and the difference between cradle-to-grave approach and cradle-to-cradle approach

The objective is to ascertain if the concept of **expandable houses** is more material efficient than conventional houses. The **measurements** are imported from the plans of the research by design part into a Microsoft Excel spreadsheet. All building elements are measured for each scenario. First, the elements that are present in the original phase are measured. Secondly, for each scenario alternative, it is measured which building elements are demolished or deconstructed and which building elements are added to achieve the corresponding extension.

To investigate the full-scale environmental impact is beyond the scope of the thesis. On the other hand, material efficiency can be used as an indicator as it is an important segment of the total environmental impact.

Indicators of material efficiency are:

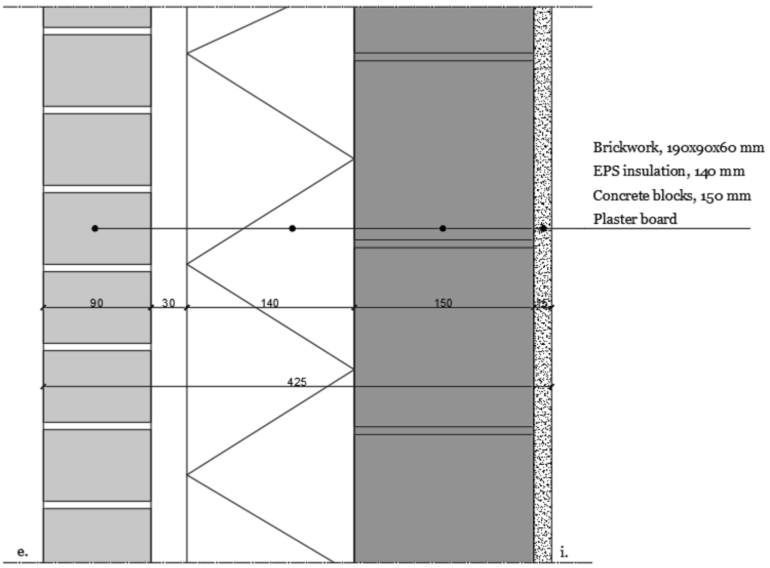
1. Estimated service life of materials or building elements
2. Total materials used (m^3/ton)
3. Recycling per total generated waste (%)
4. Total of materials that can be re-used

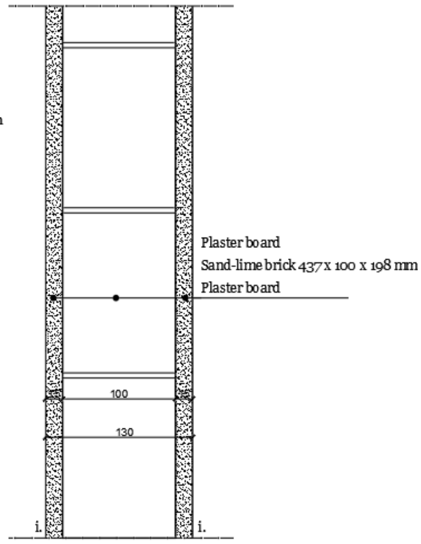
COMPOSITION OF BUILDING ELEMENTS

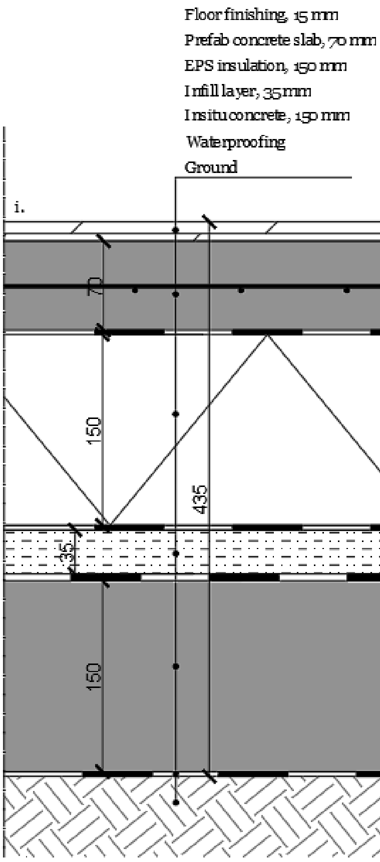
The basic unit is the **building element**. The considered building elements are: a floor at ground level, a suspended floor, a roof, an exterior wall, and a partitioning wall (Figures). For each building element a plausible detailing is elaborated. For each element, a conventional and a demountable detail is developed. The design of the demountable building elements is elaborated with reference to the article 'Using Life Cycle Assessment to Inform Decision-Making for Sustainable Buildings' by Vandebroucke, Galle, De Temmerman, Debacker and Paduart. The conventional building elements are developed based on the information of the study of Van der Veken, Creylman and Lenaert, where the conventional house is defined. Not every material is considered, as this will be too detailed for the scope of the master thesis. The main materials will evidence the material efficiency.

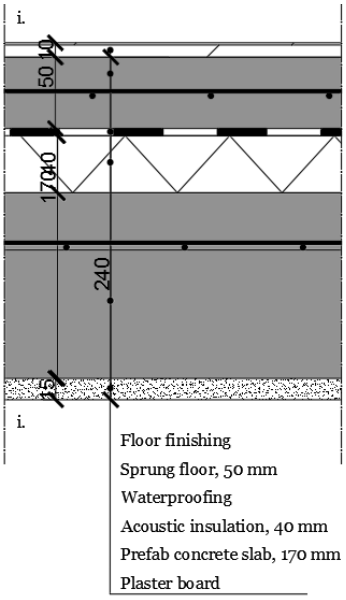
The main difference between the conventional and the alternative construction assemblies is the **jointing method**. Mortar and glue are primarily used in the conventional building components and screws in the alternative building elements. Using dry and reversible connections expansions can be made in a simple way without generating additional waste (Vandenbroucke et al. 2015). This is possible by reusing building elements and simplifying sorting and recycling components at the deconstruction phase (OVAM 2015). Preferably, these connections are simple, standardised and limited in number. For that reason, **larger** fibre cement panels are used to finish the demountable element variants. **Commonly used materials** were chosen to enable frequent reuse and reversible connections, such as plywood instead of gypsum board (Galle 2016).

Massive components, such as brick and concrete, are used in conventional building. Most alternative building element alternatives have a lower weight than the conventional building elements as the alternative structure is a timber frame structure. Furthermore, **lightweight materials** are used in transformable building to make changes easier (Vandenbroucke et al. 2015).


Brickwork, 190x90x60 mm
EPS insulation, 140 mm
Concrete blocks, 150 mm
Plaster board
90
30
140
150
15
425
e.
i.


Plaster board
Sand-lime brick 437 x 100 x 198 mm
Plaster board
100
130
i.
i.


Floor finishing, 15 mm
Prefab concrete slab, 70 mm
EPS insulation, 150 mm
Infill layer, 35 mm
Insitu concrete, 150 mm
Waterproofing
Ground
i.
70
150
435
35
150


i.
10
50
40
170
240
15
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Floor finishing
Sprung floor, 50 mm
Waterproofing
Acoustic insulation, 40 mm
Prefab concrete slab, 170 mm
Plaster board

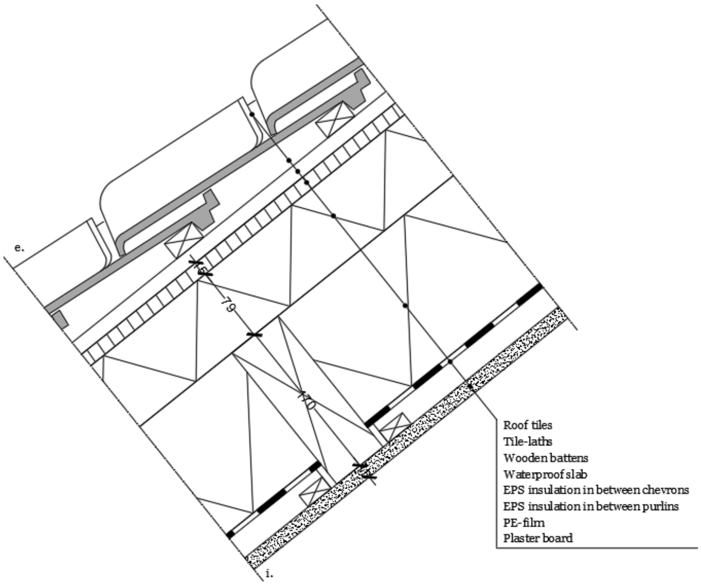
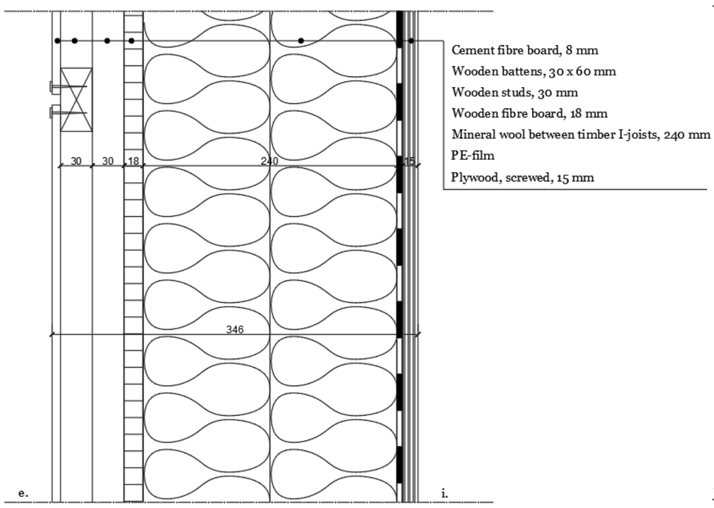
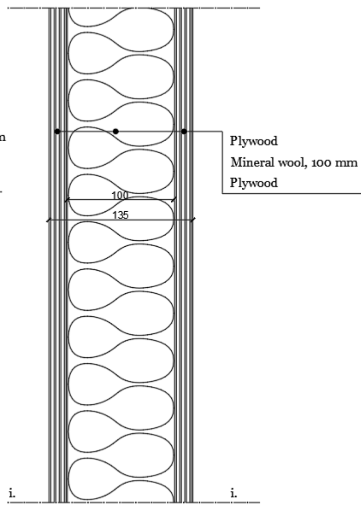


Figure 54: Conventional building elements: Exterior wall, interior wall, ground floor, intermediate floor and pitched roof





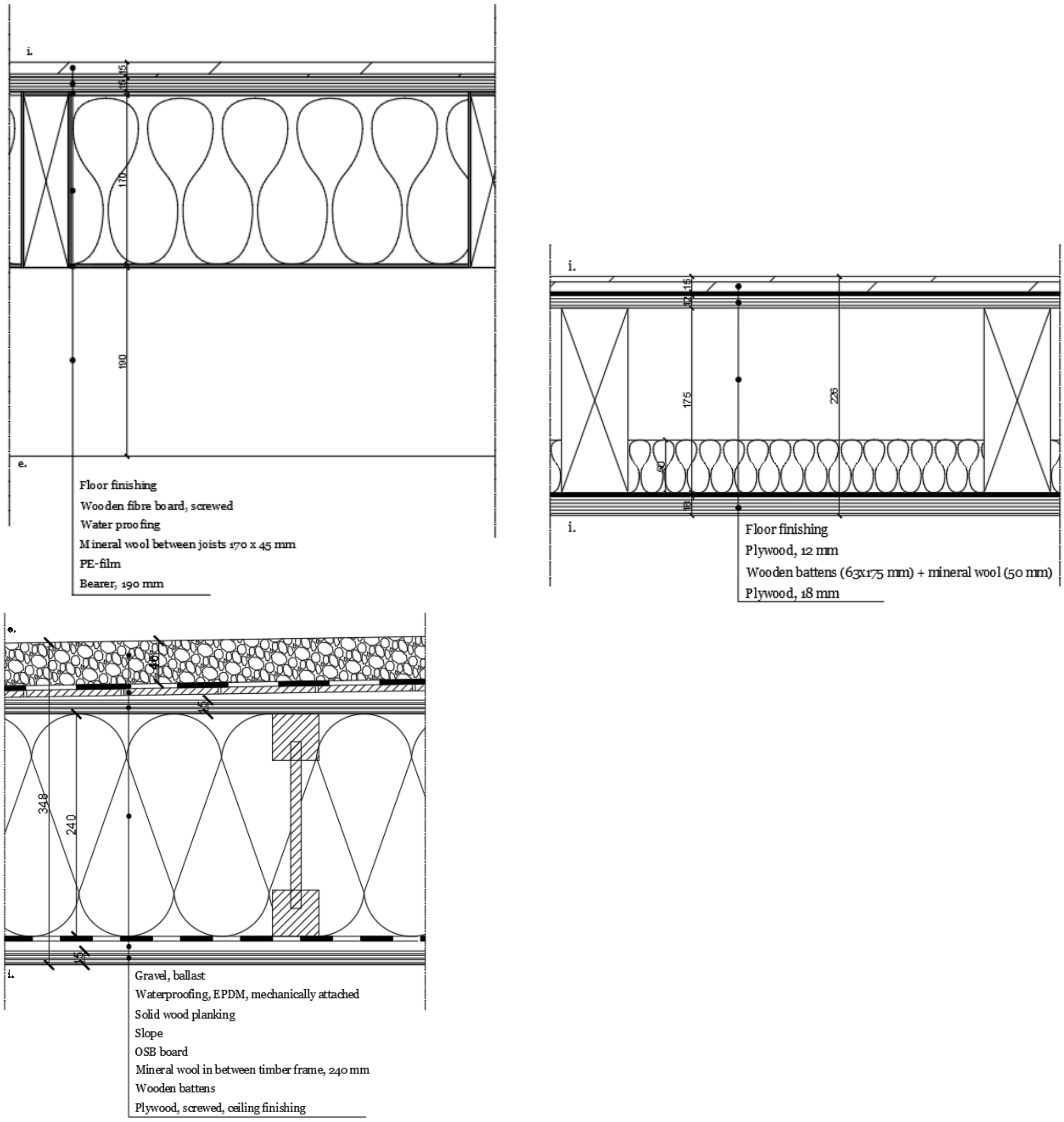


Figure 55: Alternative building elements: Exterior wall, interior wall, ground floor, intermediate floor and roof

ESTIMATED SERVICE LIFE OF MATERIALS OR BUILDING ELEMENTS

The service life of a building or building element depends on a **set of in-use conditions**: materials, design, environment, use and maintenance. A building component reaches its estimated service life when it has loss of performance. This leads to the inability to fulfil the requirements for which they were designed (Silva, de Brito, and Gaspar 2016). A replacement is then required, which is the deconstruction or demolition of it followed by its reconstruction or reassembly (Galle 2016). The estimated service life of a component (eslc) does not only depend on the service life of the materials, but also on how they are **connected** to each other to form a building element. The eslc of the structure is crucial and will typically determine the estimated service life of a building (Silva, de Brito, and Gaspar 2016). The data for the estimated service lives is collected from BCIS (2006).

Conventional building elements	Material	Eslc (years)	Alternative building elements	Material	Eslc (years)
Ground floor	Laminate	30	Ground floor	Wood flooring	50
	Concrete slab	40		OSB	30
	EPS	55		Mineral wool	55
	Concrete infill layer	40		Joists	70
	In-situ concrete	70		In-situ concrete	70
Exterior wall	Bricks	80	Exterior wall	Fibre cement	35
	EPS	55		Wooden battens	50
	Concrete blocks	85		Wooden fibre board	30
	Plaster board	37		Mineral wool	55
				Joists	70
				Plywood	35
Interior wall	Plaster board	37	Interior wall	Plywood	35
	Sand Lime bricks	72		Mineral wool	55
				Timber structure	70
Floors	Laminate	30	Floors	Wood flooring	50
	Concrete floating floor	40		Plywood	35
	Acoustic insulation	35		Mineral wool	55
	Concrete slab	70		Joists	70
	Plaster board	30			
Roof	Roof tiles	30	Roof	Gravel	120
	Wooden battens	50		Solid wood	30
	EPS	55		OSB	30
	Purlins	50		Mineral wool	55
	Chevrons	50		Joists	70
	Plaster board	30		Wooden battens	50
				Plywood	35

Table 2: Estimated service life of materials used in different building elements, based on BCIS (2006)

From Table 2 it can be derived that the estimated service life of the **structural components** (in blue) is almost equal, which is mostly 70 years. The materials of the alternative building elements and the order of layers is chosen to be able to join them with dry connections. This has as advantage that it is possible to maintain, repair or replace one of the components without damaging other layers (OVAM, 2015). In the conventional building elements, where the materials are typically joined with mortar and glue, this is more difficult. In other words, the risk to damage other layers is bigger and this has a result that the estimated service life of the material layers is lower (Bullen and Love, 2009).

Total materials used

Comparison between the housing types

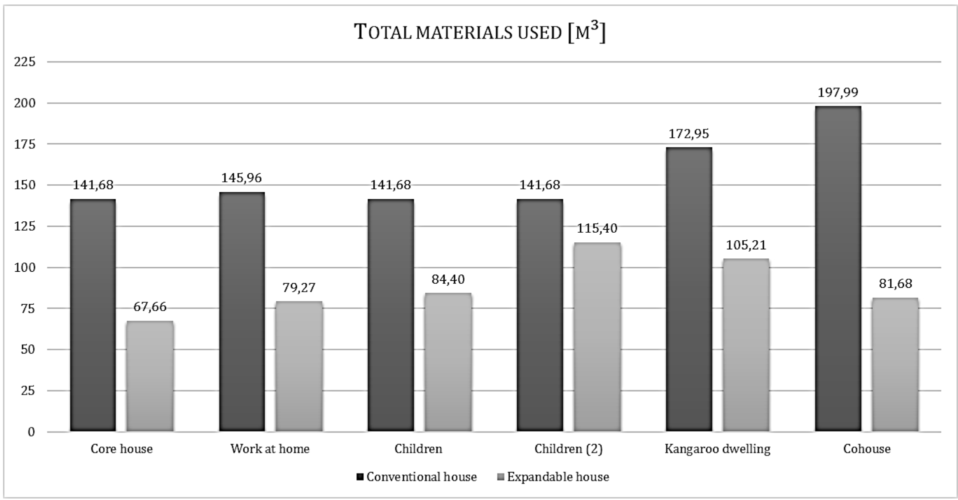
To reduce the demand for materials starts with designing buildings that need less materials. This can be achieved by designing smaller buildings but also by avoiding complex detailing, for example: extinctions, dormers, etc. The expandable house and its extensions are designed with this advice in mind.

The total amount of materials used is calculated by multiplying the areas of the different components with their thickness. For example, the kangaroo dwelling of the conventional house has an area of 207,35 m^2 of exterior walls. If each material layer is then multiplied by its thickness [m], the total materials used for the exterior walls [m^3] can be calculated (*Figure 56*). For the co-house, the total is divided by five, as it contains five row houses that are joined together.

	material	thickness (m)	m² element	m³
External wall	Bricks	0,09	207,35	18,6615
	EPS	0,14	207,35	29,029
	Concrete	0,15	207,35	31,1025
	Plasterboard	0,015	207,35	3,11025
				81,90325

Figure 56: Calculation method of total materials used

In the following graph (*Graph 1*) the total material used in m^3 per scenario and housing type is shown.



Graph 1: Total materials used in m^3 per scenario alternative and per housing type

The graph shows that the expandable house uses less material in every scenario. Comparing the core house to the conventional house, it needs even less than half of the materials. The main reason is that the floor areas of the expandable houses are smaller than those of the conventional ones (*Table 3*). Only in the scenario children (2) the use of materials differs 26,28 m^3, which is a smaller volume difference than those of the other scenarios. The 'Children' expansion is also the largest expansion of all scenarios. Furthermore, the conventional house is built for a scenario children (2) as it contains several bedrooms.

	Conventional house	**Expandable house**	**Difference**
Core house	175,58 m^2	60,00 m^2	115,58 m^2
Work at home	185,72 m^2	73,03 m^2	112,69 m^2
Children	175,58 m^2	81,40 m^2	94,18 m^2
Children (2)	175,58 m^2	119,52 m^2	56,06 m^2
Kangaroo dwelling	185,72 m^2	108,40 m^2	77,32 m^2
Cohouse	963,21 m^2	398,14 m^2	565,07 m^2

Table 3: Floor areas [m^2] per scenario and housing type

The next table (*Table 4*) shows how many cubic metres materials should be **added** to be able to **complete the expansions**. The information reveals that the expandable houses, after the initial stages are already built, needs more material during the next building stages.

	Conventional house	**Expandable house**

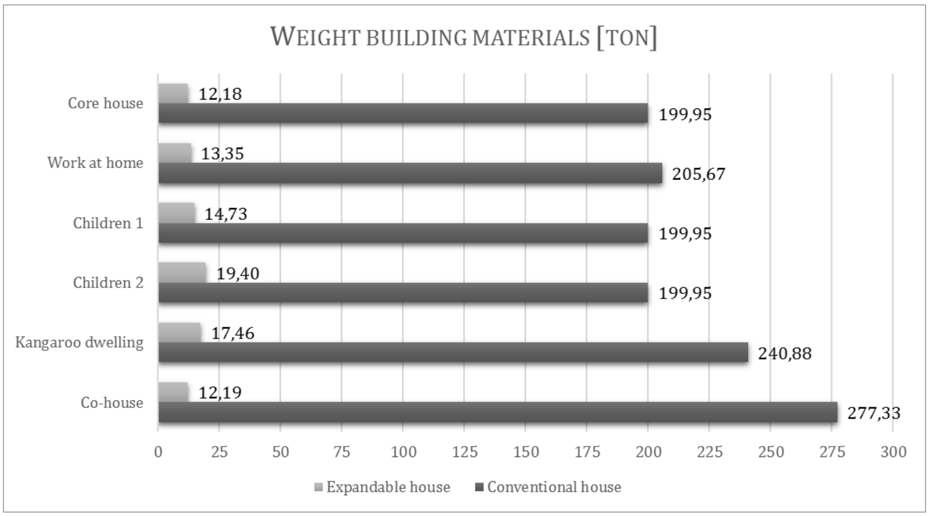
Work at home	4,3 m^3	11,6 m^3
Children	0 m^3	16,7 m^3
Children (2)	0 m^3	47,7 m^3
Kangaroo dwelling	31,3 m^3	37,5 m^3
Cohouse	56,3 m^3	14,0 m^3

Table 4: Material necessary to expand the different typologies

Furthermore, to have a more objective view of the materials used, the **densities** are taken into account (*Figure 57*) and the total weight of each house is calculated by multiplying the volumes with the corresponding densities of the materials. As Graph 3 clearly shows, the difference between the numbers of the expandable and conventional house becomes even larger. The total weight of the materials of the expandable house is much lower than the total weight of the materials of the conventional house. The reason for this enlargement of the difference, is the different materials that are used. The conventional house is built out of conventional building elements and the expandable house is built out of alternative building elements. For example, the density of concrete (2000kg/m^3) is larger than the density of the timber frame structure (900 kg/m^3). Additionally, the timber frame structure is not massively applied throughout the whole bearing structure, but only a joist every 45 cm in the length of the wall.

	material	thickness (m)	m² element	m³
External wall	Bricks	0,09	207,35	18,6615
	EPS	0,14	207,35	29,029
	Concrete	0,15	207,35	31,1025
	Plasterboard	0,015	207,35	3,11025
				81,90325

Figure 57: Calculation method of densities



Graph 2: Total weight [ton] per scenario alternative and housing type

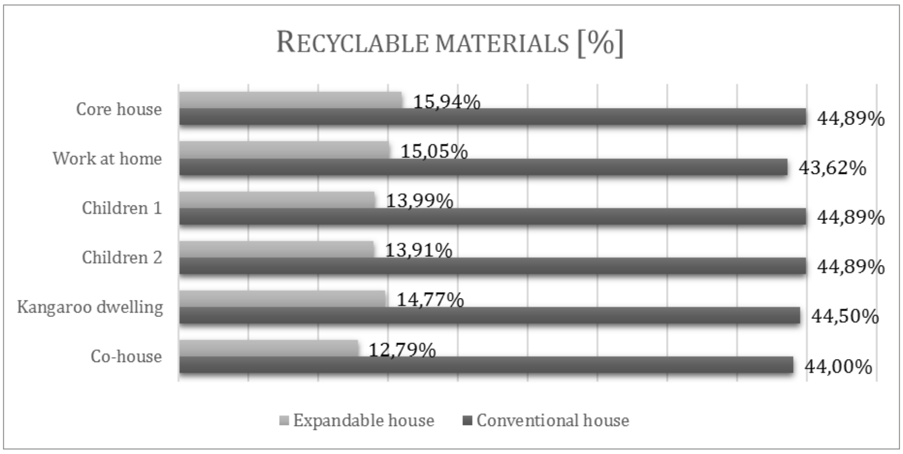
The weight of the building elements is interesting for the transport of the materials and for the assembly of the building elements. Additionally, it is also affecting the demolition or deconstruction phase, as there is an impact per kilogram demolished construction material (Vandenbroucke et al. 2015). In the context of this thesis, the real environmental impact is not calculated, but considering the build-up of the building elements, it can be assumed that the impact will be generally larger for the conventional building elements, and thus for the conventional house. However caution is needed because wood and other renewable materials have an important impact on land use, deforestation and biodiversity (OVAM Ecoliser, OVAM MMG method).

RECYCLING PER TOTAL GENERATED WASTE

	material	thickness (m)	m² element	m³	% Recycle	m³ recycled	
External wall	Bricks	0,09	207,35	18,6615	0,622	11,6075	
	EPS	0,14	207,35	29,029	0,05	1,45145	
	Concrete	0,15	207,35	31,1025	0,977	30,3871	
	Plasterboard	0,015	207,35	3,11025	0,05	0,15551	
				81,90325		43,6016	0,53235443

Figure 58: Calculation method of recyclability

The **recyclability** is calculated based on available percentages published by Nibe the Dutch Institute of Building Biology and Ecology (*www.nibe.info*). These percentages are multiplied with the material volumes. The total material volume that can be recycled is divided by the total volume and this results in a percentage of materials that can be recycled for a whole building element or for a whole housing type in a certain scenario (*Figure 58*).



Graph 3: Total recyclable materials [%] per scenario alternative and per housing type

When looking at the results of recyclability of the used materials (Graph 3), the materials used in the conventional building elements in the conventional house have a larger potential to be recycled than the materials used in the alternative building elements in the expandable house. The main reason is that concrete is recyclable for 97,7% and bricks for 62,2% (Nibe, 2017), whereas expect for the timber frame structure (69,7%), the alternative materials recyclability percentages are not higher than 10%.

REUSE

In current construction practice, building components are often not used during their entire technical life within a building. By reusing these building components in another building or, in the case of expandable houses, in the new expansions, the production of construction waste and the exploitation of new raw materials will be avoided. This also applies to the use of waste products from another sector. Today, construction waste is mainly recycled at material level. This conversion requires a lot of energy and there are only few materials that can be recycled 100% to an equivalent quality (OVAM, 2015).

Although in theory reusing building elements and components has several advantages, in practice it is not widely applied. Additionally, on the online material database of Nibe, the Dutch Institute of Building Biology and Ecology (*www.nibe.info*), the reuse percentages of nearly all materials are about 0%. Therefore, it is difficult to estimate how many elements or components can be reused in reality.

CONCLUSION MATERIAL EFFICIENCY

The **estimated service life** of the structural conventional building components is almost equal to the estimated service life of the structural alternative building components, which is about 70 years. The materials of the alternative building elements and the order of layers is chosen to be able to join them with dry connections. This has as advantage that it is possible to maintain, repair or replace one of the components without damaging other layers (OVAM, 2015). In the conventional building elements, where the materials are typically joined with mortar and glue, this is more difficult. In other words, the risk to damage other layers is bigger and this has a result that the estimated service life of the material layers is lower.

Expandable houses **need less materials** than the conventional house and its extensions. The main reason is that the floor areas of the expandable houses are smaller. On the other hand, after the initial stage, when the cores are built, more materials need to be added to the expandable houses than to the conventional houses to expand corresponding to the scenario alternatives. When multiplying the volumes with the densities, the weight can be calculated. **The total weight** of the materials of the expandable house is much lower than the total weight of the materials of the conventional house. The reason for this enlargement of the difference, is the different materials that are used in the building elements. The conventional house is built out of conventional building elements and the expandable house is built out of alternative building elements.

The materials used in the conventional building elements in the conventional house have a larger **potential to be recycled** than the materials used in the alternative building elements in the expandable house. The main reason is that concrete is recyclable for 97,7% and bricks for 62,2% (Nibe, 2017), whereas expect for the timber frame structure (69,7%), the alternative materials recyclability percentages are not higher than 10%.

Life Cycle Cost Analysis

Based on 'Scenario based life cycle costing: an enhanced method for evaluating the financial feasibility of transformable building', Waldo Galle, 2016.

LCCA (Life Cycle Cost Analysis) is an economic evaluation of buildings. LCCA does not only take the investment cost of the building into consideration, it estimates all relevant costs throughout the lifetime of a building, including maintenance, operating costs and end-of-life costs (demolition, recycling, residual value ...) (*Table 5*) (WTCB, 2012). LCCA is especially useful when **project alternatives** that fulfil the same performance requirements, but differ with respect to initial costs and life cycle costs, are to select the one that maximizes net savings (Fuller, 2016).

Life cycle interventions	Associated costs
Construction and assembly	Material costs Equipment costs Labour costs
Use and operation	Fuel costs (energy, water, heating,...)
Maintenance	Material costs Equipment costs Labour costs
Repair	Material costs Equipment costs Labour costs

Replacement	Material costs Equipment costs Labour costs
Disassembly, deconstruction and demolition	Residual values Labour costs Material processing costs Transport costs

Table 5: Life cycle interventions and associated costs

SPREADSHEET ENVIRONMENT

First of all, **financial data** needs to be collected. The main source is ASPEN (2014), a database collecting construction prices. This data is completed with the database of Bouwunie (2014). The cost figures include wages, material prices and equipment costs. This data is structured per building element and needs to be structure for each life cycle intervention. It is not possible to collect complete data. Hence, uncertainties are present and need to be identified. Taxes, designer fees, mass production and prefabrication are not included in the cost calculations. Therefore, it should be mentioned that the financial impacts that are considered in the following paragraphs relate to the building's construction and are in the first place a consequence of the design choice made in the Research by Design part. The results are an **indicator of the cost-efficiency** of each design strategy and each expansion, both set up in conventional and alternative building elements.

In the cost calculations, the life cycle analysis of the building has **period of analysis** of 60 years and a variable of 15 or 30 years. This means that transformations of the conventional house and the expandable houses are made in building years 15, 30 and/ or 45 and that they are demolished in building year 60.

CONSTRUCTION/ ASSEMBLY

The **measurements** are imported from the plans of the research by design part into a Microsoft Excel spreadsheet. All building elements are measured for each scenario. First, the elements that are present in the original phase are measured. Secondly, for each scenario alternative, it is measured which building elements are demolished or deconstructed and which building elements are added to achieve the corresponding extension.

These inventories and all necessary financial data are imported in Microsoft Excel. This data is processed to calculate the life cycle costs of the different housing types in each alternative scenario. The spreadsheet environment that is used is developed by Waldo Galle for his doctoral thesis (2016).

The **building elements are composed** by the corresponding material layers (*Figure 59*). The compositions are based on the building elements made in the section 'Material efficiency', which are: ground floor, intermediate floor, roof, exterior wall, interior wall and doors and windows. Each of them are composed in conventional building materials as well as in alternative building materials.

Element details		Element	Thickness
1	42"Bepleistering op kalkzandsteen, geschilderc	Interior walls	0,015 m
2	22_Kalkzandsteen holle metselblokken (327|10	Interior walls	0,100 m
1	42"Bepleistering op kalkzandsteen, geschilderc	Interior walls	0,015 m

Figure 59: Example of assembly of the building element 'conventional interior wall'

In the construction sector, there is a determined annual growth rate for the construction prices, the wages in construction and the construction material prices. The growth rates used during calculations are shown in Table 6.

Construction prices	2,475%
Labour growth rate	2,232%
Material prices	3,563%

Table 6: Growth rates

<u>USE AND OPERATION PHASE</u>

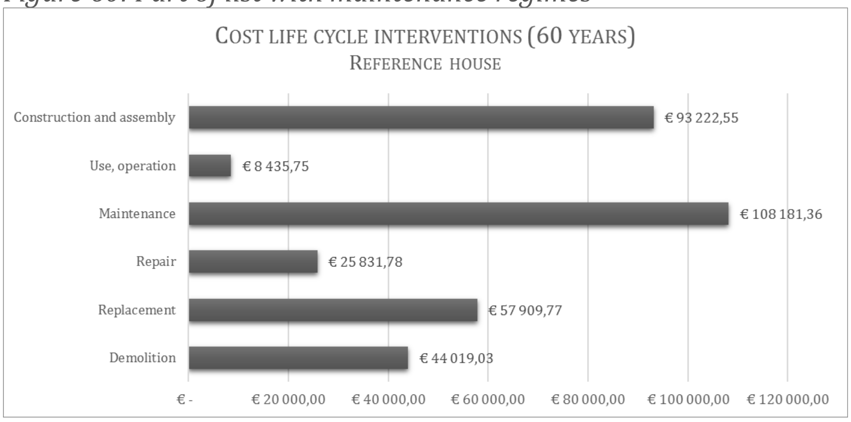
The performance assumed to be identical for each alternative. Only then a meaningful comparison of their life cycle cost can be guaranteed. In other words, it is assumed that the buildings have the same u-value[5] (Galle, 2016). If this would not the case, the u-values need to be taken into account in order to avoid that an increase in insulation would only generate additional material costs (Fuller, 2016). The operational requirements are the Flemish standards for u-values of buildings.

<u>MAINTENANCE</u>

Maintenance applies to the finishing layers of the building elements. The costs are based on the data of ASPEN (2014). The maintenance periodicity is based on the guide BCIS (2006) (Figure 60). Maintenance has an important role in LCCA, since it occurs more frequently than most life cycle interventions. This can also be seen in Graph 4. It represents the costs of each life cycle intervention for a life cycle duration of 60 years. The maintenance cost (€108 181,36) is even a larger cost than the investment cost (€93 222,55).

Item	source	unit	p [years]	p [years]	p [years]	labour	material	utilities	total
Buitenafwerking schilderwerk - parementsteen - pistool	ASPEN 2014a	m2, a	10	14	20	€ 3,35	€ 11,66	€ -	€ 3,35
Binnenafwerking voorlakken - vlakke houten deuren	ASPEN 2014a	m2, a	12	18	30	€ 6,67	€ 2,95	€ -	€ 6,67
Binnenafwerking aflakken - vlakke houten deuren	ASPEN 2014a, BCIS 2006	m2, a	4	6	10	€ 8,77	€ 3,26	€ -	€ 8,77

Figure 60: Part of list with maintenance regimes



Graph 4: Cost of life cycle interventions (60 years) of the original conventional house

It should be indicated that consistent data about maintenance is lacking. Therefore, if maintenance costs would determine the preference of a design alternative, it requires some cautiousness.

<u>REPAIRS</u>

[5] The u-value, the overall heat transfer coefficient, is a measure of heat loss through building elements.

It is considered that the repairs do not influence the estimated service life of the elements. Repairs are thus defined by their periodicity, extensity and intensity. The indicators in Table 7 are assigned to each building element layer. They are linked to factors between zero and one, although they are not verified yet. Moreover, the actions that causes repairs are not predictable. The obtained figures of the repairs should thus be taken into account with some uncertainty.

	Definition	*Descriptive indicators*
Periodicity	Number of years between two repairs	Rare, seldom, occasional, frequent
Extensity	Share of elements that is subjected to damage	Ubiquitous, widespread, common, local
Intensity	Fraction per element unit that has to be replaced	Complete, segmental, partial, fragmental

Table 7: Determining repair interventions

<u>REPLACEMENTS</u>

When a building component no longer fulfils the requirements, its replacement of is mandatory. A replacement is the deconstruction or demolition of a component followed by its reconstruction or reassembly. The factor to determine this period is the estimated service life of the component (eslc). The data for the eslc is collected from BCIS (2006).

<u>DEMOLISH/ DECONSTRUCT/ DISASSEMBLE</u>

When the service life is reached, the building element needs to be disassembled, demolished or deconstructed. If demolition is necessary, the material needs processing before it can be recycled or disposed. Consequently, demolition costs include labour costs, processing costs of unsorted materials and transport costs (*Figure 61*). In the case of deconstruction, it is more efficient to sort out different materials. Disassembly is considered when a demountable building component is removed but has not yet reached its estimated service life. The large advantage is that materials can be reused and thus have a larger residual value.

Item	labour	material	utilities	total
Uithakken van deur- of raamopeningen (20 cm)	€ 564,56	€ -	€ -	€ 564,56
Uithakken van deur- of raamopeningen (20 cm, handmatig	€ 212,37	€ -	€ -	€ 212,37
Afbreken van vloeren: Licht beton (10-50 cm)	€ 220,73	€ -	€ 5,73	€ 226,46

Figure 61: Part of list with demolition actions

Furthermore, it is possible to make a distinction between sorted and unsorted materials and between recyclable and unrecyclable materials (Figure 62).

	material/unit	labour	material	material
Afvoeren en verwerken van afval: gesorteerd, gewapend beton + gron	€ 0,01		€ 25,10	€ 18,62
Afvoeren en verwerken van afval: gesorteerd, groenafval	€ 0,07		€ 25,10	€ 22,96

Figure 62: Part of list with waste processes

For every transformation scenario and corresponding inventory, the total life cycle cost is calculated by looping all life cycle stages of all modelled building elements.

RESULTS

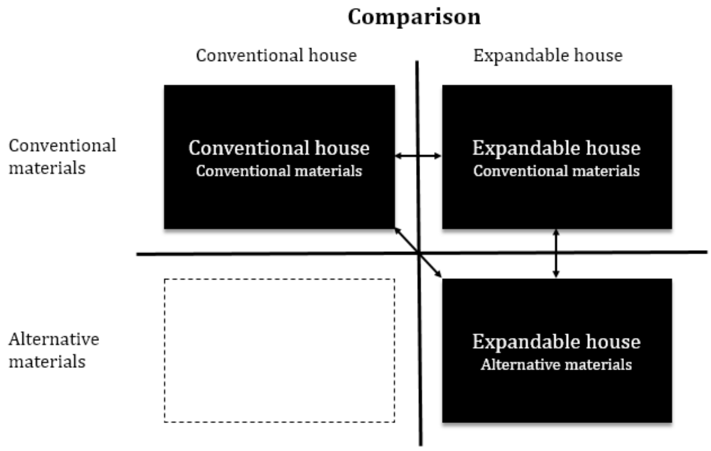
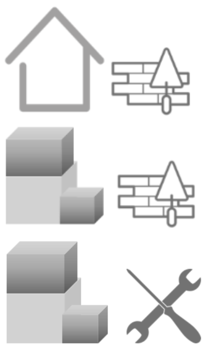


Figure 63: Comparison of housing types and building elements

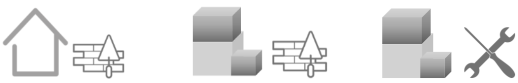
To become meaningful results, a comparison is made between:

1. Conventional house built in conventional materials
2. Expandable house built in conventional materials
3. Expandable house built in alternative materials

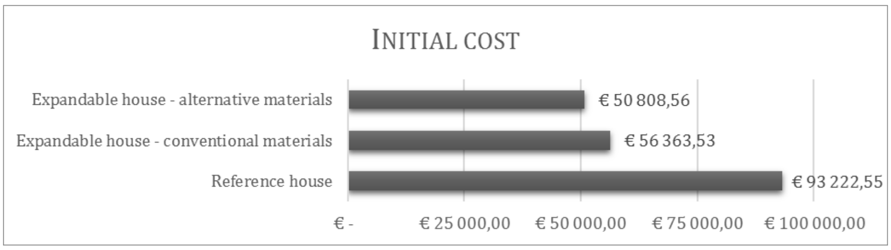


If the conventional house (conventional materials) is compared to the expandable house (conventional materials), then a comparison can be made of housing type. If the expandable house (conventional materials) is compared to the expandable house (alternative materials), then a comparison can be made of materials.

INITIAL COSTS



First, the initial costs are compared Graph 5. As mentioned before, all resulting costs are an indicator of the cost-efficiency. The costs include the main building elements that are presented in the section 'Material efficiency'.



Graph 5: Comparison of the initial cost of expandable houses (cores) made of alternative and conventional building element and initial cost of the conventional reference house

There is a clear difference between the initial cost of the expandable houses (thus the core houses) and the conventional house. Building a conventional dwelling is accompanied by high initial costs. Building the core of the expandable house is more cost-efficient. It is 39,5% more cost efficient if the conventional house (€93 222,55) is compared to the expandable house built in conventional materials (€56 363,53) and 45,5% more cost efficient if it is compared to the expandable house built in conventional materials.

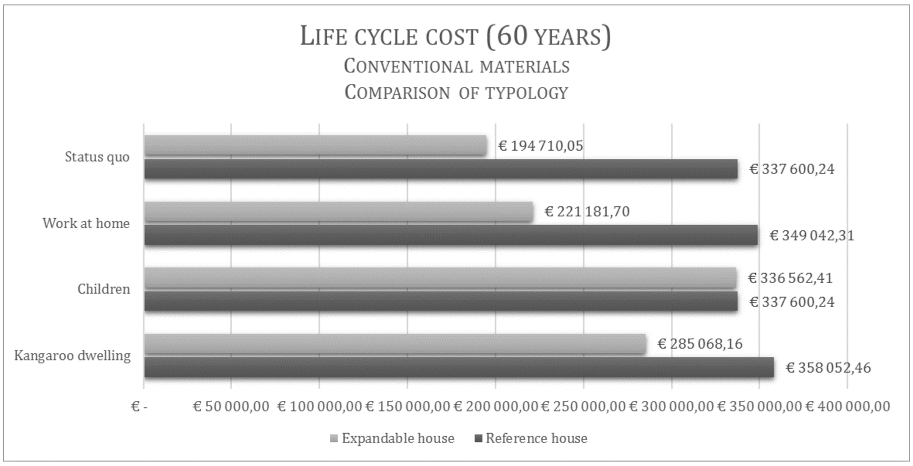
Of course, the floor area is smaller. The floor area of the core house is 60 m². The floor area of the conventional reference house is 175,58 m². Less floor area results in lower costs. Therefore, less material is used to realise the core house. There is also a slight difference between the use of alternative or conventional materials. This difference is 12.5% (€ 5555), where the use of alternative building elements is slightly more cost-efficient in the initial stage.

These results are in particular appealing for single-person households or couples that are looking for a cost-efficient starting point.

Conclusion initial costs

The design strategy of starting with a core house is beneficial for the initial costs. The use of alternative building elements is slightly more cost-efficient in the initial stage.

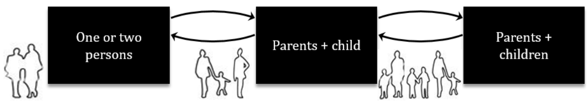
LIFE CYCLE COSTS (60 YEARS)



Graph 6: Life cycle costs of expandable houses made of conventional building elements compared to life cycle cost of conventional reference houses for each scenario alternative

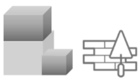
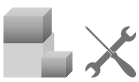
In Graph 6 the **different housing types** are compared. Both housing types are built with the same building elements, the **conventional building elements**. The life cycle costs of the expandable house are lower than those of the conventional house. This statement is valid for each scenario alternative. On the other hand, for each scenario, the floor area of the expandable house is lower than the floor area of the conventional house.

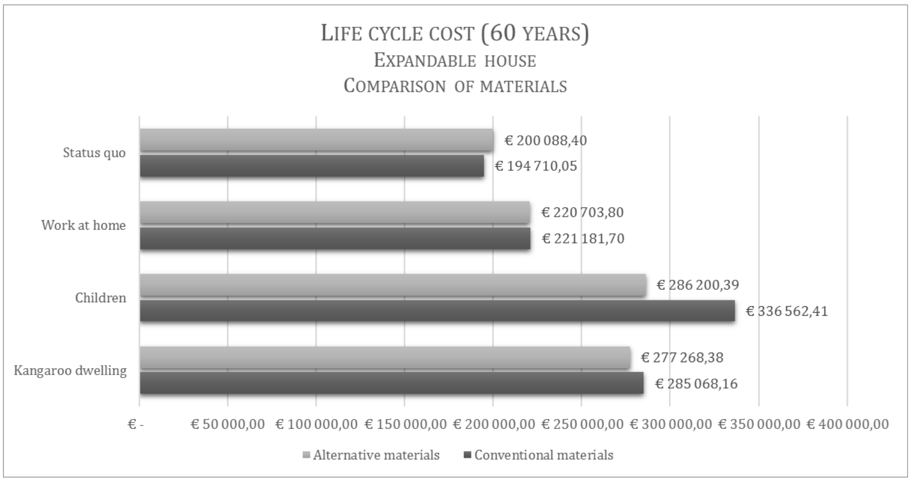
Only in the scenario 'Children' the life cycle cost of both typologies is almost equal. This has two reasons. Firstly, the floor areas 'only' differ 56 m², which is a smaller difference than in the other scenarios. Secondly, in the 'Children' scenario, the expandable house undergoes 3 times a change in terms of expansion, what augments the costs. At the same time, for the ‘Children’ scenario, in the conventional house no changes are needed and this lowers the cost. This has as effects that the life cycle cost is almost equal.



Conclusion life cycle costs – comparison of housing type

The life cycle costs of the expandable house are lower than those of the conventional house. This statement is valid for each scenario alternative.



Graph 7: Life cycle costs of expandable houses made of conventional building elements compared to life cycle costs of expandable houses made of alternative building elements

Additionally, the **different building element compositions** are compared. This is realised by applying to **the same housing type**, namely the expandable house, both the conventional building elements and the alternative building elements.

As can be seen in Graph 7, the costs do not differ a lot. This means that the difference in cost-efficiency of the materials and jointing is minimum and that, after 60 years, the same investment is needed to accomplish same expansions in different element compositions. The choice between the different element compositions be made for other reasons, e.g. material efficiency or environmental advantages.

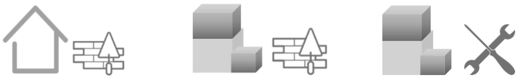
The only exception can be seen in the ‘Children’ scenario. The reason is that in the ‘Children’ scenario two expansions occur plus one shrinkage. The graph shows that if the expandable house should shrink again at some point, it is more cost beneficial to compose the building elements out of alternative components.

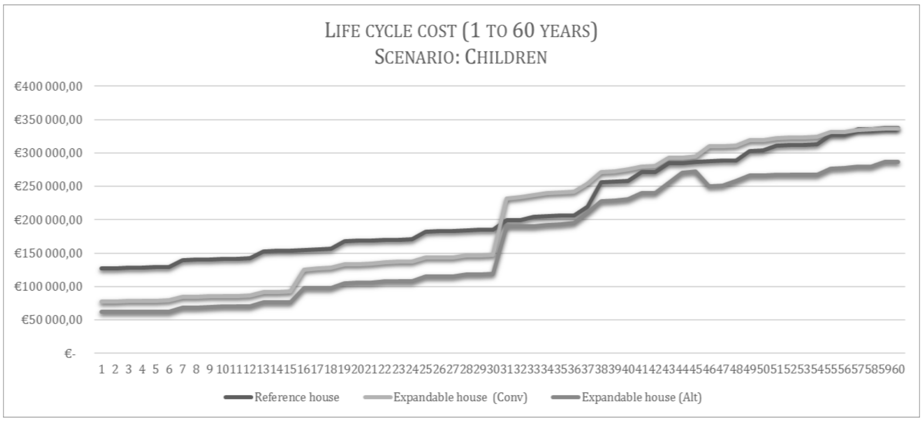
Conclusion life cycle costs – comparison of building element composition

The choice between the different element compositions for accomplishing expansions has no difference in terms of cost-efficiency. This choice should thus be made for other reasons, e.g. material efficiency or environmental advantages. On the other hand, if the construction shrinks again at some point, it is more cost beneficial to compose the building elements out of alternative components.

LIFE CYCLE COST FOR THE ‘CHILDREN’ SCENARIO (60 YEARS)

In the previous graphs the scenario alternative ‘Children’ gave different results than the other scenario alternative, therefore a sensitivity analysis is set out in Graph 8.





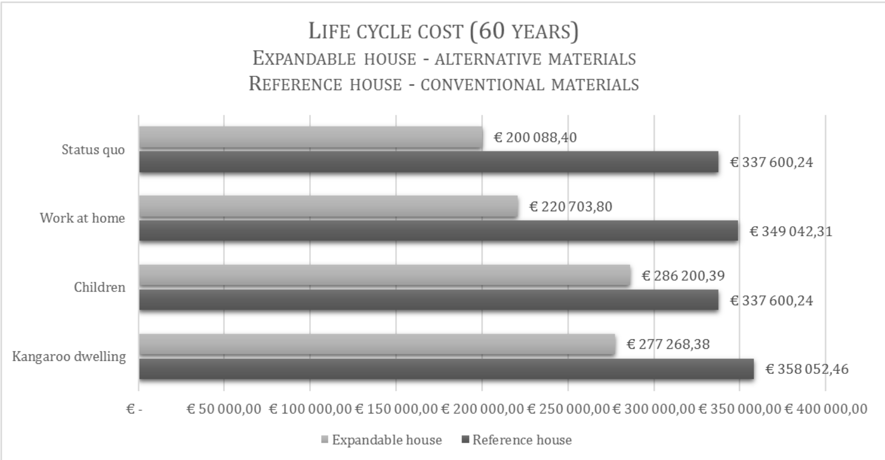
Graph 8: Sensitivity analysis of the life cycle cost for the scenario alternative ‘Children’ for both housing types and both building element alternatives

In the ‘Children’ scenario, the expandable house shrinks again at 45 years. At 15 and 30 years, it expands due to the family that grows, but in building year 45 the children move out of the house. Consequently, the expanded house does not fit the needs of the occupants anymore and shrinks again. On Graph 8 this trend is visible, but only for the case of the expandable house made of alternative building elements. The reason is that savings can be done because of the choice of layering the materials. The different component layers can be easier sorted out and this is translated in less costs. This is not the case for conventional building elements. Even if more materials can be recycled of the conventional materials (see section ‘Material efficiency’), it is a larger cost to do so and to sort them out and to demolish the materials.

As discussed previously, the initial costs of the conventional reference house are higher. Secondly, the investments, after the initial cost, of the conventional house are better spread out. This is because in the conventional house, no expansions are needed in this scenario alternative. With the expandable houses, larger investments need to be done in years 15 and 30. It is visible that the second expansion, which is an on-topping strategy, is larger than the first one. Thirdly, the expandable house made of alternative building materials is the most cost-efficient option at all times.

Conclusion life cycle costs for the ‘Children’ scenario

Investments, besides the initial cost, of the conventional reference house are better spread out. With the expandable houses, larger investments need to be done in years 15 and 30, when expansions are realised. The expandable house made of alternative building materials is the most cost-efficient option at all times. **If the house should shrink again** at some point, then it is more beneficial to build with alternative building elements.

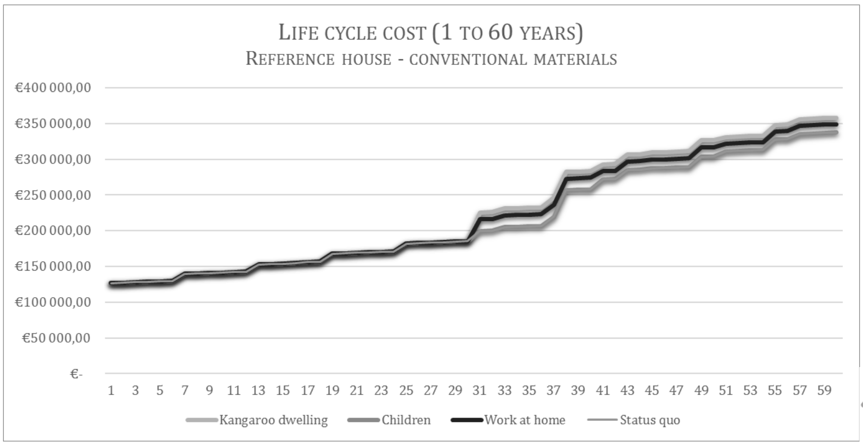


Graph 9: Life cycle cost of a conventional house compared to life cycle costs of expandable houses made of alternative building elements

Now the different typologies and different materials are compared, the two extremes can be compared, which are the reference house and the expandable house in alternative materials. On Graph 9 can be seen that for each scenario alternative, the expandable house consisting of alternative building elements is more cost-efficient than the reference house.

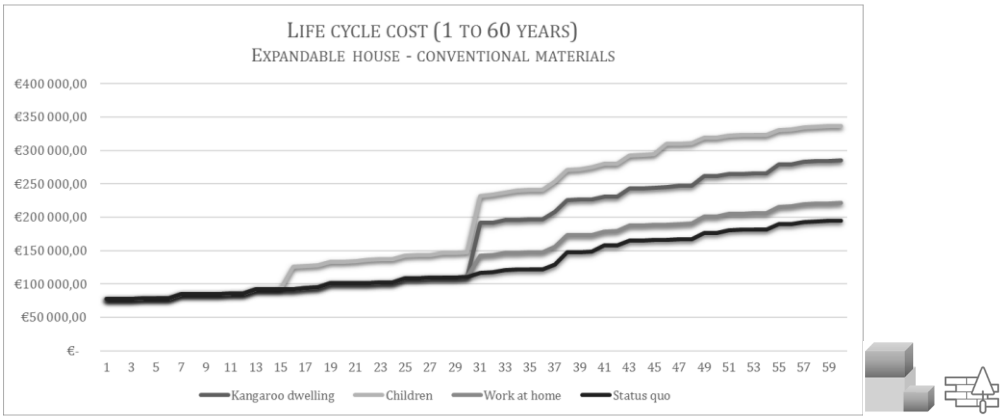
<u>SENSITIVITY ANALYSES</u>

To analyse the sensitivity of the results, the costs are calculated during 60 years. In the sensitivity analyses, the scenario alternatives are set out and compared to each other instead of the different housing types and different building elements. They all start with the same initial cost and grow apart during the years.



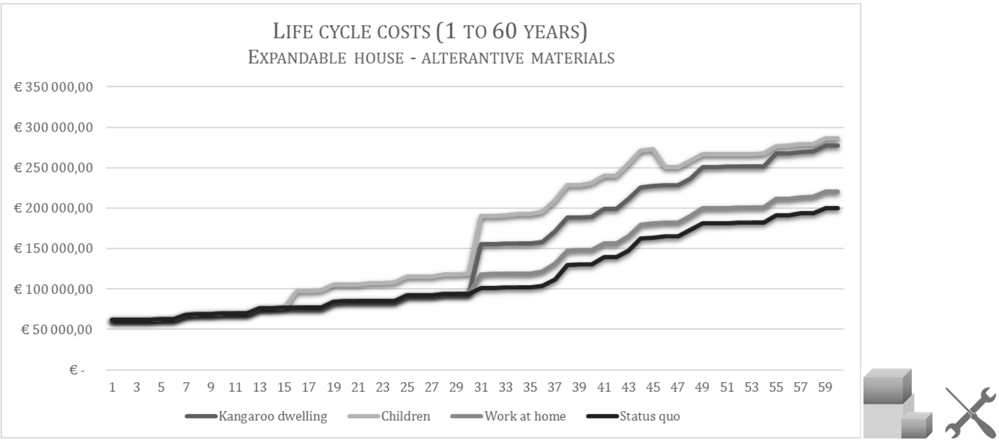
Graph 10: Sensitivity analysis of the life cycle cost for the scenario alternatives set out for the conventional reference house

Graph 10 shows that the life cycle cost during the years is **almost equal**. The costs are barely fluctuating compared to each other. The reason can be found in the fact that the expansions of the different scenario alternatives are of the same magnitude. Additionally, the expansions happen in the same building year, which is building year 30.



Graph 11: Sensitivity analysis of the life cycle cost for the scenario alternatives set out for the expandable house made of conventional building elements

Compared to the previous graph, a lot more differences occur between the different scenario alternatives. The 'Work at home' scenario contains a smaller expansion than the 'Kangaroo' and 'Children' scenario, which is translated in a less steep line. It only demands some investments in building year 30 compared to the 'Status quo' scenario. The 'Children' scenario is discussed previously in Graph 8.



Graph 12: Sensitivity analysis of the life cycle cost for the scenario alternatives set out for the expandable house made of alternative building elements

Compared to the previous graph (*Graph 11*), the costs are more fluctuating. Expanding and shrinking with alternative building elements has more influence on the costs (*Graph 12*) than expanding with conventional building elements.

<u>Conclusion sensitivity analyses</u>

The costs of the conventional house for the different scenario alternatives are barely **fluctuating** compared to each other. This is because in the conventional house, no expansions or smaller expansions are needed to obtain the same requirements as for the expanded core houses. For the expandable house built in conventional building elements, it demands some larger investments at some point to accomplish the expansions. Lastly, for the expandable house built in alternative building elements, expanding and shrinking has more influence on the costs.

MODEL UNCERTAINTIES

As mentioned before, consistent data about maintenance is lacking and the actions that causes repairs are not predictable. Consequently, the obtained figures should be considered with some uncertainty.

Furthermore, to calculate the costs, project characteristics were defined. They apply to all elements and include the period of analysis, the inflation, the nominal growth and the discount rates. These characteristics are needed to calculate the net present value.

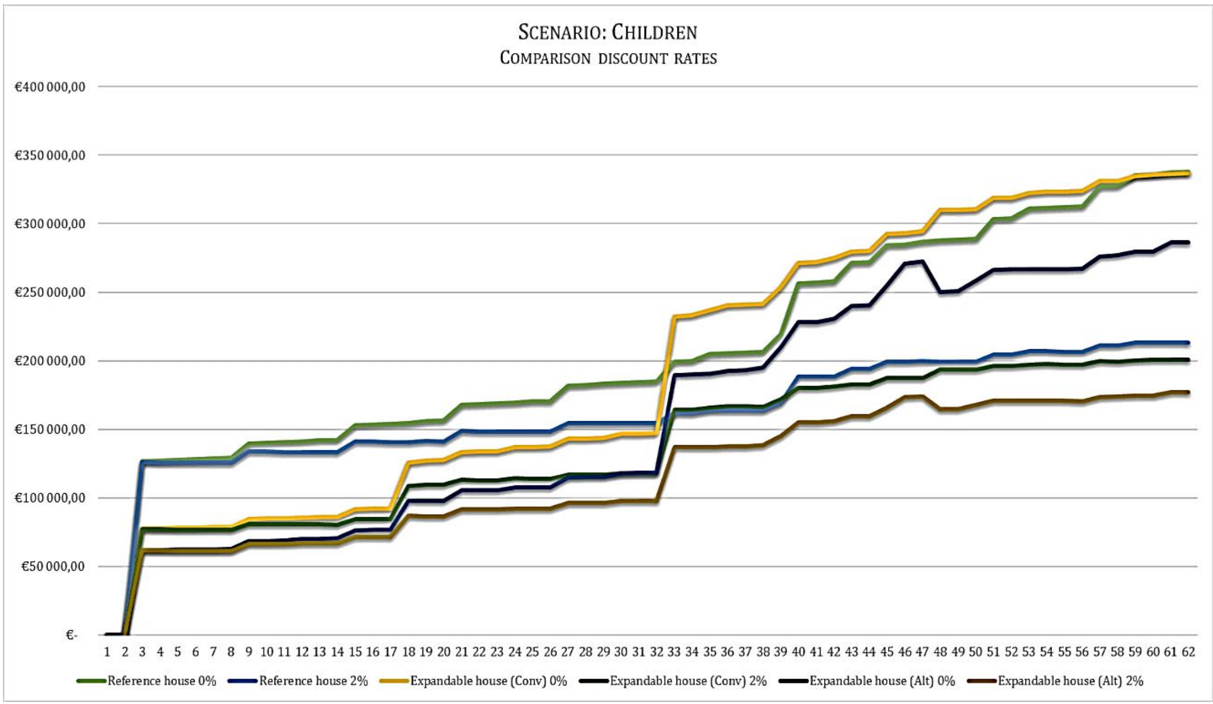
$$NPV = -C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + ... + \frac{C_T}{(1+r)^T}$$

$$-C_0 = Initial\ Investment$$
$$C = Cash\ Flow$$
$$r = Discount\ Rate$$
$$T = Time$$

Equation 1: Net present value, (financeformulas.net, 2017)

Net Present Value (NPV) is a formula used to determine the present value of an investment by reducing future expenses and savings (C_n) to their present value by discounting (r) them. This way the results are corrected for risk aversion and the endowment effect so that impacts at different moments in the future can be compared objectively (Vandenbroucke et al. 2015). The building's life cycle cost is calculated by multiplying its elements' quantities by their **net present value** per unit. In the formula, the $-C_0$ is the initial investment, which is a negative cash flow showing that money is going out.

Future costs, which are present in the case of the cost calculation of expandable houses, are discounted to consider the fact they are uncertain. However, the **discount rate** itself is also an uncertain model parameter. In the previous graphs, a discount rate of 0% was used. To make a comparison, the same life cycle costs are calculated with a discount rate of 2% (*Graph 13*).



Graph 13: Comparison in life cycle costs with discount rates 0% and 2%

The first remark is that the life cycle costs calculated with 0% discount rate are higher than those calculated with 2%. The 3 upper lines are results with a 0% discount rate and the 3 lower lines with 2 % discount rate. With a 2% rate, expenses are weighted increasingly less important when they are situated further from the reference year. Thus, with a larger discount rate, the future costs' importance decreases faster. The future costs are fully included in the NPV with a 0% discount rate.

	0%	2%	Difference
Reference house	€ 337 600,24	€ 213 316,91	€ 124 283,33
Expandable house (Conv)	€ 336 562,41	€ 200 648,3	€ 135 914,11
Expandable house (Alt)	€ 286 200,39	€ 177 040,17	€ 109 160,22

Table 8: Comparison in life cycle costs with discount rates 0% and 2%

The difference between the costs calculated with 0% discount rate and 2% discount rate differ about 61,5%.

Despite these differences, **the conclusions** made in the section 'Life cycle costs' are still valid. The life cycle costs for the expandable house built of alternative materials are still lower compared to the other two life cycle costs (Table 8). Also, the profits gained from shrinking the house are lower but still present.

Since different design strategies were defined in chapter 2 and data development was accomplished in chapter 3, the fourth and last chapter continues based on the obtained results. The last chapter contains guidelines that are developed to introduce the possibilities of expandable housing to designers, developers, occupants and governmental authorities. The guidelines are structured by the objectives of the thesis which are: changing lifestyles, material efficiency and cost efficiency.

CHAPTER 4: GUIDELINES EXPANDABLE HOUSING

The guidelines **aim to** streamline processes concerning the design of expandable housing. The guidelines are evidence-based recommendations on the topic of expandable housing, with the eye on improving expansions by planning them in advance. Guidelines are by no means binding.

The guidelines' **objectives** are to:

- Inform people about expandable housing
- Promote the designing and construction of expandable housing
- Help to guide through possible design processes for expandable housing
- An advice

Many **guidelines** already exist concerning designing **transformable building and adaptable building**. Examples are *Ontwerpgids Meegroeiwonen (Enter vzw., 2009)*, *23 Ontwerprichtlijnen Veranderingsgericht Bouwen (OVAM, 2015)* and *WTCB*, the Scientific and Technical Center for Construction in Belgium. As expandable housing is a topic of transformable and adaptable building, those guidelines are also applicable for the design of expandable housing.

It is important to mention that there is **not one correct solution** to develop expandable housing. Every element should be evaluated in its given context. Each building is unique by its physical structure, its function, as well as its relation with the users and the environment. The guidelines will not be applicable to every situation, but they contribute to a way of thinking about designing expandable housing and offer some tools to facilitate the adaptability of the building (Nakib 2010).

The guidelines are ordered parametrically with the objectives of this master thesis, namely: changing lifestyles, material efficiency and cost efficiency. **Each guideline includes an analysis** of its ability to increase success, evidence-based to support the guideline.

CHANGING LIFESTYLES

Before setting up the guidelines for expandable houses in terms of changing lifestyles, **case studies** were analysed (see Chapter 2), with their response to the identified context. Then, design strategies for expandable houses are set up. Furthermore, from experiences with the **designed expandable house** in the Research for design part (see Chapter 3), the guidelines are adjusted and complemented. Designing for change is convenient for occupants who's future is undecided and for governmental authorities to provide dwellings for different household types at once.

Design strategy 1: Core + extension

WHY?

The extensions are custom-made. It is forthwith possible to design them according to the specific needs of the users, the environment and the context of the house.

HOW?

The initial phase of the design strategy is a core house. This **core house** should minimally should include all necessary functions, such as a minimal living space, a kitchenette, a toilet, a bathroom, storage and a bedroom (*Figure 64*). To maintain a comfortable home, **the minimum areas** for dwellings of the VMSW (Flemish Society for Social Housing) can be used as guidance (VMSW, 2014).

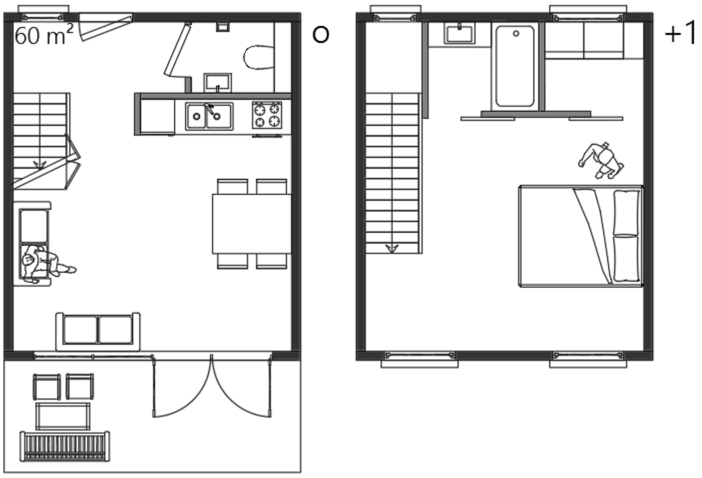


Figure 64: Example of a core house

When **expanding horizontally**, it is advisable to choose a site that allows further extensions. The boundaries of the property must be respected. To facilitate the expansion process, windows of the core house can be placed thoughtfully so they can change into doors where future expansions must come.

When **expanding vertically**, it is recommended to oversize the capacity of the bearing structure to allow vertical expansion.

Circulation considerations are significant in the compact core house. The circulation space should be minimised and the living space maximised. Avoid narrow and dead routes of which the function is only to move. Additionally, the circulation of the core house should already be adapted the future extensions. This way, less effort is needed when expanding.

RELEVANT CASE STUDY

Examples of cases where the design strategy 'Core + extension' is applied, is Quinta Monroy by Elemental (*Figure 65*) and IbbN by Koos van Lith. Figure () displays the ground floor level dwellings in **Quinta Monroy**. The green floor area is the initial core house area, and the purple floor area is the area that can serve for adding extensions.

Figure 65: Core houses of the ground floor level dwellings in Quinta Monroy ("Quinta Monroy / ELEMENTAL" 2008)

Design strategy 2: Core + modular extension

WHY?

Modular structures are often chosen over custom-made structures to achieve cost effective and rapid construction (Gunawerdena et al., n.d.).

HOW?

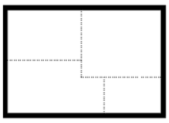
This strategy is similar to the strategy 'Core + extension' except for the use of modular volumes instead of custom-made volumes. Due to this repetition of units, a modular system often uses a grid structure. It facilitates compatibility an reconfiguration (Nakib, 2010).

RELEVANT CASE STUDY

Skilpod is an easily **replaceable** modular volume. It can be removed without destruction of the pod. Several modular volumes are developed. The pods range from 30m^2 up to 150m^2. The difference between the smaller modules and the bigger ones is that the smaller ones are meant to be mobile units, while the bigger ones are meant to be permanent quality expansions.

Figure 66: A compilation of different Skilpods (Lathouwers, 2016)

Design strategy 3: Inner wall/ outer shell



WHY?

This strategy is compelling if only a **small parcel** is available and expanding is not a possibility. It can also be applied for several people that buy a larger building together and split it up dependent on the needs of the occupants.

HOW?

The outer shell is over-dimensioned. The intention is to subdivide the space into different functional entities. These spaces are easily transformable when needed. A recommendation is to minimize the internal columns and bearing walls to obtain more freedom in arranging spaces. Internal bearing structures can compromise the building adaptability.

RELEVANT CASE STUDY

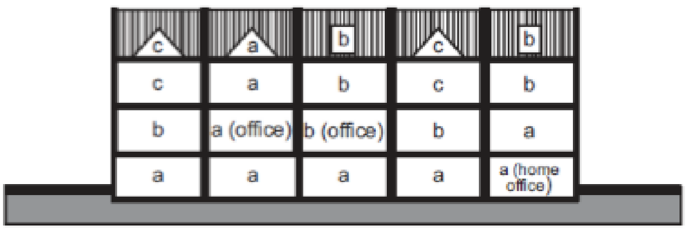


Figure 67: The Next Home by Avi Friendman (Friedman, 2015)

The Next Home is a three-story row house. The concept is to provide a dwelling that can be converted into two or more independent units by manipulating entrances and vertical arrangements.

MATERIAL EFFICIENCY

In the following sections about material efficiency, it is evidenced if the construction of a conventional house or an expandable house is more beneficial for each particular item. The target audience to apply material efficient methods is mainly governments and the developer/ designer.

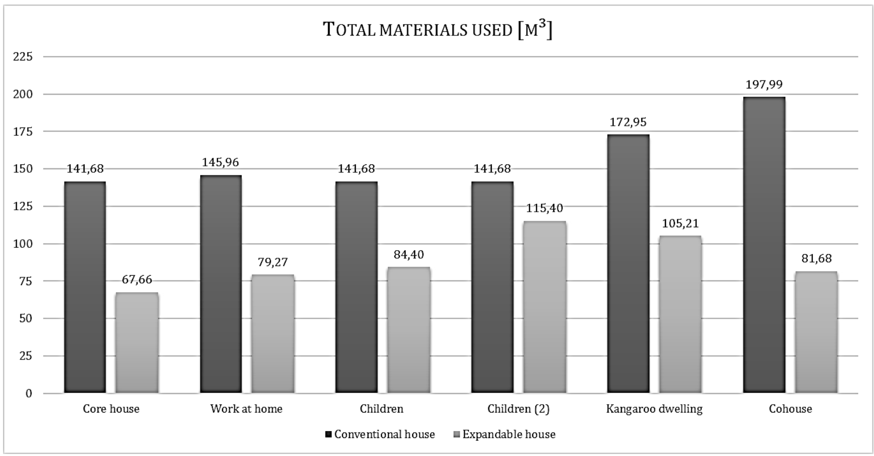
Lower the total use of materials

WHY?

Material efficiency is significant in terms of environmental awareness. Material production is energy intensive. Therefore, in first place, **reducing the demand for material** would lead to reducing extraction of natural resources, reduced energy demand and other environmental harms (Allwood et al., 2013).

HOW?

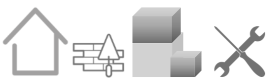
To build an expandable house, less materials is needed than building a conventional house. Especially in the initial phase, when the expandable house consists only of a core house (*Graph 14).* The considered conventional house is a conventional row house.



Graph 14: Total materials used in m^3 per scenario alternative and per housing type

After the initial stages are built, the expandable house needs more material to obtain the expansions. Nevertheless, ultimately the expandable house uses less materials than a conventional house.

Lower the total weight of used materials



WHY?

If the weight of constructing a house is an issue, then it is interesting to apply densities of materials to the previous section. As a matter of fact, lightweight materials are beneficial for the transport of the materials to the site.

How?

In the concept of transformable and adaptable buildings, the materials of the building elements of the expandable house are chosen that they are feasible to transform and expand the house. The conventional house is made of conventional building elements (*Figure 68*).

Conventional materials **Alternative materials**

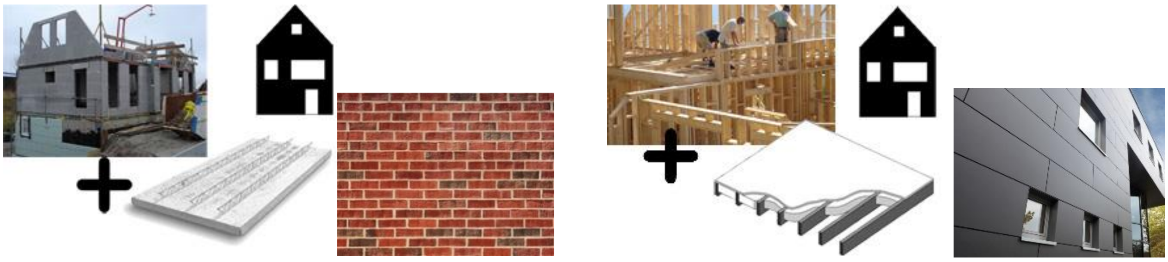
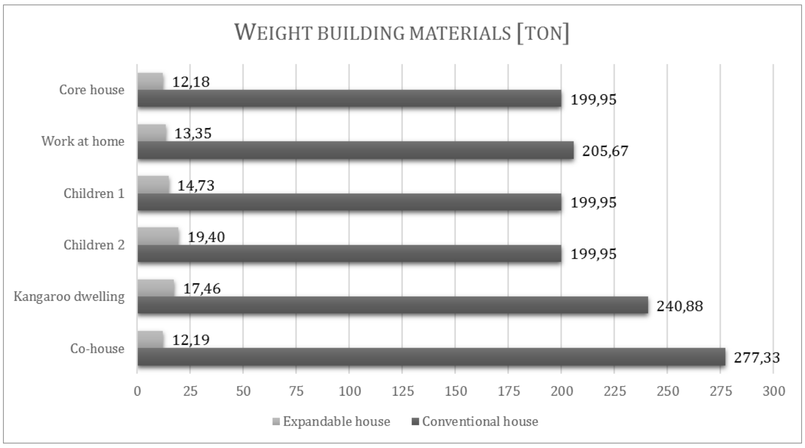


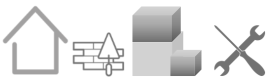
Figure 68: Example of differences in conventional materials and alternative materials (Nibe, 2017)



Graph 15: Total weight [ton] per scenario alternative and housing type

The total weight of the materials of the expandable house is much lower than the total weight of the materials of the conventional house (*Graph 15*). The reason for this enlargement of the difference, is the different materials that are used in the building elements. The reference house is built out of conventional building elements and the expandable house is built out of alternative building elements.

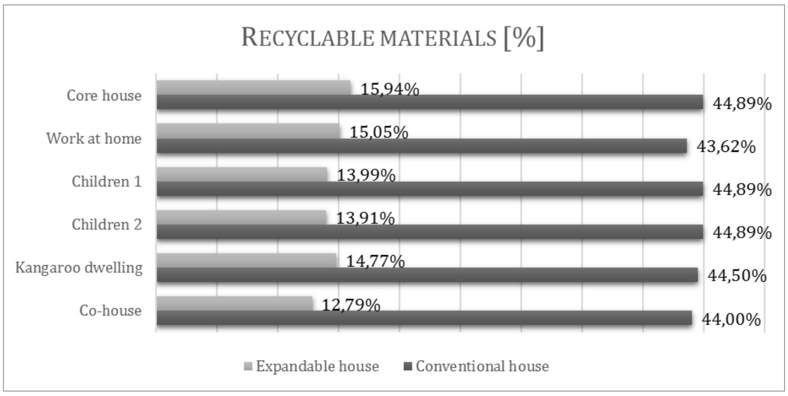
Increase recyclability of used materials



Why?

Recycling avoids more primary material production, which reduces greenhouse gas emissions and other pollutants, and reduces the need for new landfills (Bauer, Mösle, and Schwarz, 2010).

HOW?



Graph 16: Total recyclable materials [%] per scenario alternative and per housing type

The materials used in the conventional building elements have a larger potential to be recycled than the materials used in the alternative building elements in the expandable house (*Graph 16*).

COST EFFICIENCY

Cost efficiency has as aim to present optimum results for economic expenditures. The presented cost efficiency should be treated as an indicator for the real cost efficiency. Financial impacts that are considered relate to the life cycle costs of the main building elements.

Lower initial cost

What is the best solution if initial cost is the main concern?

HOW?

Building a conventional dwelling is accompanied by high initial costs. The design strategy of expandable houses is more beneficial for the initial costs. The main reason for the lower costs is that an expandable houses' initial state is its core house (*Figure 69*). The core house has a smaller floor area than a conventional house

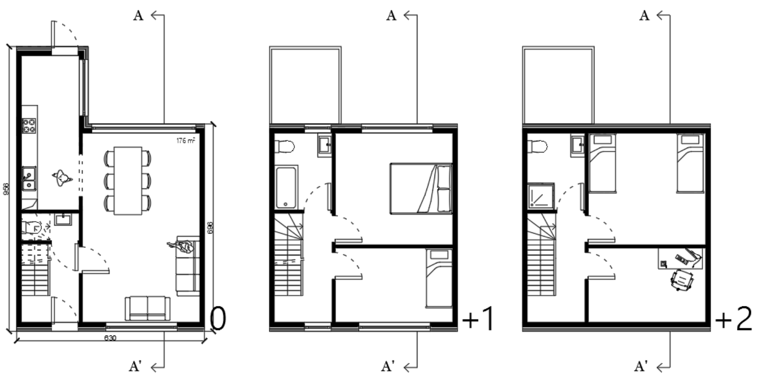
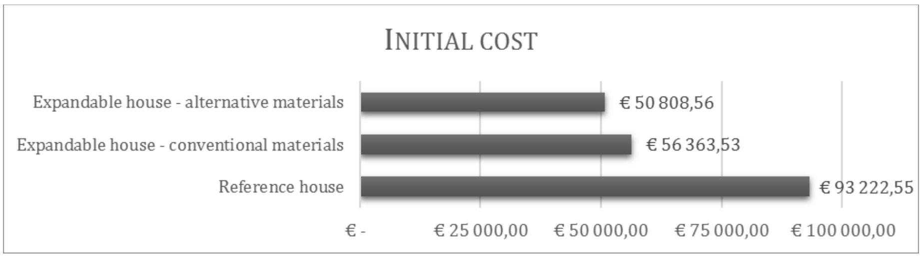


Figure 69: Floor plans of a conventional house and of the core house of the expandable house



Graph 17: Initial cost of expandable houses (cores) in alternative and conventional building components and initial cost of conventional reference house

It is 39,5% more cost efficient to start with a core house (€56 363,53) than with the conventional reference house (€93 222,55). Furthermore, it is even 45,5% more cost efficient if it is compared to the expandable house built in alternative materials (*Graph 17*).

The core house is in particular interesting for single-person households or couples that are looking for a cost-efficient starting point.

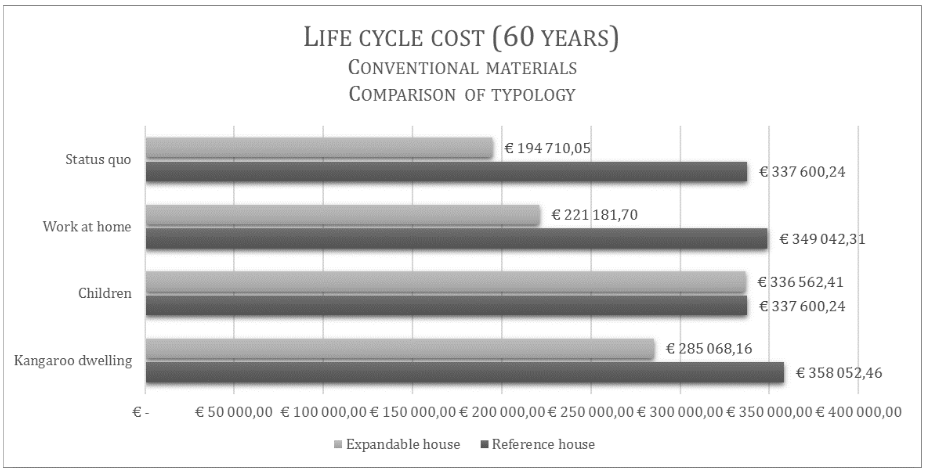
Lower life cycle costs

The core house is too small and the conventional house too expensive?

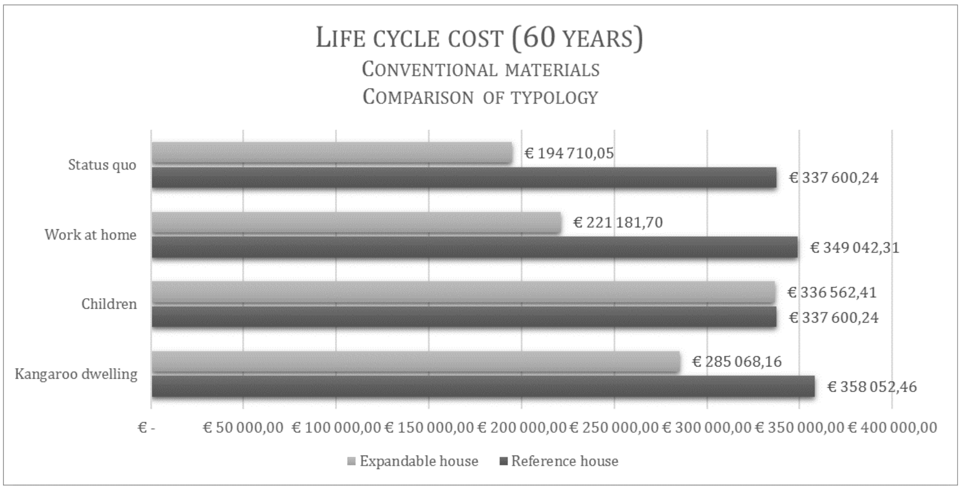
Larger households have the possibility to add an expansion to the core in the initial stage.

How?

The life cycle costs of the expandable house are lower than those of the conventional house.



Graph 18: Life cycle costs of expandable houses made of conventional building elements compared to life cycle cost of reference houses for each scenario alternative

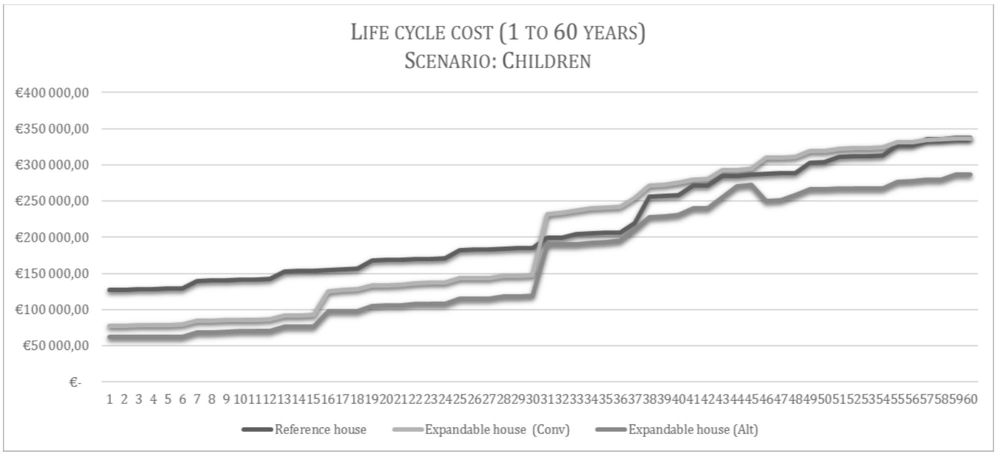


Graph 19: Life cycle costs of expandable houses made of conventional building elements compared to life cycle costs of expandable houses made of alternative building elements

The choice between the different element compositions for accomplishing expansions has no difference in terms of cost-efficiency. This choice should thus be made for other reasons, e.g. material efficiency or environmental advantages. On the other hand, if the construction shrinks again at some point, it is more cost beneficial to compose the building elements out of alternative components.

Spreading of investments

Want to spread investments gradually?



Graph 20: Sensitivity analysis of the life cycle cost for the scenario alternative 'Children' for both housing types and both building element alternatives

The investments, after the initial cost, of the conventional house are better spread out (*Graph 20*). This is because in the conventional house, no expansions or smaller expansions are needed to obtain the same requirements as for the expanded core houses.

CONCLUSION

FINDINGS

In this research the potential was explored of anticipated extensions on expandable houses in terms of changing lifestyles, material efficiency and life cycle costs.

To get a deeper insight in the subject matter of expandable houses, **different case studies of expandable houses** were analysed, which are presented in chapter two. The examination of the case studies proved that expandable housing is applicable in diverse contexts and that the extent of growth is manifested in a variety of forms. Therefore, it remains necessary to anticipate unpredictable change. The comparison of the different expandable housing projects, concepts and systems resulted in several **design strategies for expandable housing**. Three main strategies could be defined: 'Core + extension', 'Core + modular extension' and 'Inner wall partition'. Minor strategies that were characterised are 'Sliding' and 'Folding'. To complete the chapter, consequences of expanding are reviewed.

To test these design strategies, a suitable project was pursued to apply them to. The master plan for **the site '*De Molens*' in Vilvoorde** was selected in the framework of future densification and the call of the Flemish government for stimulating pilot projects for common and innovative living. Designing for changing lifestyles includes future uncertainties, these are anticipated through evaluating demographic data and by using scenario planning to develop plausible evolutions.

Subsequently, the design strategies and scenarios are applied to the master plan by a **research by design approach**. To obtain a dignified comparison in terms of material efficiency and cost efficiency, the expandable houses are compared with a conventional row house. For each considered **building element**, a conventional and a demountable detail is developed. The main difference between the conventional and the alternative construction assemblies is the jointing method and the weight of the materials used.

The **material efficiency** is investigated through the total amount of materials used and the recycling per total generated waste. First, the obtained results indicate that expandable houses need less materials [m^3] than the reference house and its extensions. The main reason is that the floor areas of the expandable houses are smaller. On the other hand, after the initial stage, when the core houses are built, more materials need to be added to the expandable houses than to the reference houses to adapt them corresponding to the scenario alternatives. Second, the difference in used materials is enlarged when converted to the total weight of the buildings. The total weight of the expandable house is much lower than the total weight of the corresponding conventional house. The reason is that the reference house is made of heavier conventional building elements and the expandable house is made of more lightweight alternative building elements. Third, the materials used in the conventional building elements in the conventional house have a larger potential to be recycled than the materials used in the alternative building elements in the expandable house. Conventional materials like concrete and masonry have today a higher recycle percentage than the materials in the alternative building elements. However, more thorough environmental life cycle assessments and uncertainty analyses on how future recycling and reuse rates might change are necessary to confirm these preliminary explorations.

To obtain illustrating results in terms of **cost efficiency**, a comparison is made between the conventional house in conventional building elements and the expandable house in both conventional building elements and alternative building elements. First, the **initial costs** are considered. Beneficial for the initial costs is to build an expandable house, as its initial phase consist of a compact core house. The use of alternative building elements is slightly more cost-efficient in the initial stage than using conventional building elements.

Second, also the **life cycle costs** of the expandable house are lower than those of the conventional house. This statement is valid for each scenario. When the building element compositions are compared, it can be observed that in terms of cost efficiency there is no difference between the different element compositions for accomplishing expansions. On the other hand, if the construction would have to shrink again at some point, it is more cost beneficial to compose the building elements out of alternative components. Furthermore, if the conventional house is compared to the expandable house built with alternative building elements, the expandable house is more cost-efficient at all times.

When considering **investments**, investments needed for the conventional house are better spread out over time. For expandable houses, larger investments need to be done at the time expansions occur. Also, for the expandable house built in alternative building elements, expanding and shrinking has more influence on the costs. Although financing costs are not considered explicitly and included in the assessments, discounting future expenditures already reflects this aspect.

FURTHER RESEARCH OPPORTUNITIES

As the concept of expandable houses is applied in many different contexts but still not widely applied, abundant challenges and thus opportunities for future research are present.

Since in this thesis the concept of expandable housing is only applied to the housing type row house, it could be studied how other **housing types**, e.g. apartment buildings, can expand. Additionally, besides 'Core + extension', the two other main **design strategies** 'Core + modular extension' and 'Inner wall partition' could be evaluated in terms of materials efficiency and cost efficiency.

To analyse the **total environmental impact** of expandable houses, more indicators than only the material efficiency, for example the optional energy savings, could be studied. Also, further research is required to investigate the opportunities of reusing building materials and building elements has to offer for expandable housing. The obtained results concerning the cost efficiency are an indicator of the real cost efficiency. To obtain the real **financial feasibility**, techniques, taxes, designer fees, etc. need to be considered. Furthermore, to be able to compare benefits of using modular volumes to expand, the consequences of mass production and prefabrication could be examined.

Furthermore, it should be outlined and detailed how the expansions can be merged with the initial phase of the house. This way, it will give more insight in how expansions are made **technically, legally and commercially possible**.

CLOSURE

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