The building as a sustainable material manager: mediating material and use

Beyond sustainable material considerations for the refurbishment of a 70s office buildings towards a material manager mediating changing use and connection of material cycles

M.Sc. Research Thesis / Explore Lab

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Abstract

The increasing importance of the material impact of buildings demands an alternative approach to the way buildings relate to materials and the way materials relate to buildings. This thesis forms the theoretical basis for the design of a refurbishment of a vacant 70s office building, towards a multifunctional material manager – focused on a beyond sustainable material application taking in account material circularity and sustainable material characteristics in relation with the user and use changes.

This demands a strategy that shifts focus towards the use phase. An important challenge to deal with is future uncertainty. With help of scenarios potential futures can be imagined. A building can deal with uncertainty in two ways: design for disassembly and design for adaptability.

For the refurbishment of a 70s office building, with a reinforced concrete structure with a generic grid, in a dense urban context – a combination of adaptability and disassembly seems best fit. It reduces construction nuisance, it spreads material flows over time and reuses the existing to best use.

Along the Open Building concept, imagined by John Habraken, a concept of structure and infill can be applied to mediate between user change and material change. The concept of ShearingLayers, imagined by Stuart Brand, forms an effective framework to facilitate design for disassembly, user change, functional change, material change and sustainable development. It adds nuance to Habraken’s twofold and divides a building into different layers that have different rates of change. These layers are: site, structure, skin, services, space plan, stuff.

To secure adaptability and disassembly the thesis describes different concepts and design strategies, such as design with oversize, different levels of fragmentation and spatial diversity.

The second section focuses on material circularity and material characteristics. In a beyond sustainable paradigm, moving the linear material process to a circular one is the primary concern. This cycle of material collection, material processing, building construction, use and disassembly allows for different ways of material and product life extension (reuse) and renewal (recycling). The difference between recyclability, reusability, pure materials and products is briefly discussed. Reusability relates to extension
of the use phase of products, while recycling relates to renewing
the life of materials. While in transition between a sustainable and
beyond sustainable paradigm, recyclability becomes of increasing
importance above reusability. However, the value difference
between materials and products is indicative. High quality
products can have a significant higher value than their pure
material components, for example a concrete structure, resulting
in preference of reuse above recycling and a certain level of
generic usability. A second type of renewal, composting, relates
specifically to the biosphere, where recycling is a renewal tool in
the technosphere.

There are many different variables that can indicate the ecological
impact (whether positive or negative) of a material or product:
recyclability, reusability, resource depletion, waste creation,
embodied energy, hazardous content, durability, maintenance,
functionality and the way in which they are used: the amount and
the extend in time.

An LCA (Life Cycle Analysis) offers a methodology to evaluate
the different variables and come to a material strategy. Different
LCA studies have been drawn from to create an overview of the
different ecological impacts per Shearing Layer. Although the
structure, with its largest mass and volume, has the biggest
ecological impact initially, during a building’s life, due to recurrent
maintenance and renovations, this shifts towards the skin, services
and space plan (stuff was not included in the overview). This
amplifies the previous assumption to move design focus from the
building as static object to a building’s use phase.

A proper LCA and a resulting green material selection process is
currently not easy, due to the abundance of sustainable variables,
intransparency of manufacturing processes, illegitimate claims of
green, lack of information, an abundance of green certificates, lack
of recycling infrastructure etc. More knowledge and transparency
is needed to indicate potential hazardous ingredients of materials
and products and their specific attributes to the built environment.
However, due to the complexity and uniqueness of the built
environment, many different sustainable alternatives might be of
equal positive (or negative) impact, each within their own
categories. Therefore it is important not to only to lead material
selection processes by quantitative data, but also by qualitative
considerations and inspirations – for example by the registry of
C2C inspired elements.
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1 Problem Description

1.1 Relevancy of Sustainability

Our society is facing big challenges. The consequences of growth cannot be ignored anymore. They result in a changing climate, depletion of natural resources, localized food and water shortages, decreasing biodiversity, disturbance of nature’s cycles and health and ecological risks as a result of hazardous emissions and ever increasing waste streams.

The building industry has a large impact on ecology: according to UNEP (United Nations Environment Program) it is globally responsible of 40% of energy use and 60% of the raw material consumption (OVAM, 2013, p. 7).

1.2 Shifting the paradigm: from less bad to more good

The current debate on sustainability and the built environment has mostly been on doing more with less: decreasing carbon emissions and energy use.

Efficiency

“...do not pollute or unnecessarily contribute to the waste stream, do not adversely affect health, and do not deplete limited natural resources.”

Whole Building Design Guide (WBDG, 2015)

In recent decennia different voices have slowly come up proclaiming that a move from less bad (more efficient) towards being good (effective, a positive output) is essential to secure a healthy future of our earth and the human race. Among these are Michael Braungart and William McDonough via ‘Cradle2Cradle’ and Peter Luscuere via ‘Beyond Sustainability’ (Luscuere & Jansen, 2014; McDonough & Braungart, 2010).

Effectiveness

“A ‘Cradle to Cradle’ building consists of differentiated elements that embrace added value, innovation and diversity through measurable improvement of the quality of material, biodiversity, air and water, the use of direct solar energy, demountability and recyclability of the physical
Although these ideas are currently widespread, there is currently minimal input for hands-on guidelines for practice (Braungart & Mulhall, 2012, p. 5).

While currently most progress is made within the direct energy consumption area the above mentioned (‘Cradle to Cradle’, ‘Beyond Sustainability’, etc.) consider a much wider field. Peter Luscure describes this wider field with a matrix built up vertically of four vectors: water, materials, top soil and energy and horizontally of three values: economy, equity and ecology. Within this matrix the built environment should strive towards a positive impact, towards circularity. Society should strive to create a built environment that positively contributes to the mentioned vectors in terms of ecology, equity and economics.

**Natural cycles as inspiration**

In nature nothing goes to waste. Every output is used as an input for another process. Thus, every element and every bit of energy is recycled and reused. Nature is a circular system, while our society is mostly a linear system. A system with an output that is not being used: waste in the literal sense of the word. If we are to have a sustainable society, we should base it on a circular system, where waste does not exist and outputs are used as inputs for other processes. Cradle2Cradle uses the cherry tree as example (McDonough & Braungart, 2010). While its primary goal might be to grow and to multiply, while doing that it offers a variety of secondary benefits: shadow, nutrients for the soil through falling leaves, oxygen, and a place to live for little animals. In return other natural systems make sure the seeds of a tree are transported to other areas. Architect Mitchell Joachim (Joachim, 2013) sees similarities between our built environment and nature:

“Cities, unlike machines, are similar to complex ecology. Ecology is capable of achieving a continuous harmonious state, even further, a positive intensification. If ecological models are productively everlasting, urban models can logically follow.”

(Joachim, 2013)
Nature’s complexity, diversity, overproduction, abundance and heterogeneity are mentioned as important factors in maintaining and developing its endless circularity.

**Nature’s destructive force**

Nevertheless, nature’s destructive force should not be left unmentioned. Deserts, oceans, typhoons and the poles are potentially destructive environments for human beings. They are an inherent part of nature’s circular system. Currently our linear society is pushing the limits of what nature’s circular system is able to absorb. Pushing the limits even further will quite possibly force nature to find a new equilibrium, to adapt its circular system in a way that is unfit for human survival. We are currently already experiencing this in form of climate change. Nature is circular by definition and human survival depends on the size of periods and intensity amplitudes of these cycles. Through nature’s inspiration we can adapt our society’s linearity and develop a balance with ecology and ourselves.

### 1.3 The Importance of Materials

Roughly, the resources used in the built environment can be seen as that what goes in the building and that what goes through the building. In other words: that what is used to create the building and that what is used to operate the building.

**Moving focus towards Materials**

There are many strategies nowadays that focus on energetic improvement of existing buildings. Unfortunately most consist of a list of interventions on different building scales, mainly reducing direct energy consumption of lighting and HVAC (Santamouris & Dascalaki, 2002; van Miert, Verburgt, & de Ruiter, 2012). There are currently not many known strategies focusing on more effective management of materials, that what goes in, the buildings.

The ratio of embodied energy (in materials) to direct energy use currently differs between 1:5 and 1:30 (Frey et al., 2012), depending on the energy efficiency of the building. But, if energy consumption is reduced in the near future towards zero or even net-positive, the material aspect will become increasingly important (Building Green, 2014; OVAM, 2013, p. 78; Sinha, Gupta, & Kutnar, 2013, p. 6). Policy change on European level
also indicates a broadening of the definition of sustainability in the built environment to include a focus on building materials (OVAM, 2013, p. 27).

1.3.1 Material Challenges

The factor of embodied energy is only one of the relevant aspects when dealing with materials in the built environment from a 'beyond sustainable' ideology. One does not only deal with the embodied energy through labor, transportation and fabrication of the building components/materials, but also with scarcity, waste, emissions, indoor air quality and destruction of fertile grounds (OVAM, 2011, p. 14).

The Living Building Challenge, an initiative that moves beyond LEED, BREEAM and similar green certifications, sees the current tradition of material use as partly responsible for unnecessary illness (sick building syndrome), squandered embodied energy, pollution and resource depletion. The initiative describes a 'successful materials economy', as non-toxic, transparent and socially equitable (Living Building Challenge, 2010, p. 29).
Scarcity / Resource Depletion

As already mentioned before the building industry has a large impact on the consumption of raw materials. Buildings contributes for about 24% to global raw material extraction. In Europe, this adds up to around 4.8 tons per capita per year in mineral extractions for buildings only (Sinha et al., 2013, p. 2).

Although the resource extraction is extremely large, scarcity and resource depletion have limited urgency for the most widely used building materials in the building industry. That is, on a global scale. Local access to these resources can be a problem. Fluctuations in prices through speculation and uncertainty in supply are of great importance for the building industry (OVAM, 2013, p. 18; Zuidema in Workshop Materials in a Circular Economy, 2015). To decrease its dependence on import of building materials, Belgium is actively researching possibilities in connecting material cycles (OVAM, 2013, p. 18).

Waste

All of the raw materials that are extracted from the earth have to go somewhere after they have been used. To address waste and resource depletion, Cradle2Cradle and similar ideologies have a strong and unique focus on the material aspect, as brought by the phrase: ‘waste equals food’ - advocating for connecting material cycles - when compared to other tools developed for sustainable improvement in the built environment (OVAM, 2011, p. 74).
Besides in quantity and impact on the landscape, the waste has a significant impact in pollution and health through carcinogenic, mutagenic and toxic properties of waste (Luscuere & Jansen, 2014).

Pollution, Toxicity & Health Hazards

Building materials can result in a significant factor of pollution, toxicity and health hazards in different stages:

> during manufacturing processes – emissions of mines and factories;
> in use – emissions from materials themselves or maintenance, many hazardous materials are currently used in the built environment, such as asbestos, lead based paints that result in health hazards;
> the end-of-life;

(Milani, 2005; Pulaski, Hewitt, Horman, & Guy, 2003, p. 1)

Embodied Energy

The resources used for extracting, processing, transporting, using and recycling building materials have a relatively large impact on the total footprint, especially compared to the depletion or the earth’s raw resources (Jan-Henk Welink in Cradle2Cradle Lab 6, 2013).

Nevertheless, as stated above, when moving towards renewable energy resources the impact of materials will rise in significance.

1.3.2 Material Solutions

Improving building materials circular metabolism will be the main force for an effective material use. In addition to that, materials should be chosen for their characteristics that contribute to improving indoor air qualities and positive contribution to topics such as biodiversity, living quality and additional qualities.

1.4 Between ideology and practice: the Existing Built Environment

‘Cradle2cradle’ describes a built environment that is inspired by nature’s circularity. Everything is designed to have several other benefits besides its primary goal. Everything is designed to be
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input for another process at the end of its lifecycle. (Currently it is theoretically possible to create almost 100% reusable buildings. Unfortunately, our built environment has a very slow turnover rate. Approximately 0.1% of our building stock is renewed each year (Frey et al., 2012, p. 8). At least 80% of current constructions will still be there in 2030 (OVAM, 2011, p. 76). Besides, the national office for statistics predicts our population growth will halt around 18 million (CBS, 2015). Therefore, in the western world, not many new building will be built in the future. Many sources confirm that the main architectural assignment is within refurbishment, renovation, restauration and transformation and not so much in the newly built (add source). It would take very long before our built environment will completely be of ‘beyond sustainability’ standards when just relying on the newly built.

Lack of tools

Unfortunately there is currently no solution offered by Cradle2Cradle (or other similar ideologies) for the existing built environment (OVAM, 2011, p. 18). There lies an interesting challenge in making the existing built environment fit for future reuse and recycling along a beyond sustainability inspired strategy.

Complex assignment

However, this is a complex assignment. The built environment is the most static product and ‘largest single stock type’ (Ochsendorf et al., 2006). It equals older beliefs on architecture, outdated technologies and usually does not meet current building standards. Above all, it equals a lot of mass consisting of a wide variety of materials and building components that is still fit for use or, perhaps, has surpassed its economic, functional or technical lifetime. In many cases refurbishment, renovation or transformation of these buildings is needed.

1.4.1 Building Reuse

A research that brings together the topics of sustainability, lifecycle analysis (LCA; mapping a building’s costs in terms of ecology over its complete lifecycle) and reuse is ‘The Greenest Building’ report by the National Trust of Historic Preservation in the U.S.A (Frey et al., 2012). The research compares the LCA of two comparable (in terms of size and use) cases of newly built and renovated buildings over a range of different typologies. Apart
from a few exceptions, the general rule is that renovated buildings have a smaller footprint over a course of 75 years than newly constructed buildings. Even in cases where the newly built was of a superior energy efficiency, the reused would still be superior overall over a course of 75 years. Only in cases where an excessive transformation was needed, reuse surpassed the ecological impact of the newly built a little. Nevertheless, renovation would still be more environmentally responsible, in terms of climate change and resource impacts, particularly if retrofitted to advanced energy efficiency (Frey et al., 2012, p. IX).

1.4.2 Office Vacancy in the Netherlands

The recent crisis has had its effect on the existing building stocks. One of the main victims and most relevant structural problems of our built environment is the office building and its vacancy. Over 8 million sq.m. office space is currently vacant (Stef Blok in Agentschap NL, 2013) and waiting for a new user, demolition, refurbishment or transformation. Unfortunately, the demand in office space is very low. Luckily, most office buildings are fit for transformation to another function, for example mixed use and housing, of which seems to be a structural lack. Can these buildings be made fit for a new user using a Beyond Sustainable inspired transformation?
2 Problem Definition

Ideas that have gained popularity in recent decades inspire for different thinking: away from doing less bad and towards doing more good. Connecting different flows that were previously regarded as waste help develop new frameworks for a city’s circular metabolism and offer besides ecological improvement, economic opportunities.

One of the main users of materials in our world is the built environment. There are opportunities to improve health, material metabolism, quality of the environment and biodiversity by means of effective material selection and management and at the same time solve the problems of ever increasing landfills and waste streams, depletion of natural resources and toxic emissions.

Regarding material circularity in the built environment as one of the goals in the near future, the topic of the existing built environment cannot be neglected as approximately 80% of the current buildings will still be in use in 2030 and the future’s building assignment mostly considers the task of transformation, reuse and refurbishment (Botti, 2012).
3 Research Goal

This research thesis considers the material aspect of the retrofit of a 70s vacant office building in an urban context. It focuses on the application of a beyond sustainable thinking to the material aspect and adapt the building in a way that it is designed with the aspect of time in mind: fit for adaptability, disassembly and recycling to connect material cycles while improving the interior environment and user comfort through an effective application of materials. The result will be implemented in the design process.
4 Research Question

How can a design strategy focused on the material aspect inspired by circular principles help bring a 70s office building in an urban context in its retrofit beyond material sustainability?

Circular Material Principles / Beyond Material Sustainability:

> **Food is Waste**: materials do not end up as landfill, but are reused without compromising their quality. Waste of one generation becomes the raw material of the next generation. They can be reused at different points in their lifetimes in different stages of assembly.

> **A building can be seen as a material manager**. A step further than the material bank, for example explained by Thomas Rau (7.1.3 Buildings as Material Managers): a focus shift from the building as a static product towards a building in use designed to mediate between user change and material flows. How does it use materials and facilitate materials’ and products’ proper flow out of the building?

> **Materials have a positive impact** on their environment, they add value throughout their lifetimes as part of their properties or assembly. From less bad efficiency to more good effectiveness.

Methodology:

> **Literature Study** As part of the literature study, different sources have been drawn from. The most important sources are:

  o Stuart Brand’s book ‘How Buildings Learn’, describing the Shearing Layers,

  o OVAM - a Belgian organization that originated from end-of-life recycling, demolition, disassembly, sorting processes and waste processing and moved its expertise up the cycle towards building design to stimulate the connection of material cycles;

  o Different studies on LCA’s of building elements;
• The Whole Building Design Guide (WBDG) and other online sources discussing the difficulties of evaluating beyond sustainable materials;
• Workshops on materials in a Circular Economy organized by Bob Geldermans of the TU Delft where taken part in;

> **Develop Strategy** Out of the theory different considerations, conclusions and design strategies are drawn to be tested and applied to a design case.

> **Experiment by Design**
5 Research Scope & Thesis Build-up

5.1 Retrofit Elements

The material element of the retrofit of a 70s vacant office building in an urban context focuses on the following three steps. This research specifically considers laying the theoretical groundwork for the second and third step.

1) What is currently there / What happens to it?
2) What stays / How is it adapted?
3) What is added?

![Figure 3: Steps of building refurbishment – own diagram](image)

5.2 The Building

The parts considered of a building are roughly everything related to its physicality, from the site to furniture with a focus on structure, façade, services and interior finishing; and in time the construction process, use process and end-of-life process. Stuart Brand’s Shearing Layers (source): site, structure, skin, services, space plan and stuff are used as a framework – with a main focus on structure to space plan, the main architectural tools. Further explanation of these layers follows in the thesis (7.4 Shearing Layers).

5.3 Efficiency and Effectiveness

The thesis draws a connection between the move from efficiency towards effectiveness as advocated for by Cradle2Cradle (McDonough & Braungart, 2010). Within the thesis, their definition is approached as depicted in the diagram below, showing that one does not exclude the other.
As is shown, sustainability is commonly approached as increased efficiency, being less bad while doing the same. Extending lifetimes and spreading the impact. Beyond Sustainability is a complete turnaround, moving away from a negative impact, or a zero impact, towards a positive impact. Renewing lifetimes through recycling.

Be efficient with everything that is effectively negative and be generous with everything that is effectively positive.

### 5.4 Two perspectives on materials

The thesis approaches materials from two perspectives (figure 5), as depicted in the diagram showed above. These perspectives are not necessarily separate, but at times overlap and complement.

**Building Perspective**

Starting with the building perspective (1) - materials in assembly – the main question evolves around how a building framework can facilitate a beyond sustainable material focus: connecting cycles and adding value. To design a proper lifecycle for materials a view upon the sustainability of the built assembly is essential as well (OVAM2,88). Therefore, topics of design for adaptability, design for disassembly and Stuart Brand’s Shearing Layers are discussed, shifting focus from a building as a finished product to a building in use dealing with future uncertainty.
Material Perspective

The second part deals with the *material perspective* itself (2), how it cycles through the built environment and adds value along the way. Different variables in material metabolism are discussed in addition to the specific qualities and performances of beyond sustainable materials.

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*Figure 5: Two parts of the research: from a building perspective (1) and from a material and product perspective (2)*

— own diagram
Building Perspective: The Building mediating user and material

Connecting material cycles in the built environment means proper design, proper assembly, proper management, and proper end-of-use handling.

As the material and the assembly of it is a specific product of its time and projected use and the future is full of uncertainties assumptions on potential future reuse and recycling are difficult to make.

This section focuses on time and future uncertainty from the perspective of the material as assembled - the building - and how a building can be designed to facilitate the currently unknown future and therefore, material reuse.

As an introduction to the section, a short elaboration on the factors that influence the lifespan of a building. This is followed by an elaboration on the different variables of change and the way a building can adapt to these. The second chapter of this section bridges the gap between theory and practice and indicates tools that can assist designing a building for change.
6 Factors of Change

6.1 Change in the built environment

The lifetime of a building is commonly defined by all, one or a combination of three factors:

> Technical
> Economical
> Functional

(Fernandez, 2012)

Technical → Economical

The previous century encountered a shift from the technical factor as defining the end-of-life towards the economical factor as defining (Fernandez, 2012, p. 37). In his book ‘Sustainable Materials’ MIT professor John Fernandez (2012) shortly summarizes the history of end-of-life and the development of obsolescence in the built environment.

Before industries, when houses were built with only natural materials, their lifetime was defined by the technical characteristics of these materials. They were usually low performance, low durability and demanded seasonal maintenance (Fernandez, 2012, p. 37).

Currently the end-of-life of a building is decided by forces that do not have any direct relation with the physical condition or the design of the building itself (Fernandez, 2012, p. 40). Fernandez mentions “aesthetic discrimination, user preferences, market-related fluctuations and evolving social norms for work and living”. The end-of-life, or obsolescence, is defined by “real estate and financial markets, urban planning and zoning code agencies, corporate and governmental owners and building managers” (Fernandez, 2012, p. 40).

Three Discourses

Fernandez refers to three different discourses that have defined obsolescence in the built environment in the last century (Fernandez, 2012, p. 37). The financial discourse creates obsolescence when the costs of demolition and new construction can be covered by increased rent or income. Often, this is a result
of the value of location. The location of a building is as important as the physical presence of the building itself. Often potentials of place (or the lack of) are driver behind defining obsolescence. Fernandez explains two types of rent: LDR (location-dependent rent) and BDR (building-dependent rent). When the potentials of LDR exceed BDR generously, space for improvement is created.

The urban discourse creates obsolescence as part of urban redevelopment schemes. Large building stocks are replaced by new urban developments.

Lastly, the consumer discourse introduces progressive obsolescence, planned obsolescence and creative waste to stimulate and fulfill the constantly evolving consumer needs by artificially creating redundancy through styles, fashion and purposely phased technological advancements (Fernandez, 2012, p. 42; Marchand, 1985, p. 156).

Fernandez doubts the possibility to understand building lifetimes and predictions of future utility when the “enormous material consumption of construction” is completely based on the constantly changing and “constructed notion of obsolescence” (Fernandez, 2012, p. 41).

The goal is to bring permanence back into the cycles of the built environment, either by reusing materials or even complete buildings, while still facilitating change.

**A building's lifetime**

Often is referred to a building’s projected lifetime with one time period, mostly around 60 years (OVAM, 2013, p. 88). In the aspect of technical lifetimes, this does unfortunately not take in account the diverse range of lifetimes the different physical elements which the building is constructed of. For instance, the lifetime of the reinforced concrete structure of an average building could be standing for as long as 100 to 200 years, while the technical lifetime of the interior divisions or façade ranges from 2 to 30 years. These different layers will be elaborated in [7.4 Shearing Layers] along the theory of Shearing Layers developed by Stuart Brand.
**Resonation between material and use**

Highly generalized, change and the built environment is a two-fold that engages in a highly reciprocal relationship: internal driven changes (technology) and external driven changes (economics and function). The main goal of this section is to find how these two, the building as a physical entity and the way in which a building is used, can resonate.

→ **[Design Strategies]: Change**

Design a building that mediates use and material change.
6.2 Change in the building

“The only constant is change”

Modernism has created the idea of the perfect building, a finished product (Brand, 1995, p. 36). But as described by Fernandez buildings should not be seen as a static product, but as something that changes over time to fit its changing user’s needs, changing social and economic environments and to incorporate technological improvements (OVAM, 2013, p. 88). The built environment should be designed with the passing of time in mind.

Unpredictable Future

As already stated in the previous paragraph, predicting the future, and thus the future use of a building, is impossible. Nevertheless, assumptions can be made using a scenario strategy – as will be elaborated further on (6.2.3 Scenarios).

“We should not try to predict what will happen, but we should try prepare for that what cannot be foreseen.”

John Habraken in ‘De dragers en de mensen’ (1961)

Evolution and change should be anticipated. Buildings should be designed with the ability to facilitate different uses in time (Braungart & McDonough, 2009).

[Design Strategies]: Design with time

Design with time in mind: consider the uncertain future, develop different future scenarios for the building and allow for change.

6.2.1 Focus on Use Phase

“The most interesting period for a building is between creation and demolition or preservation — when it’s changing.”

Stuart Brand (1995, p. 10)

Stuart Brand advocates for a shift of focus from the building as a finished product towards a building as a changing process. He refers to Jane Jacobs and Christopher Alexander for a shift from ‘cataclysmic money to gradual money’, investments spread over the lifetime of a building, at the start into the structure, during life
into maintenance, refurbishment and adaptation (Brand, 1995, p. 85).

Brand criticizes the fact that a disproportional amount of initial investment is spend on finishings and the façade, while the structure of the building is the basis for potentials of adaptation, and is the part of a building that lasts longest and most users can profit from (Brand, 1995, p. 190).

Nevertheless, also in Brand’s theory, over time the total investment into finishing and the façade can be much more than into the structure, due to renovations, maintenance, etc. This will be addressed in a more quantified and qualified manner in the second section of this thesis, that addresses the issue from a material and component perspective (chapter 8 and specifically 8.5 Impact of materials, building components, building elements).

![Figure 6: Accumulated costs over the use phase – figure by Frank Duffy via (Brand, 1995, p. 10)]

| Figure 6: Accumulated costs over the use phase – figure by Frank Duffy via (Brand, 1995, p. 10) |

[Design Strategies]: Focus on Use Phase

Focus on the use period and allow for future changes facilitated by a division between more permanent and more temporal building elements.

6.2.2 Variables of Change

Different variables change over the course of time, driven by forces as mentioned in the first paragraph: economics, technology.
and functionality. The division proposed in that paragraph and the ambition to resonate these two is continued in these variables, external and internal.

These variables need to be mediated by a building’s physical facility. These variables have to be taken into consideration when designing a building for adaptability.

**External: Client / User**

Because a building usually outlasts its primary client, it needs to be designed with future clients in mind as well. It can be seen as a cross-generational product (Ochsendorf et al., 2006). Therefore, a building should go beyond its primary program of demands to be able to facilitate future uses as well.

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*Figure 7: a normal product and its relation to its client (left), a building product and its relation its client (right) – image via MIT OCW (Ochsendorf et al., 2006)*

Park 2020 in the Haarlemmermeer is an example where the developer Delta Developments stimulated attention for post-usage: “the design must […] not only involve the current requirements of the principal/project developer but must also consider the changing requirements of subsequent owners or tenants” (OVAM, 2011, p. 67).

The scenario planning discussed in the next paragraph forms an alternative for architects to a client-specific program or brief (Brand, 1995, pp. 178-181).

**Adaptation to serve the user**

Adaptation to changing clients does not only originate from a need for material circularity. It is also a way to serve the client:
allowing adaptation to the user will make the client feel more at home, more appropriated (Frans v/d Werf in Workshop Materials in a Circular Economy, 2015).

Client adaptation

Even though this thesis focuses mainly on adaptation from a building and material perspective, the user can change as well. By changing its customs, traditions or daily cycles a user can fit itself to a specific physical facilitation. This can be very minimal adaptations, as accepting a higher interior temperature when outside temperatures reach a certain height, or maximum adaptations, by changing places and moving to other spaces. This distinction follows the earlier described twofold of internal and external driven changes – user adaptability and building adaptability (Rob Geraedts and Remko Zuidema in Workshop Materials in a Circular Economy, 2015).

External: Function

Scenario planning can also be a tool to map potential function changes in the future. Brand refers to William McDonough as an architect that always insists that new offices can be retrofitted into dwellings, because dwellings are the core building type (Brand, 1995, p. 174). Apart from dwellings, less extreme function changes can be imagined as well, different types of offices, shops and conference centers. More extreme function changes would be a cinema or cultural center, as they need spaces of a significant different size.

A building that can adopt function change is more efficient with both material and space use. It allows a city to easily manage the dynamic of demography, growth of cities, etc. (OVAM, 2013, p. 94).

Buildings that are situated in dense urban fabric, should generally be able to shift between housing, different office trends and commercial activities (Brand, 1995, p. 7).

Internal: Materials / Technology

Material or technology can be a variable as well. For a beyond material sustainability perspective, there might be the need that
materials have to be recycled, or they are services and are out of lease. Then, they have to be able to be changed by something else.

There is also the possibility that new and improved materials, components or technologies are available. The ambition to change the material might result from either the Program of Ambitions and the Roadmap, or from stricter legislation. For instance, the norms for lighting, ventilation and energy use have been doubled in the last ten years. Buildings should be made to be able to adapt to these new rules (OVAM, 2013, pp. 88-90). Another possibility is the discovery of new hazardous materials.

**Internal: Program of Ambitions and Roadmap**

‘Cradle to cradle’ aims for a world where all food is seen as waste. Because a true ‘cradle to cradle’ building is not possible yet, buildings and clients can only speak out the wish to become ‘cradle to cradle’. During the design stage, a Roadmap is defined along a Program of Ambitions that maps future improvements or milestones towards becoming 100% ‘cradle to cradle’ (McDonough & Braungart, 2010).

### [Design Strategy]: Variables of Change

- Design the building for future clients;
- Design the building for future functions;
- Design the building for future technical innovation, guided by a roadmap;

### 6.2.3 Scenarios

“All buildings are predictions. All predictions are wrong.”

*(Brand, 1995, p. 178)*

Scenarios can identify possible futures. Stuart Brand describes a short method to identify different possible scenarios that can move the design process towards a focus on the use phase.

“Gather consensus expectations about future from major players:

1) Day one: Identify focal issue or decision. Explore driving forces. Identify most important and uncertain forces. Identify basic plot lines of scenarios — should be both plausible and shocking. Think the unthinkable.
Section 1: Building Perspective: The Building mediating user and material

2) Day two: Adjust scenarios, name them (2-5 scenarios, ignore probability). Devise a strategy for the focal issue/decision that is viable in all scenarios. Identify leading indicators that will show which scenarios (if any) will come to pass.”

(Brand, 1995, pp. 181-183)

[Design Strategy]: Scenarios

➢ Develop a scenario, along lines inspired by Brand’s scenario design process. Indicate within this scenario how variables such as users, functions, technology and the sustainable development can evolve.

➢ Allow change of separate parts of the building, without harming other parts.
6.2.4 Qualities of Buildings that Stay

To learn of buildings in time, it is essential to have a look in history. Many buildings in our built environment have been built decades, centuries or even thousands of years ago. Among these buildings are works that have been specifically built to last, like pyramids and mastabas. Others are still standing because of a variety of other reasons, for example: silos, barns, houses and warehouses (Mora, 2007, p. 1333). How come they are still here? Is this because they are so adaptable and/or durable or because of some other reason?

Durability and maintenance

Physically, buildings last due to either one of two reasons: material durability and maintenance. If buildings are made out of materials that can survive extreme circumstances, they tend to last. But if buildings are made out of low performance materials, but are maintained well, they can last as long as their durable counterparts (Mora, 2007, p. 1334).

Unfortunately, in many buildings regular maintenance is often replaced by occasional repair or reconstruction, only after damage has inflicted and the building’s function is significantly compromised (Mora, 2007, p. 1331). This severely influences a building’s potential age.

Buildings with qualities

Buildings that have qualities that facilitate a comfortable environment to reside, often live longer, and are more often reused, than buildings that clearly lack comfort. A healthy interior environment, proper daylight penetration, a comfortable interior temperature, aesthetical qualities, proper acoustics and adaptable spaces all create a building that people want to keep (OVAM, 2013, p. 20). These qualities might ask for a bigger prior investment, but will save future expenses and add extra value.

Over time, buildings can become ‘loved’. People tend to prefer old buildings that show life, history and age. Buildings that show they are part of the evolution (Brand, 1995, pp. 10-11). However, many buildings that at some point enjoy being ‘loved’, do not experience this from their conception. For Jouke Post, architect of the further elaborated temporary office building Project XX, buildings should always have an ‘end date’ – it does not matter.
whether this is 20 or 200 years. At a point where they might become ‘loved’ efforts can be made to extend this planned lifespan (Jouke Post in Workshop Materials in a Circular Economy, 2015).

**Material circularity**

That building’s last does not necessarily mean that they are more sustainable than others that do not last. In some way could be stated that they are more efficient, because they spread their impact over a longer time period. However, due to their permanence and durability they do not allow many changes, that might overall be more effective. In addition to that, when moving towards a circular material economy, durability in a sustainable sense becomes less important (Jouke Post in Workshop Materials in a Circular Economy, 2015).

The next paragraph relates to two strategies for a building to deal with future uncertainty and time. One of the strategies strongly relates to buildings that tend to last, while the other approaches time and material circularity from a completely different perspective.

---

**[Design Strategy]: Qualities of Buildings that stay**

- Develop a building with user comfort;
- Find a balance between durable materials and maintenance, in line with earlier mentioned permanence and temporality.
  Allow easy maintenance, if needed.
### 6.2.5 Dealing with future uncertainty

Ways through which can be dealt with future uncertainty can be split in the following categories:

<table>
<thead>
<tr>
<th>Renovation</th>
<th>Demolition and new construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptable / flexible buildings</td>
<td>Design for disassembly / temporary constructions</td>
</tr>
</tbody>
</table>

*Table 1: Inspired by (Ochsendorf et al., 2006)*

The left two and the right two can each be seen as two extremes of the same strategy. Renovation and demolition do not anticipate change beforehand, while flexibility and disassembly do – and thus potentially have a much smaller impact when the need for change arises. In the table below, both strategies are compared in the way they anticipate uncertainty.

<table>
<thead>
<tr>
<th>Uncertain futures</th>
<th>Designed for disassembly / permanence in materials</th>
<th>Adaptable building / permanence in building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoiding uncertain futures.</td>
<td>Anticipating uncertain futures</td>
<td></td>
</tr>
</tbody>
</table>

| Adopting change | Designed for a fixed amount of time and a planned date of disassembly. All materials are planned to be reused or recycled. | A building designed for an indefinite period of time and is shaped in a way to be able to adopt different functions. |

| Materialization | A demountable framework that is assembled for a specific function but can be reused or recycled to fit other shapes as well. | A generic grid of high performance materials with the ability to serve different functions. |

| Positives | + Custom-fit on all scales + Low impact on site | + Saves resources + Saves demolition and construction energy + Saves nuisance of demolition and new construction |
## Table 2: Comparing Design for Disassembly and Design for Adaptability (own table)

<table>
<thead>
<tr>
<th>Negatives</th>
<th>Effective or efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Energy intensive</td>
<td>- More effective in terms of material circularity;</td>
</tr>
<tr>
<td>- Resource intensive</td>
<td>- Materials will be designed for a fixed period of time, that relates to the period of use. Products can become services;</td>
</tr>
<tr>
<td>- Burden of demolition and new construction</td>
<td>- More efficient in terms of material circularity;</td>
</tr>
<tr>
<td></td>
<td>- The ‘negative’ impacts of a building are spread over a longer time period;</td>
</tr>
<tr>
<td>+ Gradual change is allowed</td>
<td>- Custom-fit only on lower scale</td>
</tr>
<tr>
<td>- Energy intensive</td>
<td>- Heavy impact on site</td>
</tr>
<tr>
<td>- Resource intensive</td>
<td></td>
</tr>
<tr>
<td>- Burden of demolition and new construction</td>
<td></td>
</tr>
</tbody>
</table>

### Nuisance

Within this context, construction nuisance and context of a building is an increasingly important factor that adds to the urgency of building adaptability. In a world where most big cities, growing at increasing rates, never do without big construction projects, being amidst of construction workers, cranes and fences, is increasingly more rule than exception. The nuisance of construction projects results in, especially in dense urban areas, temporally reductions of economic profits and building and land value. Remko Zuidema expressed during the circularity workshops the rising willingness of municipality, businesses and other actors towards lean buildings in the main Amsterdam business district, the Zuidas (Remko Zuidema in Workshop Materials in a Circular Economy, 2015). This offers an opportunity to stimulate material circularity at the expense of reducing construction nuisance.

Stuart Brand (and Fernandez, in the introduction of this chapter) mentions the high prices of land in compared to buildings. He refers to Tokyo as an example: the average building lifespan during the 1980s was only 17 years (Brand, 1995, pp. 81-82). Until now, this has resulted in an extreme high turnover of buildings.
Remko Zuidema elaborated that new building regulations in Japan legally demand the application of the Open Building concept (Workshop Materials in a Circular Economy, 2015).

> [Design Strategies]: Dealing with future uncertainty

- Consider the aspects of design for adaptability and design for disassembly to create a building that can deal with future uncertainty.
- Construction nuisance in dense urban contexts can temporally result in reduced profits and building and land value, this can be an extra incentive for adaptive construction.

### 6.2.6 Lessons from Practice

Throughout this thesis, two project are often referred to in particular. Project XX, an office project by XX Architecten (Jouke Post), was built in 1999 to remain standing for only 20 years. The Solids are multifunctional buildings in Amsterdam, based on the ideas of structure and infill by John Habraken, as elaborated later (7.3 Open Building).

### 6.2.7 Disassembly example: Project XX

Project XX is an office building in Delft that has specifically been designed for a use period of 20 years by XX architects (then headed by Jouke Post). After the 20 years, the building can be disassembled and all materials can be reused or recycled. This way the technical lifetime of the building has been designed to the economic lifetime (Post & Klomp, 1998, pp. 15,16,19). During the use period, adaptability of the office plan is allowed, cubicles, small offices and larger open office plans are all possible (Jouke Post in Workshop Materials in a Circular Economy, 2015).

The ideas of Jouke Post are clearly present in this building. He states that the initial investment of adaptability is often too high and use is uncertain. He considers the correct management of materials, and securing the circularity, of a higher importance. Within that thought, it is important to decide on a certain lifespan of the building, whether this is extremely long (200 years) or short does not matter, as long as material management is appropriated to it. He agrees with Habraken that future uncertainty might decide differently, but if a building (with a temporal character) might be still of use when approaching the end-of-life date,
measures can be taken to maintain it (Jouke Post in Post & Klomp, 1998; Workshop Materials in a Circular Economy, 2015).

Figure 8: Project XX in Deft by Jouke Post – image via Leo Hooijmans

[Design Strategies]: Lifetime of a building

- Define the end-of-life of a building, or of building components, to secure a plan for material recycling. However, allow future uncertainty to change these plans.

6.2.8 Adaptable example: Solids

The three recently finished Solid buildings in Amsterdam are an example of the application of the ideas of John Habraken of Drager (structure) and Inbouw (infill). They are the result of three objectives: increased freedom of choice, increased profit and a longer lifespan (Wallagh, 2013, p. 2). These buildings are designed to the excellent durability of a structure and the adaptability of the infill. Within a durable structure that facilitates accessibility, routing and primary services and installations users are free to construct their own infill and influence fragmentation of the building in different apartments, offices and shops. Ownership is divided along these ways as well: the structure is owned by the investor, the infill is owned by the user. They are free to use their cell for almost any function, as long as they do not cause excessive
nuisance to their neighbors. Most common functions are dwellings, working and gathering (Wallagh, 2013, p. 50). The structure and facilities for services have a certain oversize to facilitate the different possibilities, for example generous floor heights and floors dimensioned for 5 kN/m² (Wallagh, 2013, p. 13).

In a sense, this building may be seen as a combination between design for adaptability and design for disassembly.

A post-occupancy study, which will be referred to when discussing the concept of Open Building further on (7.3 Open Building), indicates, among other things, that opportunities are researched to re-appropriate existing buildings into multifunctional, Solid-type buildings (Wallagh, 2013, pp. 2,32), to connect the problems of structural vacancy, the need for flexible functions in urban environments and sustainability.
7 Tools to Change

This chapter focuses on more practical tools, guidelines and methods that form the bridge between the above theoretical part to everyday design practice. The chapter covers both the topics of design for disassembly, design for adaptability and connects these with the shearing layers concept of Stuart Brand and the structure and infill concept of John Habraken.
7.1 Design for Disassembly

This chapter focuses on the importance of disassembly of a construction to facilitate recycling and reuse of materials and building components.

First, the currently most common challenges in design of disassembly are quickly viewed upon. This is followed by the main part, different important lessons to take in account in disassembly design. Lastly, disassembly is related to another view on buildings: as material banks.

Design for deconstruction is a critical component of sustainable design that strives to close the loop on material reuse.

(Pulaski et al., 2003, p. 9)

7.1.1 (Dis)assembly Challenges

Lack of correct product assembly

One of the important challenges in connecting material cycles lies in a renewed relation between architect and manufacturers of building products designed and fabricated for recycling and reuse. The task of the architect is not only to choose the right product, but the correct application of these products into the building. The wrong assembly of, for example, a ‘Cradle to Cradle’ certified material, can shatter the created potentials for connecting material cycles. There is a very important role and challenge for the architect to design a proper assembly (OVAM, 2011, p. 74). The way products currently are used in a building, often hinder reuse (OVAM, 2011, p. 52). In the second section of this thesis material circularity will be focused upon from the material and product point of view.

Lack of knowledge and tools

OVAM notices a lack of concepts and building products for ‘dynamic retrofitting and new construction’. This, in addition to financial and infrastructural constraints, complicates the ability to design for disassembly to facilitate the connection of material cycles in practice (OVAM, 2011, pp. 74, 86).
7.1.2 Principles of Disassembly

Pulaski et al (2003) proposes ten principles to improve the design for disassembly of a building. Some of the principles are rather general and already touched upon in other parts of this thesis. The six principles below are used as a basis and partly elaborated on from other sources, for example: IFD (Industrial, flexible and demountable building), as described by OVAM (OVAM, 2011, p. 2).

[1] Design for prefabrication, preassembly and modular construction

The discussion on modular construction is elaborated in the second section of this thesis (8.1.8 From material to product: the level of assembly and the potential of recycling or reuse). Although standard sizes are commonly seen as facilitators of reuse and recycling (OVAM, 2013, p. 43), customization of sizes is currently as easy as the once standard sizes due to the rise of the computer and parametrization.

Prefabrication and preassembly allow for an improved (dis)assembly, besides reducing construction times and nuisance (OVAM, 2013, p. 88; Post & Klomp, 1998, p. 20).

[2] Simplify and standardize connection details

Stimulates connections to be fastened mechanically instead of chemically (welding, adhesives, etc.) (Pulaski et al., 2003, p. 8). Make sure connections are accessible (WBDG, 2015).

Principle six is related: “Select fittings, fasteners, adhesives and sealants that allow for quicker disassembly and facilitate the removal of reusable materials” (Pulaski et al., 2003, p. 5).

A few innovative examples are mentioned during the circularity workshop, for example the ‘Clickbrick’, a brick that can be used without cement. This both improves reuse potential and recycling potential, as the stone is not mixed with concrete (Re:Purpose and Jouke Post in Workshop Materials in a Circular Economy, 2015).

[3] Simplify and separate building systems

This principle resonates with the Brand’s Shearing Layers as elaborated in the following paragraphs. To allow easy disassembly of different systems with unique characteristics, one should be
able to replace the one without touching another. For instance, separating services and structural walls (Pulaski et al., 2003, p. 4). This way early demolition of a complete building can be avoided, because it would be too expensive to replace a certain component (OVAM, 2013, pp. 88-90)


A building of change: allow frameworks and infrastructure for save adaptations of building elements. For instance, minimize the amount of overhead work, design light weight construction elements that are easy to handle (Pulaski et al., 2003, p. 4).

Principle seven is related: “Design to accommodate deconstruction logistics” (Pulaski et al., 2003, p. 5).


Polaski mentions the minimization of finishings by making the structural elements fit as finishing (4).

However, if certain paints or finishings have a positive effect on the interior comfort, for example by collecting dust particles, use should not be minimized. Minimization of material use is elaborated in the second part (8.1.10 Reducing depletion and waste: Minimize Material Use).

[8] Reduce building complexity

Polaski mentions for instance the use pre-stressed beams as increasing the building complexity (Pulaski et al., 2003, p. 5). However, the same pre-stressed beams could be a product of prefabrication that can be reused in modular construction and easily disassembled.

The next paragraph elaborates the necessity of information technology and proper facility management to secure disassembly, adaptability and proper material management during the use phase of the building. A reduced building complexity can make this process much easier.

In the second section a paragraph is focused on the trade-off between increased functionality and assembly and decreased potential for reuse. Especially in the light of composites, this is an
important discussion (8.1.8 From material to product: the level of assembly and the potential of recycling or reuse).

7.1.3 **Buildings as material managers**

The goal to which design for disassembly is a means is to increasingly see buildings as material banks. In anticipation of the increase of urban mining, building mining and landfill mining one could see our complete building stock as material banks that hold valuable raw materials for future use (Rau, 2015). Materials can be seen as the future currency (Braungart & McDonough, 2009).

New buildings (and old buildings) should have material passports to increase potentials for and facilitation of material pooling and reuse (Mulhall, Braungart, & Hansen, 2013).

They should include information on:

- Disassembly
- Materials
- Flexibility / adaptability

*(WBDG, 2015; Workshop Materials in a Circular Economy, 2015)*

**Improving maintenance and facility management**

According to Stuart Brand, facility management should be of much higher importance, to allow for more priority for the use period (Brand, 1995, pp. 110-132).

The above mentioned information could be a vital ingredient to proper facility management. Drawings are never made of the building as built. Information management of the building in use phase should be improved (Brand, 1995, pp. 196-200).

Stuart Brand refers to designer/builder John Abrams. For each building he created a book, full of pictures of the building in construction that showed information on services, connections and used materials (Brand, 1995, pp. 196-200).

In modern times, BIM is a tool to do this. The material passport, where all materials and their status present in a building are kept up to date, can be integrated into the BIM model (Workshop Materials in a Circular Economy, 2015).
Proper information dissemination to the right scales is of importance as well. Schools are often equipped with moveable interior walls to separate or join two classrooms, mostly these are not used, because teachers are not told how to. During the circularity workshop at the TU Delft, Rob Geraedts mentions an example of a housing project, where an extra foundation was poured to allow future expansion. After several years appeared that most people did not expand their houses, and the people that did, did not make use of the foundation – because they were not aware of it (Rob Geraedts in Workshop Materials in a Circular Economy, 2015). This raises questions on the value of the extra investment needed for these foundations and the way in which these potential for change are communicated.

[Design Strategies]: Buildings as Material Managers

- Develop a framework for information management in materials, adaptability and disassembly to serve the goal of material pooling, connecting material cycles, but also improved maintenance and improved management of adaptability.
7.2 Open Building and Shearing Layers

Two theories resonate with the idea of a combination between design for adaptability and design for disassembly. The Open Building concept by John Habraken, that divides a building into structure and infill both in physical sense as in management and ownership. The Shearing Layer concept of Stuart Brand adds nuance to this division and divides a building into six different layers: site, structure, skin, services, space plan and stuff.

Both theories complement each other and allow a framework that can facilitate the connection of material cycles in a building.
The concept of structure + infill is an idea that is in accordance with the division between disassembly and adaptability as expressed above: structure (a 100- or 200-year framework that allows different functions, adaptable) + infill (specific for each function, changes over time, demountable). The principle of open building attempts to have the change in use resonate with a minimal but effective amount of physical.

An important aspect of Open Building is the division of ownership. The structure is supplied and owned by the investor, the infill is supplied and owned by the user.

Examples or building typologies that relate to the idea of Open Building are for instance shopping malls and the Groothandelsgebouw in Rotterdam (Wallagh, 2013, p. 2). In different countries around the world similar concepts are applied, for example in Helsinki and in Japan. The latter, mostly related to the concern expressed before, as the difference between housing and land prices stimulates very short building lifespans and an enormous disturbance of building projects (Remko Zuidema in Workshop Materials in a Circular Economy, 2015).
[Design Strategies]: Open Building

Resonate ownership and use with the division between more permanent building systems and more temporal building systems as advocated by John Habraken.

7.3.1 Additional benefits of user influence

The approach of Habraken leads to increased customization. Users have a bigger impact on the interior layout, what, according to Brand, creates ownership and connection (6.2.4 Qualities of Buildings that Stay). This influences the usability and the comfort of a building. The Open Building system also allows a new user to more quickly adapt his surroundings to his needs (Brand, 1995, p. 164). Brand quotes Brain Eno, age and influence have people appreciate buildings:

"An important aspect of design is the degree to which the object involves you in its own completion. Some work invites you into itself by not offering a finished glossy, one-reading-only surface. This is what makes old buildings interesting to me. I think that humans have a taste for things that not only show that they have been through a process of evolution, but which also show they are still a part of one. They are not dead yet."

(Brian Eno in Brand, 1995, pp. 10-11)

Brand sees this capability of having users adapt the building as ‘satisficing’ (Brand, 1995, p. 165). Although he sees this in a rather extreme DIY-way that many users might not experience as satisfactory, the opposite of the perfect ‘stylistic’ interior, done by professional interior designers, is probably less appealing – as there is zero tolerance for user adaptation (Brand, 1995, p. 166).

Through these encounters, a building can learn. Crafty solutions done by users can slowly and organically develop into real solutions, integrated in the infill. This way a resilient structure can be developed through time (Brand, 1995, pp. 21,167).

7.3.2 Level of adaptability and division structure and infill

The Solids are a recent application of the concept of Open Building. In a study done some time after occupants moved into their new accommodations some lessons for future adaptable buildings were learned (Wallagh, 2013). The main doubt was the need for the high level of adaptability and the high extra initial
investments that resulted from it (Wallagh, 2013, p. 50). New Solids, should still have a generous freedom of choice, but a somewhat limited level of adaptability. Not maximum adaptability everywhere, but the right amount at the right place, to limit initial investments, a Solid Light (Wallagh, 2013, pp. 2,32). Special functions, such as restaurants and cafés can only settle at these locations, that should be supplied with extra service amenities as well (Wallagh, 2013, p. 51).

The saved investments could be shifted towards improved service amenities as part of the structure, such as the bathroom. In the original Solid buildings they are part of the infill and the user. But due to the complexity and the rather obvious location of the wet cells, many clients expressed that this could be part of the structure (drager). Service installations such as the fuse box were also mentioned to be better part of the common structure (Wallagh, 2013, pp. 2,33).

Facilitating adaptive activities

As the construction of the structure and infill do not occur at the same time, the essence of vertical connections was mentioned at several occasions to facilitate construction activities. For example, the window sizes of the Solids are dimensioned to facilitate these activities (Wallagh, 2013, pp. 20,50). In an Open Building project, that also stimulates material circularity, facilities like these would be even more important – to perhaps temporally store certain building elements.

[Design Strategies]: Structure and infill

- Define the border of structure, infill and ownership ideal for researched scenarios, functions and clients.
- Find an appropriate level of adaptability ideal for the to be refurbished building, researched scenarios, functions and clients.

7.3.3 Open Building and Material Circularity, a potential conflict

Connecting material circularity and Open Building do not necessarily go hand in hand. While in a technical way the concept forms a proper framework for material circularity, it can be questioned whether this will happen in practice without any extra measures.
To ensure sustainable material use, both investor and user need to conform to use certain materials and a specific type of assembly – to allow reuse and recycling (and sustainability in general). This is where the Open Building principal complicates the connection of material flows, especially the decentralization of the responsibility for building materials with the highest ecological impact. This impact is further elaborated in the next section, where the ecological impact is estimated for each of the Shearing Layers (8.1.8 From material to product: the level of assembly and the potential of recycling or reuse).

Different strategies can be adopted to stimulate material circularity in an Open Building framework.

**Strict rules**

Strict rules for users to abide to in terms of material selection and design for disassembly is one option to secure material circularity. Nevertheless, the complexity that comes with sustainable material selection, as explained in the second section, might go beyond the willingness of the user.

**Common infill**

Material flows might be best secured top-down and not bottom-up. A flexible infill system applied top-down might be a solution, allowing flexibility for the user, with common sustainable material selection and disassembly approved connections. However, this contradicts the concept of Open Building.

**Infill-contractor**

During the material circularity workshop meetings different companies are mentioned that are looking to or are already specialized in the design and fabrication of infill packages. These companies could be the security of material circularity of the infill, as they can develop as service providers instead of product manufacturers. Take-back guarantees or fixed time lease contracts secure reuse and recycling (Workshop Materials in a Circular Economy, 2015).

**Connecting decision making and (financial) relevance**

From another perspective decentralizing decision making might automatically stimulate reuse and recycling. Downscaling decision making to a scale where the directly related are much more
involved in the financial and logistic benefits and drawbacks of recycling and reuse. If recycling and reuse opportunities and related infrastructure and businesses are more widespread in society, this triggers a more natural development of material circularity at a much more relevant scale – the scale of the people. An example: the trouble of going through the sale of a component, say a kitchen, is for the direct owner a much smaller hazard than for a building owner or manager.

**Combination**

A combination of the last two seems to be most in accordance with a beyond sustainable scenario. A specialized infill contractor that provides a service for the client. Who, in his or her part, is aware of the financial and ecological benefits resulting from material recycling. This might limit the freedom of choice up to a certain level, but as was learned in the previous paragraph, the level of adaptability – compared to the Solids project – might be a little bit toned down.

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**[Design Strategies]: Open Buildings and Material Circularity**

- Secure material circularity of the infill by having a material infill subcontractor or consultant to manage material flows and secure scalability of reuse and recycling.
- Define guidelines and specifics for infill to stimulate material performance, interior comfort and material circularity.
7.4 Shearing Layers

As already expressed before, the Shearing Layers add an extra distinction to the division between structure and infill of the principle of Open Building.

Buildings are complex assemblies of different materials and building components that have different characteristics, lifetimes and functionalities or, as stated in John Oschendorf's lecture on MIT OCW: ‘buildings are meta-systems composed of complex semi-autonomous systems (with distinct lifecycles)’ (Oschendorf et al., 2006). Viewed from a perspective that looks to effectively use materials, a building should be designed in a way to guarantee a material’s or building component’s optimal flow through the building-, built environment-, biosphere- and/or technosphere cycles. The previously mentioned concept of Shearing Layers by Stewart Brand is fit to do so by a frictionless division of a building into different layers, being: site, structure, skin, services, space plan and stuff. In general, the concept of Shearing Layers help a building grow and adapt over time, within this framework material cycles can be connected.

Of course Stuart Brand’s layers are not the only theory that divides a building into different entities with different characteristics. Frank Duffy divided a building into four layers, being: shell, services, scenery, set, and was an inspiration to Brand (Brand, 1995, p. 12).
Frictionless interfaces

As each layer has its own properties with different responsible actors, designers, lifecycles, ages, uses and adaptabilities. The slower changing should not block the faster changing, there should be some allowance free of friction. Nevertheless the slower layer (structure, for example) do form the framework for change of more fluent layers, but in return, structural changes of these fluent layers can affect the slower layers (Brand, 1995, p. 17).

"the quick processes provide originality and challenge, the slow provide continuity and constraint."

(brand, 1995, p. 17)

This is an effective framework to facilitate design for disassembly, user change, functional change and development. Nevertheless, it contradicts some current philosophies on efficient sustainability, such as minimal material use through the integration of different building components. This might result in initial savings on material use, but through more intense recurrent construction work during the use phase of a building this will increase the total lifecycle impact. This is further elaborated in the second section of this thesis (8.1.8 From material to product: the level of assembly and the potential of recycling or reuse).

If designed, used and produced properly, materials and building components could end up in new buildings, products or be returned to nature as a nutrient. How do we handle the reordering of material at each shearing layer?

Brand also mentions a few examples that are specifically bad or good. A slab-on-grade is a bad example, as service pipes are buried in concrete and usually there lacks a basement for storage, expansion, maintenance and services. A timber-frame is a specifically good example, as it allows for further application of frictionless interfaces. The balloon-frame on the other hand, is over connected and would therefore not allow sufficient adaptation (Brand, 1995, p. 20).
Section 1: Building Perspective: The Building mediating user and material

<table>
<thead>
<tr>
<th>Site</th>
<th>Ownership</th>
<th>Layer Lifecycle and the corresponding Layer's Material Lifecycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Community/Landlord</td>
<td>The foundation and load-bearing elements are perilous and expensive to change, so people don’t. These are the building.</td>
</tr>
<tr>
<td>Skin</td>
<td>Public</td>
<td>Façade, insulation, windows</td>
</tr>
<tr>
<td>Services</td>
<td>Landlord</td>
<td>Technical, ducts and shafts, electricity, plumbing, HVAC, elevators. Buildings are demolished if services system is too much integrated into the building.</td>
</tr>
<tr>
<td>Space plan</td>
<td>Tenant</td>
<td>Walls, ceilings, floors, doors. Turbulent commercial spaces every 3 years.</td>
</tr>
<tr>
<td>Stuff</td>
<td>Individual</td>
<td>Furniture / mobilia</td>
</tr>
</tbody>
</table>

Table 1: Shearing Layers with estimated years and ownership, based on (Brand, 1995) – own table

The shorter use period of certain layers does not necessarily mean that the lifecycle of the building components and materials in those layers is identical to this use period. Building components and materials can and will be reused in other buildings, assemblies or functions at different assembled scales. This is especially the case when building components are removed because of economic or functional reasons, their technical condition is probably still fit. The building components and materials can be seen as separate entities with their own properties that can move beyond the lifetime of a building.
An interesting, slightly out of context, example, is furniture. Grandma’s cabinet can live a much longer life than the structure of many buildings.

Same goes for valuable historic facades. They will remain as their supporting structure will be replaced. Nevertheless, the size and type of the structure will probably remain the same.

→ [Design Strategies]: Shearing Layers
   ➢ Using the defined roadmap and scenarios identify the importance of different layers for potential material circularity, performance and impact.
   ➢ Create frictionless interfaces between different shearing layers.
   ➢ Indicate material performance and material conditions for each layer to be used for material selection.

7.5 Principles of Adaptability

In relation to the principles of disassembly as discussed above, below are some guidelines for an adaptable building identified. These guidelines encompass themes such as the neutrality of the structure, oversize and spatial diversity.

A potential conflict is that many principles aim for an increase in space, load bearing capacity or other options, what goes hand in hand with an increase in material use and a possibility that these options for adaptability are not even used (for example, 7.1.3 Buildings as material managers). The conflict arising from this issue is further addressed in the second part of this thesis (8.1.1 Reducing depletion and waste: Minimize Material Use).

Increase options

Increasing options relates to scenario planning. Excluding certain potential scenarios is not desirable. Stuart Brand uses the analogy of a chess player: “favor moves that increase options” and “work from strong positions that have many adjoining strong positions” (Brand, 1995, p. 186).

Facilitate growth

Increase the structure to handle extra loads, create frameworks for growth by allowing easy removal of facades for the construction of extensions and avoid unorthodox materials that are not easy to
get by for extensions, maintenance or renewal (Brand, 1995, p. 186).

However, Brand also relates to the problematics of additions, as they might be in conflict with the logics of the original structure and for instance, daylight penetration. There is a risk of leaving spaces “dark and desolate” (Brand, 1995, p. 23).

**Oversize**

Aim for a ‘loose fit’. Add storage, attics, basements and ‘unfinished rooms without windows’, these storage spaces might develop into something useful later on (Brand, 1995, p. 186). OVAM mentions a generous design of circulation spaces, to allow for overflow of functions from adjacent areas (OVAM, 2013, pp. 88-90).

An oversize in service capacity is mandatory to facilitate adaptability, either to upgrade services to a more technically advanced system, to increase its capacity, or to change its functions (Brand, 1995, p. 186).

Nevertheless, as learned from the Solid project (7.3 Open Building), endless possibilities for adaptability are not always necessary. It should be a weighed balanced between initial investment, potentials of space, scenario possibilities, the needed level of future refurbishment. For example, allowing space for future service expansion, but avoiding the upgrade to different or bigger installations until really needed.

In case of use of all recycled or reused and reusable and recyclable materials over size is less of an issue in terms of sustainability, and more of an issue of economics (Michael Prins in Workshop Materials in a Circular Economy, 2015). More on minimalizing material use in (8.1.10 Reducing depletion and waste: Minimize Material Use).

**Diversity in space sizes**

Create a diversity in space sizes. Though medium-sized rooms are most flexible for different uses, some activities demand spaces with higher ceiling heights or larger spans (Brand, 1995, p. 186).

Design spaces that can be adapted to different sizes (OVAM, 2013, pp. 88-91). Make sure usage of dynamic elements to create different interior configurations to be clear and easy. Complicated
processes to change interior layouts are often forgotten and avoided in practice (workshop circular materials).

To allow for different space sizes, it is important that different wall configurations can be facilitated. An important variable is the façade bay dimension as this allows walls to connect to the facade (Wallagh, 2013, p. 44).

**Allow changes at different impact levels**

Changes can happen at different scales. Functions might change, that results in change of services and interior layout or even the combination or separation of different lots. Next to that, function might stay the same, but the client might change. This could result into a change of furniture and different finishing. A third level of change could be daily, weekly or monthly, to allow different spatial configurations: meeting rooms, open office plan, etc.

The first two levels probably connect with material cycles outside of the project area, new materials are put in, older materials are put out and recycled. The third level of change might be best facilitated through the flexibility of interior elements. These could consist of non-structural wall dividers that can easily be reconfigured (WBDG, 2015). In all three levels, avoid lowered ceilings for essential equipment that needs periodic changes (Brand, 1995, pp. 168-169).

**Fragmentation / division / routings**

To allow different sizes of functions different configurations of routings, fragmentations and divisions should be possible (Rob Geraedts in Workshop Materials in a Circular Economy, 2015). For example, if a certain user prefers to rent a whole part of the building, would it still need to share access points with other users?

But more importantly, maintain an ideal minimal cell size: “small lots will support resilience because they allow many people to attend directly to their own needs by designing, building, and maintaining their own environment.” (Anne Vernez Moudon in Brand, 1995, p. 18).
Material Perspective: Beyond Sustainable Characteristics of Materials, Building Components and Building Elements

The second section of this thesis handles the topic from a material and product point of view. The goal of this part is too learn the different ecological impacts and beyond sustainable characteristics of materials, products, building components and building elements and the route they travel through the built environment and a short elaboration challenges on material evaluation in the design process.

To start off, a short explanatory note on the complexities of the built environment.

A complex built environment

The built environment is a complex collection of materials, variables and forces. Four main difficulties are described in Scheurer et al (Scheuer, Keoleian, & Reppe, 2003, p. 1049).

- Complex assembly
- Time and its long life: change and uncertainty
- Custom product
- Intransparency

He addresses the complexity of buildings in materials and functions; its dynamic character of its relatively long lifetime, changing user requirements, the limited service life of building components and the accompanied uncertainty; the unique character of each building that demands a much more customized production process than any other product; and the complexity of a building’s production and material assembly that results in lack of transparency in and information and data on, for example, its content, process of manufacturing and demolition and construction details (Scheuer et al., 2003, p. 1049).

Through rational and logical thinking, this chapter tries to tie these different part together and find the most important considerations for material selection, trade-offs and application based on ecological impact and additional benefits, for a common aim towards a positive footprint.
8 Beyond Sustainable Material Characteristics

The characteristics described below combine both intrinsic material qualities, such as their toxic content, as the way in which materials are applied, for example minimal material use. The characteristics deal with both efficient as effective topics.

The sustainable characteristics have been drawn from a variety of sources. Ecological impacts have been drawn from different LCA studies (Life Cycle Analysis) done on buildings and building elements. The shearing layers are used as a framework to characterize different building elements with common properties. The following topics will be touched upon in this chapter:

Figure 12: (1) connecting cycles; (2) different levels of assembly; (3) hazardous content; (4) embodied energy; (5) material functionality – own diagram

Connecting cycles [1]: reuse and recyclability – will shortly talk about moving away from a linear system towards a circular system to engage challenges such as resource depletion, waste through reuse, recycling, composting and effective material application in the biosphere and technosphere.
This will also include the topic of materials and products: the different levels of assembly and processing [2] to discuss subjects as pure materials, composites, reusability, recyclability and modularity.

Thirdly, shortly three other topics will be addressed: hazardous content [3], embodied energy [4] and (beyond sustainable) material functionality.

All of the above mentioned topics influence the ecological impact of materials, either positive or negative. Different LCA studies are referred to for an indication of the ecological impact per shearing layer.
8.1 Connecting material and building product cycles

This paragraph considers the material and product cycle through the built environment, the different related variables and the move away from a linear system with an in- and output towards a circular system.

8.1.1 Different stages of the material and product cycle

Many different sources describe the current lifecycle of materials through the built environment. The following steps are based on a linear model (OVAM, 2013):

1) Primary resource extraction or recovery of resources from previous use;
2) Manufacturing of products and processing of raw materials;
3) Design and project development phase (not a phase physically relevant for their movement through the process, but relevant in terms of decision making);
4) Transportation to the building site and construction phase;
5) Operation phase, maintenance and renovations;
6) End-of-life;
7) Disposal;

The diagram below sketches the situation when moving from a linear to circular system. Different aspects that will be discussed further on, such as levels of assembly, biosphere and technosphere, can be placed within the framework of the diagram.

The continuous arrows show the traditional linear path of materials (ending with incineration and landfill). Along these phases raw materials and energy are used and waste is produced. The main goal is to move away from waste generation and resource depletion, towards a focus on the dotted arrows. The dotted arrows show the paths of potential reuse and recycling.

Post-consumer recycled content is recycled material that has been used in society, pre-consumer recycled content is waste as a product of fabrication processes, for instance iron-ore slag that is used for mineral wool insulation, or fly ash that is used in concrete. However, pre-consumer recycling is only considered
recycling if it is outside of the originating industrial process (Building Green, 2014; WBDG, 2012).

8.1.2 Different levels of assembly and processing

These dotted arrows can be put in a hierarchical order of different levels of connecting material cycles. They range from:

---

Figure 13: The inner grey circle represents the built environment and the technosphere, the outer green circle represents nature and the biosphere. The numbers relate to: (1) Post-consumer recycling; (2) maintenance and renovation; (3) reuse of components; (4) reuse of components after remanufacturing; (5) pre-consumer recycling; (6) composting, landfill and waste; (7) input of virgin and renewable resources. The last two are both left-overs of the linear system and important components of the biosphere. – own diagram.
Section 2: Material Perspective: Beyond Sustainable Characteristics

1) Maintenance and renovation
2) Reuse of components
3) Remanufacturing of components
4) Recycling of materials (technosphere)
5) Composting (biosphere)

[1], [2] and [3] are products of the original linear material process, relating to reuse. They extend the original life cycle of a material or product, but do not 'renew' the cycle, while [4] recycling and [5] composting do.

[Design Strategy] Hierarchy of Connecting Cycles

In the previous part is referred to Project XX. Project XX drafted of a list of priorities to secure an ecological responsible end-of-life stage for its used materials. In the table below, the priorities related to material use, with examples:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Materials can be returned to raw material state after twenty years.</td>
<td>Cardboard ventilation ducts, floors filled with sand.</td>
</tr>
<tr>
<td>2</td>
<td>Materials can be reused for other purposes.</td>
<td>Timber and glass.</td>
</tr>
<tr>
<td>3</td>
<td>Materials can be reused for other purposes after processing.</td>
<td>Hollow core slabs and the demountable structural system.</td>
</tr>
<tr>
<td>4</td>
<td>Materials are recycled into homogenous raw materials.</td>
<td>All other materials.</td>
</tr>
</tbody>
</table>

Table 3: hierarchy of reuse and recycling - sources: (Post & Klomp, 1998, pp. 19,38,39)

As it is not possible to have all materials closed loop recycled in the technosphere or composted in the biosphere develop a hierarchy of reuse.

- Maintenance
- Recycling and composting
- Reuse
- Manufactured reuse
- Manufactured reuse
- Downcycling
- Waste
8.1.3 Maintenance

Maintenance is the first step in improving the material cycle. It improves the durability of materials and components. Timber products are an example that need maintenance to become durable, especially for outside use. A proper maintenance plan or focus, as mentioned in the previous chapter, is essential, as often maintenance is pushed forward until visibly needed (WBDG, 2015).

Durability

Durability is defined as the period of time over which a building can fulfill its function without compromise, free or maintenance or repair (Sinha et al., 2013, p. 3). Traditional materials such as bricks, stone and concrete are often mentioned. They should be able to resist “moisture, heat, sunlight, insects, ozone and acid rain, use, style and natural disasters” over time (WBDG, 2015).

Durable materials and products are often referred to as sustainable because they have a long lifespan. This is a clear idea of efficiency, as the negative impacts of a material (embodied energy, resource depletion, emissions and waste) are spread out over a larger time period (Prins in Workshop Materials in a Circular Economy, 2015).

Extending a Material's Lifespan / Not compromising recyclability possibilities

Unfortunately, high durability often goes hand in hand with low adaptability. In an ever-changing society this demands special means of adaptability, as mentioned in the first part of this thesis.

In a beyond sustainable material scenario, durability and maintenance-free lifespans is not a goal for all, but material performance should match the functional and economical lifetimes to increase opportunities for recycling and reuse. During the design phase a clear strategy should be chosen for a building’s and component’s lifespan (Post & Klomp, 1998, p. 15). If needed, at the end of the lifespan may be decided upon to extend its use, if technical feasible. Potential compromise of future recycling should be taken in account.
8.1.4 Reuse and recycling

The words reuse and recycling are commonly interchanged. Even though the difference may sound clear, misinterpretations are easily made because reuse and recycling are not necessarily opposites, but ends of a gliding scale. To make it more difficult: recycling is reuse but reuse is not necessarily recycling. Along this scale both upgrading and downgrading of use is possible.

8.1.5 Reuse

Reuse commonly refers to transposition of certain product, materials or complete buildings in another project. For example, the reuse of an office building, or the disassembly and assembly of a temporary stadium. Sometimes the products need to be slightly adapted to serve their new uses, in those cases is spoken of remanufacturing of components.

Upgrading and downgrading in reuse can be seen from a variety of perspectives: economic, social and cultural, technical and functional.

The examples mentioned below mostly relate to more creative and innovative ways in approaching the waste and reuse challenge – as a mere end-of-life solution than a designed solution. The paragraph on modularity, focuses on the designed solution for reuse (8.1.8 From material to product: the level of assembly and the potential of recycling or reuse). As almost every challenge...
needs its own specific solution, structural application of found ‘creative reuse’ solutions might be hard. Nevertheless, in the built environment almost every project is a custom-fit, where there might be potential for a structural plan for creative ways to deal with waste.

**Functional upgrading - Brownfields**

This could be a former industrial area (or brownfield) that is redeveloped as a cultural center.

**Economical upgrading – Houseboats at the Ceuvel**

The reuse of the houseboats on De Ceuvel is regarded as upcycling. From a very general economic perspective this might be true: office space is of higher value than housing. Nevertheless, the houseboats can currently not conduct one of their main qualities: keeping afloat.

**Stylistic upgrading (social-cultural) – Coffeebar TU Delft**

Of the same category is the coffee bar by Superuse Studios at the faculty of architecture of the TU Delft. Former mass produced window frames were reused for the construction of the coffee bar. Though they currently serve a higher cultural value of ‘design’, they are downcycled in terms of functionality: they do not use their full capacity of, for instance, insulation.

**Technical upgrading - Bricks**

Bricks that have once been used as a fence and have aged well, are reused in the façade of a new museum. There they serve a higher technical value as façade element, a higher cultural value and a higher functional value.

> [Design Strategies]: Reuse and upgrade

- If recycling is not possible for one of many reasons, find appropriate reuse possibilities with upgrade in one or more aspects.

### 8.1.6 Recycling

Before moving towards a beyond sustainable scenario of endless recycling with maintained quality, products and materials that cannot technically (or economical beneficially) be recycled (yet)
have to be taken into consideration. In those cases down cycling can be a solution, nevertheless as the term indicates, this is merely an end-of-life solution to extend use.

**Upcycling or Recycling**

Recycling materials of greater or (usually) equal value. Cradle2cradle usually refers to this type of recycling as upcycling, as recycling has a strong semantic connotation with downcycling. For example, using carbon dioxide emissions as food for algae (Luscuere, 2015).

**Recycling or Downcycling**

Recycling materials in a product of less value. For instance the use of crushed concrete as granulate for roads and foundations.

**Incineration and Landfill**

Incineration is burning up waste for heat and/or energy. Nevertheless, always much more energy and potentials go to waste than are returned in power and heat (Wellink in Workshop Materials in a Circular Economy, 2015).

### 8.1.7 The Biosphere and the Technosphere

In general, two main material cycles can be identified: the biosphere cycle and the technosphere cycle. Multiple sources relate to this division, among them Cradle2cradle (McDonough & Braungart, 2010).

![Diagram of Material Flow Model](image)

**Figure 13. Materials Flow Model**

*Source: Geiser, 2001*

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*Figure 14: an older diagram indicating the biosphere and the technosphere by (Geiser, 2001) via (Oehsendorf et al., 2006)*
This diagram clearly shows the difference between the biosphere cycle and the technosphere cycle. The technosphere cycle is closed and controlled in the built environment, where the biosphere cycle is open and semi-controlled. The latter consists of materials that can be composted in nature, including synthetic materials such as biopolymers. These products are renewable, usually have a limited use period and are of a lower performance than their technical counterparts (OVAM, 2011, p. 11).

The technosphere deals with materials that are non-compostable, such as polymers and minerals. Recycling refers to products in the technosphere. Their quality should be maintained or upgraded during their cycle, to secure its continued existence (OVAM, 2011, p. 11). Examples of materials that can be recycled in a closed loop technosphere cycle are for instance, steel and other metals, glass and types of plastics (WBDG, 2012).

To profit most from both cycles, it is essential to clearly separate the two, or two make them easily separable (Zuidema in Workshop Materials in a Circular Economy, 2015).

**Biobased content and sustainable harvesting**

Although the biosphere cycle sounds very sustainable and includes natural and renewable resources (WBDG, 2012), their ecological impact might be surprising. There are a couple common challenges.

The production of timber is a first good example. The exact rate of renewal depends on the type of tree, but is indicative for the amount of trees that can annually be harvested without compromising future renewal. There are different types of certifications, but the Forest Stewardship Council (FSC) is the most known (WBDG, 2015).

Other materials have a faster rate of renewal and these might be seen as more sustainable, for example: linoleum, cork, wool, sisal and organic cotton (WBDG, 2015).

Besides an appropriate annual yield, other factors are important as well for bio-based materials: the use of chemicals, fuel, land use intensity, pollution, competition with food crops, etc. (Building Green, 2014).
Another sustainable source of bio-based products are by-products of other agricultural activities, such as straw (Building Green, 2014).

[Design Strategy:] Biosphere and Technosphere

- Use biodegradable materials for short time use periods where it is unsure if there is a clear recycling or reuse possibility.
- Make sure for disassembly between biosphere and technosphere.
- Avoid bio-based products that lack certification that secures a sustainable harvest.
- If possible, use by-products of other agricultural activities, such as straw.

8.1.8 From material to product: the level of assembly and the potential of recycling or reuse

Whether a product is fit for reuse or recycling depends on the level of assembly and how much energy, effort or ecological impact it will take (if negative) to create a product that can be applied elsewhere (reuse) or can be a resource for a new product cycle (recycle).

The graph below (table 5) shows the relation between (horizontal axes) the measure of customization of a certain product or component, to serve a specific function, (red line) the amount of embodied energy used to process this customization and (blue line) the potential of recyclability.

In case of (a), it is beneficial to disassemble the product to its original materials, in case of (b) it will be too costly to disassemble the product for profitable recycling. In that case, reuse or extension of use should be stimulated. Unfortunately, with high customization or processing, usually comes less genericity for reuse.

A concrete structure is a good example of a building component that has a high embodied energy and a very low recyclability value as the result of a very specific functionality / assembly.

If potentials for recyclability improve (c), for instance by improving the recycle infrastructure the possibility for situation (a) will increase as well. If products can be more easily disassembled or customized, perhaps by use of renewable energy sources (d),
this might increase possibilities for situation (a) as well. Then, it might be more efficient and effective to reprocess products in a new, more functional, assembly. From a material point of view, the maximum value is gained when the material is brought back to its original raw state (Zuidema in Workshop Materials in a Circular Economy, 2015), as in this state, it can be processed to anything else, to custom-fit specific purposes. If it is reused in an assembled state, usually it does not perfectly fit its new application.

Table 5: product/material specificity, processing energy and potentials for recycling – own diagram

Improving the recycling infrastructure can include big and tiny improvements, ranging from complex industrial processes to recycle plastics and composites, to the most simplest small innovations, for instance a small tool to more easily disassemble the Desso carpet tiles (Re:Purpose in Workshop Materials in a Circular Economy, 2015).

Recycling is a means

It is important to see recycling as a means and not as an objective. There have been studies on curbside collection programs that indicate that recycling can have a larger ecological footprint than new production would have (Building Green, 2014). However,
most of this footprint is the product of primary energy use, when moving to renewable energy and improving the infrastructure and processes of reuse and recycling, the benefits might surpass the costs. This can be related to the (b) process of the earlier diagram comparing customization, recyclability and processing energy.

The ‘raw’ material

It is essential to specify the term ‘raw’ material. Raw materials are mostly not useful, for instance, pure iron is useless, while steel polluted with some chrome is much more valuable (Bram van Grinten in Workshop Materials in a Circular Economy, 2015). Disassembly and recycling should be at the most valuable level: where materials are pure and not necessarily raw (Zuidema in Workshop Materials in a Circular Economy, 2015).

Value of the product

A product usually has much more value than materials. Unfortunately, this value is mostly only useful for a single project and cannot be easily transposed to another project, as it needs to fit custom dimensions. For certain high grade products, with a big value difference between assembly and original pure materials, a certain amount of modularity can be beneficial. For low grade materials, the difference between value of assembly and original material state is too little to strive for genericity (Post en Zuidema in Workshop Materials in a Circular Economy, 2015). Jouke Post, architect of Project XX, refers to his modules used in […] that have been effectively disassembled and assembled in different compositions a couple of times in only twenty years. Taking these notes in consideration, a green line specifying reuse could be added. A single material equals low processing energy, high reusability and high recyclability. A custom product equals low reusability, medium recyclability and medium processing energy. A generic product equals high reusability, high processing energy and low recyclability.
Modularity

Jouke Post also mentions the recent revolution in the manufacturing process of products, boosting customization possibilities above standardization (Post in Workshop Materials in a Circular Economy, 2015). For him, modularity on a product level becomes less and less interesting, only when it considers a high value component as addressed above. He sees the possibility to improve the measure to which client needs are met. Referring to his recently built house, he addresses the integrated framework that facilitates change, without using standard dimensions. The material is modular, but the product is not. Jouke Post sees material cycles connected at the level of the pure material, not the product (Post in Workshop Materials in a Circular Economy, 2015).

Jan-Henk Wellink, also a participant in the workshop, adds a nuance, in the realm of the private houses, technology shapes to the user, but in larger utility buildings, technology and the user have a more reciprocal connection – creating a basis for product modularity (Wellink in Workshop Materials in a Circular Economy, 2015).
Section 2: Material Perspective: Beyond Sustainable Characteristics

Products that cannot be disassembled: Separation of Assembled Products

In line of products, pure materials and raw materials, in material terms, recent development is the composite. A composite is made out of different types of materials that cost too much energy or take toxic processes to divide. Relating to the earlier diagram that compares customization, processing energy and recyclability, this would be an extreme example of (b).

“The purity of a product promotes its re-usability enormously: a building material should therefore preferably be made from just one material. Composites are often not re-usable, or this is much more difficult. The separation of composites takes extra energy and (often) requires toxic substances. In addition, the building material itself may contain no toxic substances and no toxic substances may be used during the production of building materials. […] Architects and building engineers must design buildings in such a way that all building materials are easy to disassemble and separate into their pure forms.”

(Rau, 2015)

Nevertheless, composites are rising in popularity, due to their excellent performance and functionalities (OVAM, 2013, p. 41). Together with their increasing potentials, their complexity is rising as well (Zuidema in Workshop Materials in a Circular Economy, 2015). Though they have a very bad reputation for recycling, their potential in terms of energy and structural efficiency might outperform homogeneous alternatives. However, if in the near future energy consumption might be mainly supplied through renewable energy sources, the benefits of composites might not surpass their burden on environment. Until there are more ecological sound possibilities for recycling, composites should be avoided.

[Design Strategy:] Application of Material and Product

- Match material and product characteristics with functional requirements of the related building systems;
- High grade products with a big value difference between assembly and original pure materials: modularity and genericity can be beneficial.
- Low grade products with a small value difference between assembly and original pure materials: customization is preferred.
Use materials that can easily be disassembled and returned to pure material state

[Design Strategy:] Composites

- Avoid composites, use building products that have been made out of one type of material.
- If composites appear to have a significant advantage in terms of ecological impact over regular building products and no alternatives are available – they are an option.

8.1.9 Measuring impact of reuse or recycling

When reusing, repairing, upgrading and/or recycling a product or a complete building, the benefits are difficult to measure, as the effort of production has already been made in another time and another context. One option is to take the original impact and reduce it from the total impact. A more realistic approach would be to measure the impact a comparable product would have had, created out of virgin materials – an avoided impacts approach (WBDG, 2015).

8.1.10 Reducing depletion and waste: Minimize Material Use?

Many sources proclaim that green strategies should minimize material use (OVAM, 2011; Pulaski et al., 2003; WBDG, 2015). From a sustainable perspective this sounds logical, as materials are commonly seen as a negative impact on the environment. This is a clear example of improving sustainable efficiency.

But, if we are to move to a beyond sustainable material paradigm and a built environment that connects material cycles and buildings can function as material banks – there are reasons, beyond, for example, the above mentioned thermal functions, to avoid minimization of material use out of ecological necessity.

What if materials increase in value over time, because of their scarcity and weathering qualities, or what if they have excellent recycling possibilities, and can create positive waste at the end-of-life or what if they influence the environment in a positive way, by cleaning air?
Nevertheless, even in a scenario like this, minimizing material use could still be profitable in terms of building costs, processing costs, financial costs, etc.

But in this context more importantly, strategies that allow minimization of material use often contradict the ability of flexibility and demountability. Taking the further on described impact of material recurrence (8.5 Impact of materials, building components, building elements) in mind, combining different shearing layers may save materials at the moment of a building’s conception (Pulaski et al., 2003; WBDG, 2015), but could result in much higher material expenses during the use period. If layers are combined, all needs to be replaced when the ‘weakest link’ of the combination is at its economical, technical or functional end-of-life.

**[Design Strategy:] Minimize Material Use?**

- Avoid or minimize material use of materials that are toxic, contain hazardous materials or have limited possibilities for reuse.
- Carefully weigh the minimization of materials when in conflict with the shearing layers, or the increase of material use for creating oversize for adaptability.

**[Design Strategy:] Responsible sourcing**

- Recycled content
- Renewable content
- Agricultural waste
- Minimal raw materials

**[Design Strategy:] Recycled Content**

- If there are no clear risks for hazardous ingredients, prioritize products and materials with recycled content;
- Avoid reusing or recycling products that might be energy intensive in non-renewable resources;
8.2 Hazardous Content

There are many currently known hazardous ingredients but there might be even more unknown hazardous ingredients. As production processes and logistics are sometimes extremely intransparent, it can be unclear whether some materials or products contain certain hazardous ingredients (WBDG, 2015).

List of hazardous ingredients

There is a very long list of many kinds of chemicals and plastics. Within the context of this thesis, it is more important to know in what materials and components these hazardous ingredients are contained than to know the names of each of them. From different sources information was drawn to create a small overview of which building parts contain the most significant amount of hazardous materials. All hazardous materials are commonly known to cause effects of allergies, irritation, nausea, headaches but quite often they are also carcinogenic or mutagenic. A couple hazardous materials are described in a little bit more detail, to create a general understanding of hazardous content.

<table>
<thead>
<tr>
<th>Group</th>
<th>Hazardous content</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>Chlorinated Polyethylene and Chlorosulfonated Polyethylene43</td>
<td>Primary use is packaging</td>
</tr>
<tr>
<td>Rubber</td>
<td>Chloroprene (Neoprene)</td>
<td>Rubber</td>
</tr>
<tr>
<td></td>
<td>Flame retardants</td>
<td>Home furniture, electronics, insulation, plastics, textiles, surface finishes, coatings, electrical appliances, plastic pipes and plastic cable [1,2]</td>
</tr>
<tr>
<td>Softeners</td>
<td>Phthalates</td>
<td>Wood finishing, paints, coatings, plastics, rubbers and seals</td>
</tr>
<tr>
<td>Organic compound</td>
<td>Benzidine</td>
<td>Paints, textiles, papers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td></td>
<td>NPE / APE surfactants</td>
<td>Paints, plastics</td>
</tr>
<tr>
<td>Metals</td>
<td>Lead, cadmium, mercury</td>
<td></td>
</tr>
<tr>
<td>Petrochemical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizers and</td>
<td></td>
<td>HVAC</td>
</tr>
<tr>
<td>Pesticides45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: examples of hazardous materials and known related construction products (Building Green, 2012; Living Building Challenge, 2010; WBDG, 2015)

<table>
<thead>
<tr>
<th></th>
<th>Asbestos</th>
<th>PVC (polyvinyl chloride)</th>
<th>VOC (Volatile Organic Compound)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Natural mineral, built up out</td>
<td>Widely used plastic, made of</td>
<td>Organic chemical, for example:</td>
</tr>
<tr>
<td>of fibers;</td>
<td>of fibers;</td>
<td>petroleum with help of sodium chloride;</td>
<td>(hydro) chlorofluorocarbons (CFC) and formaldehyde.</td>
</tr>
<tr>
<td><strong>Characteristics</strong></td>
<td>Strong, durable, thermal</td>
<td>Durable, lightweight;</td>
<td>Volatile means easily vaporated</td>
</tr>
<tr>
<td></td>
<td>properties, noncombustible,</td>
<td></td>
<td>at low room temperatures, this</td>
</tr>
<tr>
<td></td>
<td>cheap;</td>
<td></td>
<td>is also referred to as off-gassing;</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Currently prohibited, but many</td>
<td>Pipe, doors, windows, packaging</td>
<td>They are often found in new</td>
</tr>
<tr>
<td></td>
<td>old buildings (mostly pre 1980)</td>
<td>plumbing, electrical cable</td>
<td>furnishings, wall coverings,</td>
</tr>
<tr>
<td></td>
<td>still contain the material. For</td>
<td>insulation, rubber replacement,</td>
<td>solvents, paints, adhesives,</td>
</tr>
<tr>
<td></td>
<td>example, asbestos cement used</td>
<td>flooring, vinyl siding, gutters;</td>
<td>carpeting, and office equipment</td>
</tr>
<tr>
<td></td>
<td>in roofing materials, sewage</td>
<td></td>
<td>such as copymachines. CFC's</td>
</tr>
<tr>
<td></td>
<td>piping, spray asbestos;</td>
<td></td>
<td>can be found in service</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>installations. Formaldehyde can</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>be found in MDF, laminates,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>work surfaces, doors and many</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>other components (resins used</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>in adhesives, laminates,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>substrates, molded objects).</td>
</tr>
<tr>
<td><strong>Layers</strong></td>
<td>Structure, Skin, Services</td>
<td>Services, Space Plan, Stuff</td>
<td>Services, Space Plan, Stuff</td>
</tr>
</tbody>
</table>
Section 2: Material Perspective: Beyond Sustainable Characteristics

<table>
<thead>
<tr>
<th>Health hazards</th>
<th>Release chemical gasses that are related to health concerns, allergies and are, more importantly, carcinogenic. Severity depending on concentration and time of exposure.</th>
<th>VOC's are most commonly related to the sick building syndrome. Severity depending on concentration and time of exposure.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No danger in bounded state, but during construction processes the carcinogenic fibers get airborne and can get stuck in lung vessels. Severity depending on concentration and time of exposure.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Release chemical gasses that are related to health concerns, allergies and are, more importantly, carcinogenic. Severity depending on concentration and time of exposure.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC's are most commonly related to the sick building syndrome. Severity depending on concentration and time of exposure.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 8: Three examples of hazardous content: VOC, Asbestos and PVC and their characteristics - VOC**
*(Braungart & McDonough, 2009; Wang, Ang, & Tade, 2007; WBDG, 2012); Asbestos (TNO & RIVM, 2010); PVC (AZOM, 2013; Titow, 1984)*

**Hazardous trade-off**

If hazardous materials are necessary, they are not released in the environment and are completely recoverable in technical pathways (Braungart & McDonough, 2009).

In the case no other building products are available and (potentially) hazardous materials are necessary, they should be recyclable in a closed cycle in the technosphere – while minimizing possibilities for pollution and health risks (Braungart & McDonough, 2009).

For example, during the London Olympics the benefits of the use of PVC lead to a reduction of the total ecological impact. A strict policy on use and recycling were adapted to avoid unnecessary risks.

Most of these chemicals are found in building materials that are applied in a small amount, mostly in the stuff, finishing/space plan and services layer, as is indicated in the following table. Usually, as is elaborated in the paragraph on quantifying ecological impacts, these materials have a relatively big LCI (Life Cycle Impact) per weight unit, mainly resulting from their production process (Dimoudi & Tompa, 2008, p. 92).

**Recycled goods and hazardous content**

Secondly, apart from the related effort in reusing or recycling products a problem resides in the content of these products. As long as there is a lack of tools like of material and building passports that can show the exact ingredients of certain products, there is a high risk of hazardous content in recycled products.
(McDonough & Braungart, 2010; WBDG, 2015). During recycling, refurbishment or reuse, hazardous materials should be removed (OVAM, 2013, p. 10).

**[Design Strategy:] Hazardous Content**

- Hazardous content and toxic ingredients should by all means be avoided. In case there are no other possibilities, they should be completely recoverable in close technosphere cycles with minimized pollution or harm to the environment.
- Hazardous content is mainly a topic to be included in the Shearing Layers of services and space plan.
Materials are used for their functionality. This ranges from the most simplest things as loadbearing properties to more complex properties as carbon capturing. Materials are applied in a trade-off between expenses, ecological impacts and benefits. The paragraph relating to quantifying material impacts (8.5 Impact of materials, building components, building elements) will further elaborate on these trade-offs. The move from a sustainable to a beyond sustainable paradigm will rebalance these trade-offs, by shifting previously negative impacts towards positivity.

**Materials that do good**

Beyond sustainability is about doing good. Making sure no toxins are used in materials is less bad, but having materials add to a healthy interior environment is doing good. Materials should be designed and picked to hold secondary functionalities that move beyond their primary function of structure: from materials that combine simple extra functions such as weather protection or insulation towards energy harvesting and providing daylight. Products that measurably impact human health and the environment (soil, air and water) (Braungart & McDonough, 2009). It may be clear that these ideas are not innovative by any means. Layered glass is a great example: it provides daylight, it protects against the elements, it ‘harvests’ solar heat and it insulates.

The interior climate and comfort can greatly benefit from correctly chosen interior materials: they can improve the quality of air, the comfort of the interior temperature and the relative humidity (WBDG, 2015). This is beyond the regular services installations that use air filters, humidifiers and sorts.

Certain paints or finishing can clean air by capturing fine dust. Materials like loam stucco have the property of buffering the interior humidity levels. Other products, like some vapor-permeable weather-resistive barriers can stop moisture, but also help the façade dry when it gets wet (WBDG, 2012).

The added value can be at different times in the lifecycle and in different scales (Braungart & McDonough, 2009):

- Their production or disassembly produce valuable side-products;
Section 2: Material Perspective: Beyond Sustainable Characteristics

> They have secondary functions while in use for their primary function;
> They become ‘food’ at the end of their lifecycle;

Social / Materials, Aesthetics, Social and Culture

Some characteristics of materials and components are quantifiable, others are less so. Characteristics that relate to social, cultural and aesthetical qualities are less quantifiable.

The WBDG article on Living Buildings mentions these qualities as well, they relate to and overlap with people’s health, happiness and productivity. They can create a sense of place and aesthetic appeal (WBDG, 2011). This relate to ‘building with qualities’ that become ‘loved’ as described in the previous section (6.2.4 Qualities of Buildings that Stay).

During the Circular Workshop organized by Bob Geldermans at the TU Delft this topic was shortly addressed as well in an example of an old English freestanding bathtub. Stimulated through the tradition of antique, culture and style older products experience revival and increase in popularity. Nevertheless, qualities like durability, craftsmanship, material use and disassembly are essential for this revival. Reuse of our current bathroom appliances is currently unthinkable from stylistic and ostensible hygienic aspects, but is also counteracted by incorporation of the appliances in the interior design of a bathroom and the lack of craftsmanship (Workshop Materials in a Circular Economy, 2015).

In the U.S.A. there are multiple initiatives that sell timber beams and columns from old barns. Because the timber ages well, it becomes more valuable over its lifetime. Though driven by a stylistic force, the durability of the timber facilitates its reuse. The history, the life and the previous use that culturally sticks to these aged elements is comparable to the attractiveness of older buildings. Unfortunately for the barns, the popularity of the aged timber beams even results in the premature demolition of barns (OVAM, 2011).

➤ [Design Strategy:] Materials that do good
   ➤ Identify materials for secondary benefits, such as excellent insulation values, purification of air, carbon capture, etc.
   ➤ Prioritize materials used in the interior on their abilities to improve the climate.
Building or interior elements that have generic dimensions and generic adaptability can be manufactured with high durability and craftsmanship (either new or reused) to add life, culture and meaning to place and facilitate future further reuse. As inspired by the freestanding English bathtub and the beams and columns of American barns.
8.4 Embodied Energy

The embodied energy is all energy related to the processing of materials and products ranging from the primary activity of mining to the energy consumption of an end-of-life solution and everything in between. A main component of embodied energy is the transportation energy. As long products are produced with unrenewable energy resources and sustainable alternatives are not available, the embodied energy should be minimized by focusing on locally or regionally produced materials.

The embodied energy can be divided into two parts: initial embodied energy and recurring embodied energy. The initial embodied energy “includes the up-front energy investment for extraction of natural resources, manufacturing, transportation, and installation of materials”, the recurrent embodied energy is “needed over time to maintain, repair, or replace materials, components or systems during the life of a building.” (Frey et al., 2012, p. 16). This will be elaborated upon in the next paragraph related to the impact of different Shearing Layers.

[Design Strategy:] Embodied Energy

- Prioritize products that are of local origin.
- Prioritize products that have been produced using renewable energy sources.
8.5 Impact of materials, building components, building elements

This paragraph focuses on the impact of materials on the environment. Results from a variety of LCA studies are combined in the framework of the Shearing Layers. Unfortunately, the expressed difficulties above prohibit the inclusion of all potential material characteristics. Most LCA studies are limited to embodied energy and lack the account of building and materials impacts in human health, social effects, end-of-life solutions, resource depletion and hazardous materials.

> Included in most LCA’s
  - Impact of embodied energy
  - Impact of greenhouse emissions

> Not included in most LCA’s
  - Impact of waste
  - Impact of resource depletion
  - Impact of toxic materials / human health
  - Impact of pollution
  - Potentials for recycling
  - Additional benefits, thermal properties

To improve future LCA studies to evaluate performance and important tradeoffs among material selections and appropriate the LCA for the design phase, more detailed data and transparency is needed (Scheuer et al., 2003, p. 1062).

This paragraph first shortly reviews the relation between embodied energy and operation energy, then compares different sources to approximate the ecological impact of different Shearing Layers, and ends with a short discussion on the use of embodied energy.

Definitions

<table>
<thead>
<tr>
<th>Initial Embodied Energy</th>
<th>The embodied energy included before the use phase of the building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recurring Embodied Energy</td>
<td>The embodied energy specifically dealing with maintenance and replacement during the use phase</td>
</tr>
<tr>
<td>Total Operating Energy</td>
<td>Energy used during the use phase</td>
</tr>
</tbody>
</table>
8.5.1 Embodied energy versus Operation Energy

As already addressed in the problem description, the total embodied energy compared with the life cycle energy use is relatively small, between 3 to 20% (Frey et al., 2012). Different studies confirm these numbers: ranging from 5% to 16% (Cole & Kernan, 1996; Scheuer et al., 2003, p. 1059). Cole et al mentions the initial embodied energy of an office building with underground parking in Vancouver to be 9.2% of the life cycle energy use (Cole & Kernan, 1996, p. 314).

Differences between these numbers result from the calculation method, building energy efficiencies, building management, building maintenance, habits of use and building lifespan (Frey et al., 2012, p. 16).

Future reductions in operating energy use

As is currently the trend, operation energy use of buildings is quickly diminishing. Different aspects such as using energy renewables, technical innovations, changing use patterns and improved energy consumption management add to this development (Scheuer et al., 2003, p. 1061).

Cole et al indicates that a reduction of 50 to 75% is feasible in the near future (these were predictions made in 1996). This will increase the embodied component to 30 or even 45% of the life cycle energy use (Cole & Kernan, 1996, p. 314).

As stated before, this will increase the relative importance of the ecological impact of the material part (Scheuer et al., 2003, p. 1061).

Effective material use / trade-off

Quite often, an improvement in operation energy use also results in an absolute increase in the ecological impact of the material part. To be more precise: the effective increase of material use is the
cause of an improvement in operation energy, for example: thickening the insulation of the building envelope is compensated by a decreased heating demand (Scheuer et al., 2003, p. 1061).

Up to some point, effectively increasing material use (and thus, embodied energy impact), will result in a reduction of the total life cycle energy consumption. The graph below shows a correlation between a decrease in operating energy and an increase in embodied energy.

![Graph showing Operating vs Embodied Energy](image)

**Table 9:** Operating vs. Embodied Energy (Ramesh, Prakash, & Shukla, 2010, p. 1597)

But at some point, when the increase in materials is not compensated by a decrease in operation energy use, the total life cycle energy consumption will rise with the increase in embodied energy (Ramesh et al., 2010, p. 1598).

![Graph showing Life Cycle vs Embodied Energy](image)

**Fig. 6.** Life cycle versus embodied energy for case studies reviewed [32].

**Table 10:** Life Cycle Energy vs. Embodied Energy (Ramesh et al., 2010, p. 1598)
The exact position of the tipping point is difficult to obtain, as there are many variables to take into account. Ramesh mentions the dependence on “the mix of active and passive measures, climatic conditions of the place, and materials used in the construction” (Ramesh et al., 2010, p. 1598).

### 8.5.2 Distribution of Embodied Energy and Ecological Impact

Studies that give perfect distributions of the ecological impact of each Shearing Layer in terms of embodied energy, emissions, toxicity, recyclability etc. do not exist – mainly because of the reasons already addressed above: complexity and intransparency of the built environment.

There are several studies of LCA’s that make a smaller distribution, mostly in terms of embodied energy and related emissions. As a result of the same complexity and intransparency of as well the built environment as the diversity in LCA’s, they indicate different values, for example:

<table>
<thead>
<tr>
<th>Structure (concrete + rebar) = 60% of embodied energy</th>
<th>Honey and Buchanan via (Cole &amp; Kernan, 1996)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure (concrete 42 + rebar 24) = 66%</td>
<td>(Dimoudi &amp; Tompa, 2008, p. 92)</td>
</tr>
<tr>
<td>Façade = 25%</td>
<td></td>
</tr>
<tr>
<td>Concrete and rebar = over 20% of emissions in every studies impact category</td>
<td>(Junnila, Horvath, &amp; Guggemos, 2006, p. 12)</td>
</tr>
</tbody>
</table>

The most detailed result is obtained in the study of Cole et al (Cole & Kernan, 1996). The embodied energy is distributed over a variety of layers similar to the Shearing Layers, as shown in the table below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Wood (GJ)</th>
<th>Wood (%)</th>
<th>Steel (GJ)</th>
<th>Steel (%)</th>
<th>Concrete (GJ)</th>
<th>Concrete (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With underground parking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site work</td>
<td>1246</td>
<td>5.9</td>
<td>1246</td>
<td>5.3</td>
<td>1246</td>
<td>5.6</td>
</tr>
<tr>
<td>Structure</td>
<td>5935</td>
<td>28.3</td>
<td>5964</td>
<td>25.2</td>
<td>5398</td>
<td>24.4</td>
</tr>
<tr>
<td>Finishes</td>
<td>2900</td>
<td>13.8</td>
<td>2825</td>
<td>11.9</td>
<td>2945</td>
<td>13.3</td>
</tr>
<tr>
<td>Services</td>
<td>5263</td>
<td>25.1</td>
<td>5263</td>
<td>22.2</td>
<td>5263</td>
<td>23.8</td>
</tr>
<tr>
<td>Construction</td>
<td>1373</td>
<td>6.5</td>
<td>1549</td>
<td>6.5</td>
<td>1447</td>
<td>6.5</td>
</tr>
<tr>
<td>Total</td>
<td>20,984</td>
<td>100.0</td>
<td>23,683</td>
<td>100.0</td>
<td>22,121</td>
<td>100.0</td>
</tr>
<tr>
<td>GJ/m²</td>
<td>4.54</td>
<td></td>
<td>5.13</td>
<td></td>
<td>4.79</td>
<td></td>
</tr>
</tbody>
</table>
For concrete buildings, used for most of the Dutch office buildings, the distribution of total initial embodied energy is as follows:

- Site work: 5.6%
- Structure: 24.4%
- Envelope: 26.3%
- Finishes: 13.3%
- Services: 23.8%
- Construction: 6.5%

*(Cole & Kernan, 1996)*

### Weight and impact

Although the structure might seem most dominant in mass and volume, it is on average only responsible for a quarter of the total initial embodied energy / ecological impacts. As conceptually indicated by Remko Zuidema, mass does not necessarily mean impact.

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Metals</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Timber</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Plastics</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

*(Zuidema in Workshop Materials in a Circular Economy, 2015)*

Chau et al (Chau, Yik, Hui, Liu, & Yu, 2007, p. 1848) performed a similar study as Cole et al for buildings in Hong Kong. They used the eco indicator 99 to include topics of human health, ecosystem quality and resource depletion in a total Life Cycle Impact score (Chau et al., 2007, p. 1846).
Their results show clearly that the mass of materials only has a very limited contribution to the total life cycle impact (LCI). While concrete contributed for about 74% to the total weight, it only contributed for 14% to the total LCI. On the other hand, the building services, only accounting for 2% of the total mass, accounted for 27% of the total LCI (Chau et al., 2007, p. 1849). After 50 years of building use, was projected, the contribution of the building services to the LCI would increase even more, to over 30% on average, as shown in the diagram below.

Chau et al (2007, p. 1850) indicated ten materials not related to building services and ten materials related to building services with the biggest contribution to the total LCI. Due to the many incorporated materials with high embodied energy, high emissions, resource scarcity and etc. relative to their weight incorporated, building services have a large contribution to the total ecological impact of a building. The combined top 10 materials and their percentage of the total building material LCI includes building services related materials at number 3 and 4:

<table>
<thead>
<tr>
<th></th>
<th>Material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete</td>
<td>14.4</td>
</tr>
<tr>
<td>2</td>
<td>Rebar</td>
<td>10.8</td>
</tr>
</tbody>
</table>
Section 2: Material Perspective: Beyond Sustainable Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Material</th>
<th>Replacement Burdens</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Power cable (building services)</td>
<td>8.2</td>
</tr>
<tr>
<td>4</td>
<td>Busbar trunking or busduct (building services)</td>
<td>7.9</td>
</tr>
<tr>
<td>5</td>
<td>Galvanized steel</td>
<td>7.7</td>
</tr>
<tr>
<td>6</td>
<td>Plaster, render and screed</td>
<td>7.4</td>
</tr>
<tr>
<td>7</td>
<td>Tiles</td>
<td>5.1</td>
</tr>
<tr>
<td>8</td>
<td>Stones</td>
<td>3.5</td>
</tr>
<tr>
<td>9</td>
<td>Aluminum</td>
<td>3.4</td>
</tr>
<tr>
<td>10</td>
<td>Structural steel</td>
<td>2.9</td>
</tr>
</tbody>
</table>

*Table 14: As a percentage of total building LCI / Table (Chan et al., 2007)*

Replacement Burdens

Scheuer et al (2003) comes to similar findings. Besides the high impact per weight they mention another reason for the prominent impact of non-mass related building elements: the replacement rate. Materials in building services, skin and interior finishing have a higher maintenance and replacement rate than the structure and foundation, resulting in a higher ecological impact (Scheuer et al., 2003, p. 1057).

Examples that are mentioned are copper for wiring and nylon and latex for carpeting (72, 125 and 70 MJ/kg, respectively). Insignificant in terms of weight, but have high replacement burdens and material production energy factors (Scheuer et al., 2003, p. 1057).

Scheuer et al mentions different solutions relating to other parts of this thesis to avoid the high replacement burdens, for example the use of carpet tiles (design for disassembly) and not integrating relatively durable copper wiring with building elements with shorter lifecycles (Shearing Layers) (Scheuer et al., 2003, p. 1057).
Recurrence

The concept of the replacement rate is an integral part of the theory of Shearing Layers. EPEA created the following diagram, showing that for the building structure to change once, the furniture (stuff) can change multiple times (here eight) and thus generously increasing its impact.

![Diagram showing material recovery](image)

**Table 15: Replacement rate of different Shearing Layers – by EPEA**

Brand links his six Shearing Layers to previous ideas of Frank Duffy, whom displays in the diagram shown earlier (6.2.1 Focus on Use Phase) the generous impact in capital costs of the replacement rates of services and space plans, multiplying the initial costs by 3 after 50 years.

Studies on the environmental impact of recurrence show a similar potential impact. Chau et al indicates 33% of total LCI related to building materials to accumulate during 50 years of service (Chau et al., 2007, p. 1849).

Of the study addressed earlier, by Cole et al (Cole & Kernan, 1996), only the initial embodied energy was elaborated upon. But the recurring embodied energy was also included in their study. They find that for 25 years use, the embodied energy of the finishing, envelope and services is increased by respectively 133.4%, 65.3% and 64.0%; after 50 years 322.0%, 150.7% and 188.5% and after 100 years 725.7%, 338% and 438.8% (Cole & Kernan, 1996, p. 312) - closely similar to the replacement rates visualized in the conceptual diagram of EPEA. As shown in the diagram below, the total embodied energy that is accounted for
after 100 years is almost three times higher than the initial embodied energy.

**Table 16:** The hatched area indicates the contribution of LCI as a product of recurrence during the 50 year use period (Chau et al., 2007, p. 1849).

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Initial</th>
<th>25 years</th>
<th>50 years</th>
<th>100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>25% to 60%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Skin</td>
<td>25%</td>
<td>16% (+65%)</td>
<td>38% (+150%)</td>
<td>85% (+340%)</td>
</tr>
<tr>
<td>Services</td>
<td>25%</td>
<td>16% (+65%)</td>
<td>48% (+190%)</td>
<td>110% (+440%)</td>
</tr>
<tr>
<td>Space plan</td>
<td>13%</td>
<td>18% (+135%)</td>
<td>42% (+325%)</td>
<td>94% (+725%)</td>
</tr>
</tbody>
</table>

**Table 17:** Embodied impact per layer as percentage of the initial total embodied energy, between brackets the growth percentage per layer. Based on (Cole & Kernan, 1996, p. 312)

Taking in account a lifetime of 50 years, recurrent embodied energy would contribute to about 7-8% of the total life cycle energy use (Cole & Kernan, 1996, p. 312).
The finishing, or fit-out, is comparable to the ‘infill’ of the Open Building concept, containing partitions, doors, floors, walls, ceilings and mechanical and electrical services. They have both a higher replacement rate than other layers, plus they consist of materials of higher embodied energy, such as plastics and copper (as part of the service related infill part) (Cole & Kernan, 1996, p. 312).

![Graph showing embodied energy growth over lifespan](image)

**Table 18: The embodied energy growing in years.** (Cole & Kernan, 1996, p. 312)

Cole at al mention that especially commercial and retail sectors, are subject of high recurrent embodied energies due to a high frequency of interior refurbishments (Cole & Kernan, 1996, p. 312).

The problem with recurring embodied energy, is the future uncertainty. Nevertheless, due to its significance, it will remain of importance (Cole & Kernan, 1996, p. 313).

**[Design Considerations:] Impact per Shearing Layer**

- Impact of different Shearing Layers does not follow the amount of mass. Structure, services and skin all contribute to about a quarter of the initial impact, over time, due to recurrence, this can be taken over by the space plan changes.
9 Challenges of Material Evaluation

This chapter deals shortly with the challenges involved in material selection in the design process. This relates to design tasks informed by both shape and material, a renewed relation between the manufacturer and architect and the challenge of evaluating and picking materials.

9.1 Materials as part of the design process

Designing with a material focus requires a 180 degrees different attitude of the architect. As normally an architect designs from a shape, and then applies materials – designing with a limited pallet of materials partly requires a turnaround, and having materials much more inform the shaping process than before (Building Green, 2014). The language of form changes, informed by constructive material properties (Duzan Doepel in Workshop Materials in a Circular Economy, 2015).

The Living Building Challenge formed the basis for the following four steps for integrating sustainable material selection in the design process (Living Building Challenge, 2010, p. 34).

1) Design
   a. Develop material characteristics and priorities for each building layer or element.
   b. Develop a reuse or recycling strategy for the existing.
   c. Develop a remanufacturing strategy for parts that remain.
2) Construction - optimize the collection of wasted materials.
3) Operation – include a plan for maintenance and replacement of products and materials. This could resonate with sustainable development of the building in use and material.
4) End-of-life – include a plan for adaptable reuse and deconstruction.

⇒ [Design Strategies]: Materials as part of the design process
- Inform the design in teamwork of both shape and material;
9.2 Collaborations with product manufacturers

To improve possibilities for material recycling, beyond sustainable material characteristics and the correct application of materials in the built environment the collaboration between architects, building developers and product manufacturers needs to be improved. Architects can deliver feedback on different material specifics they are looking for, manufacturers supply information on correct ways of application. Alternative business models support this relationship: from products with take back – guarantee of the manufacturer, to replacing the purchase of a product with the subscription to a service (Rau, 2015).

For example, as the roofing material of Project XX is derbygum, with limited possibilities for recycling, a take back – guarantee has been agreed upon with the manufacturer. Therefore the roofing material is easy to disassemble, with dry connections (Post & Klomp, 1998, p. 26).

The concept of Turntoo, an initiative of architect Thomas Rau, has for example resulted in the lease of a lighting service from Philips by a supermarket, instead of the purchase of lamps. This way, Philips is responsible of cutting energy costs and maintaining the lamps (OVAM, 2013, p. 94). As the product is still owned by the manufacturer, it will not be wasted at the end-of-life of the building (Braungart & Mulhall, 2012, p. 14).

[Design Strategies]: Collaborations with product manufacturers

Improved relationships between manufacturers and architects to secure material sustainability and circularity. Alternative business models with take back guarantee and service plans instead of product purchasing can be frameworks of these relationships.
9.3 Challenges in evaluating materials

As expressed in the introduction, the process of securing that materials used or to be used in a building project comply with the specifics as specified above is extremely difficult due to a variety reasons as explained in the paragraph below. It briefly covers the topics of certification, material availability and evaluation tools.

Drawing from sources that deal with one of the most harsh green building certifications: the Living Building Challenge, an overview of challenges has been identified (Living Building Challenge, 2010, p. 34).

- Too many Sustainable Variables (as described in the previous chapter);
- Illegitimate Claims of Green;
- Lack of Transparency and Information;
- Lack of Green and Certified Products;
- Lack of Recycling Infrastructure;
- Too many different Certificates and Standards;

9.3.1 Too many Sustainable Variables

The beyond material sustainable variables are explained in the previous chapters. Due to the earlier described complexity of the built environment and the many involved variables, it is extremely difficult to quantify and qualify these different variables (WBDG, 2012).

It is important to make careful trade-offs between a “healthy interior climate, minimal detrimental environmental impacts [or positive, TS], options for reuse cycle closure and the recuperation of used raw materials” (OVAM, 2011, p. 72).

Trade-offs and top priorities

Extending on the many different characteristics of materials and their different impacts on ecology and sustainability, different building elements have different priorities. When evaluating materials and building components, it is important to take the main priority in account to make effective decisions. For example, an energy efficient operation for HVAC, electrical appliances and plumbing is top priority. Nevertheless, it is essential to be aware of the material properties of the system and the development towards renewable energy sources.
The appendix to the conclusion specifies all found characteristics per Shearing Layer (appendix A).

<table>
<thead>
<tr>
<th>Building Product</th>
<th>Top Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC, electrical, and plumbing</td>
<td>Efficient operation</td>
</tr>
<tr>
<td>Envelope systems</td>
<td>Effective moisture &amp; thermal protection</td>
</tr>
<tr>
<td>Structural systems and non-structural materials</td>
<td>Embodied impact</td>
</tr>
<tr>
<td>Interior finish</td>
<td>Indoor emissions</td>
</tr>
</tbody>
</table>

*Table 19: priorities per Shearing Layer (Building Green, 2014)*

### 9.3.2 Illegitimate Claims of Green

There is no shortage in available materials proclaiming to be green. Greenwashing proclaims materials to be green, while they are in fact not or less so (WBDG, 2015). The lack of transparency in the building material market prevents clarity in green claims.

### 9.3.3 Lack of Transparency and Information

Due to a lack of information on the manufacturing process and the origin of content, most ‘green’ variables cannot be quantified or compared because there is too little known on their positive or negative impact (Living Building Challenge, 2010, p. 29). Quite often manufacturers themselves are unaware of what is in their products, as their products are assemblies of other products, that are assemblies of other products, etc.

### 9.3.4 Lack of Green and Certified Products

Many different architects mention the lack of ‘green’ products that meet current standards. Jouke Post, that designed the XX building back in 1999, indicated that the search for products was one of the most difficult parts of the design process (Post & Klomp, 1998, p. 22).
9.3.5 Lack of recycling infrastructure

As expressed throughout this thesis, to move towards a true beyond sustainable paradigm a proper recycling infrastructure is needed, both of materials and products that are currently present in the environment, not designed for reuse or recycling, and for materials and products specifically designed for recycling and reuse. Nevertheless, especially with the first, due to the complexity and intransparency of the existing built environment it is a very difficult task to identify all potential materials in a building, and easily dismantle them for reuse and recycling (OVAM, 2011, p. 79).

9.3.6 Too many different Certificates and Standards

There are many different certificates and standards that measure and evaluate green materials, but they all relate to different system boundaries, take in account different sustainable goals and different material variables. It is important to develop tools and certificates that can be developed while in use (WBDG, 2012). LCA’s are a good example of this, as their standard of measurement is not absolute, but relative to the sustainability of other materials or analyzed elements.

Different types of certifications also result into the problem that materials that have been certified by only one, are not comparable to other materials. For example, biodegradable products could get a high C2C certification, but because there are certificates specifically related to biodegradability (Natureplus, BNIBE, VIBE) the manufacturers do not need a C2C certification to prove greenness of their products (OVAM, 2011, p. 52).

Of all platforms that stimulate green building, C2C relates most to materials, mainly through its waste equals food motto. Therefore, it is interesting to shortly look at some remarks made on their certification tools by, among others, OVAM.

C2C: focus on material circularity and doing good

C2C focuses on materials more than other certifications, waste equals food. Besides that, it focuses on a beyond sustainable paradigm: doing more good, instead of less bad. However, C2C is not a certification such as LEED or BREEAM, but an innovation
platform to stimulate sustainability (Mulhall in Cradle2Cradle Lab 5, 2013; OVAM, 2011, p. 74).

**An innovation platform, not a certification**

C2C as an innovation platform limits its usefulness for consumers to draw conclusions from certified materials. Although there are several levels of certification that indicate the quality of recyclability, health hazards and toxicity (OVAM, 2011, p. 51), the greater goal is to stimulate manufacturers of certified materials to move from one level to another, and only secondary, serve as a communication tool, or label, to potential clients. For example, the demands of the basic level are extremely low and they are not necessarily more sustainable than non-certified products. Anything minor than the platinum level does actually not really comply to the C2C philosophy (OVAM, 2011, p. 52).

**Expensive and long**

Added complication to this are the time and costs involved in C2C certification. Although some products may suffice to the requirements, they cannot afford certification (OVAM, 2011, p. 51; Rau, 2015). Especially smaller companies have a problem getting their products certified (Workshop Materials in a Circular Economy, 2015).

This results in a lack of certified products, but that does not mean necessarily mean that there are not enough green building products (OVAM, 2011, p. 51).

**C2C Elements**

Materials and products can only become *really* sustainable in a correct application and context – where architect and manufacturer meet. To stimulate sustainable building solutions, it is therefore important to communicate lessons for application as well. Therefore C2C initiated the C2C Registry Identifying Elements and Delights in Buildings (Mulhall in Cradle2Cradle Lab 12, 2013). A database consisting of different built features containing concepts and applications of beyond sustainable architecture. Examples of these elements are: atria, air handling systems, etc. It is not necessarily about ranking, but about inspiration (Mulhall et al., 2013).
9.3.7 What is needed

All of the above mentioned challenges are strongly related to each other. Integral tools are needed that can identify, quantify and qualify the different sustainable aspects of materials, products and buildings to maximize the overall impact. A first step into this direction is more transparency in material manufacturing processes, the creation of material databases, building passports and one certification method. On different fronts is worked to develop these tools, nevertheless, it is essential that the different tools are comparable and exchangeable to increase transparency (OVAM, 2013, p. 42).

However, exact evaluation and quantification is not always adequate to move towards excellent material selection and application and move towards a positive footprint – especially in an environment that is so complex and works with so many different variables. Therefore it is interesting to see where C2C is heading with their database on building elements – not only to bridge the gap between product and architecture, but more importantly, to show possibilities and inspire. In the complexity of the built environment, many different sustainable solutions might be of equal positive (or negative) impact, each within their own categories.

➔ [Design Strategies]: Challenges of Material Vetting

➤ Trade-offs are often necessary in a material strategy. Total Life Cycle Impact should be taken in consideration as well as the main project sustainability goal.

➤ Many different alternatives might be of equal impact, let solutions be inspired by lessons from practice.

➤ To improve evaluation of different material characteristics: top priorities are indicated for each building element or Shearing Layer.
10 Conclusion

The increasing importance of the material impact in buildings demands an alternative approach to the way buildings relate to materials and the way materials relate to buildings. The conclusion is in twofold, just as the thesis itself, but not without drawing important relations. The first part relates to the way buildings can mediate between adopting changing uses and beyond sustainable management of materials, the second part focuses on different beyond sustainable variables of materials and how these can add value to a building.

The thesis forms the theoretical basis for the design of a refurbishment of a vacant 70s office building, towards a multifunctional material manager.

10.1 Building Perspective

External and internal change

Buildings are subject to change driven in general by the external factors of economy and function and the internal factor of technology. Technology represents the physical subject of the building of which the material cycles need to be connected. The change originating from these cycles should resonate with the other two factors, represented by the variables of function and user.

Change of function and user can be facilitated in two ways: adaptation of behavior (shift in daily routines, working methods, acceptance of certain interior temperatures) or adaptation of place: either by moving or physical adaptation through construction. In the context of this thesis, the latter is most important as it directly relates with the potential of connection of material cycles.

Focus on use phase

To find resonance between these variables, a focus on the use phase is essential, where currently the focus is on the building as a finished design. Therefore, time and change should be incorporated in the design phase to improve material management, connect material cycles and ultimately reduce the total ecological footprint and better serve an ever-changing society.
A focus on the use phase involves the future and change and uncertainty. To identify future possibilities, scenario development is essential.

**Beyond sustainability partially depreciates importance of durability**

Sustainability, representing the less bad paradigm, was all about minimalizing material use and maximizing material lifespans. This relates to historical buildings that have proven to withstand the force of time: through durability, love and/or proper maintenance. Moving towards a beyond sustainable paradigm that focuses on doing good instead of less bad, negative impacts of materials do not have to be spread over a longer time period, but they can be renewed into a new product or building.

**Dealing with uncertainty**

Simply, this relates to two different approaches to deal with future uncertainty: demolition or renovation. Or in more sustainable terms: design of disassembly - a building with a (short) fixed life span and planned disassembly and recycling at the end-of-life - and design for adaptability - a building with a long life span with a generic structure that allows multiple functions. Both have their benefits and drawbacks.

**Adaptability and disassembly combined**

Within the context of this thesis, focusing on the refurbishment of an existing office building in a dense urban context, an adaptable framework in combination with a finishing designed for disassembly might be best fitted. The existing concrete column structure is based on a grid that can facilitate multiple flexible uses. It will allow a gradual change, a flux of materials spread over time and remodeling activities of low intensity – resulting in a low burden to its surroundings, but allowing change in use and connection of material cycles.

An example that combines both is the concept of structure and infill, as described by John Habraken. The more permanent part of the building, with a relatively low impact (stone-like materials) remains, while the more fluent layers, infill, services etc., with a relatively (and in time absolute) higher potential ecological impact are designed to change over time and integrated in material reuse and upcycling. The principle of open building attempts to have the
change in use resonate with a minimal but effective amount of physical.

**Appropriate level of adaptability**

The approach of Habraken leads to increased customization. Users have a bigger impact on the interior layout, what, according to Brand, creates ownership and connection. However, post occupancy studies on recent similar examples such as the Solid projects in Amsterdam, which allowed a great amount of adaptability, indicate the need for a limited but appropriate level of adaptability.

In return, this allows a greater potential for a beyond sustainable material strategy, connecting material cycles and improving material selection, interior climate and building quality.

**Open Building and material sustainability**

Securing material sustainability in an Open Building concept is both a potential and a challenge, due to the decentralized and downscaled decision making to the end-user. A good solution might be a specialized infill contractor that provides the service of infill, merely as a consultant or as a full package, for the end-user. The contractor is responsible for proper material selection and circulation. However, due to the increased freedom of choice and related responsibilities and financial possibilities the user is also more aware of the financial and ecological benefits resulting from material recycling – especially in a beyond sustainable paradigm where financial benefits become apparent through improved recycling infrastructure and beyond sustainable product availability.

**Design for adaptability and disassembly**

In appendix B is a list of different design strategies and considerations that have been collected throughout the thesis. These design strategies relate mostly to considerations for design for adaptability and design for disassembly (and material selection), as they form the bridge between theory and practice.

Adaptability guidelines encompass themes such as the neutrality of the structure, a certain oversize, fragmentation, different levels of change to resonate with necessary impact and spatial diversity to facilitate different scenarios, growth and change. A potential
conflict is that many principles aim for an increase in material use, through these added measures of adaptability. Nevertheless, if all materials are applied from a beyond sustainable paradigm, fully recycled and recyclable and with additional benefits, extra material use is of minor concern than in a sustainable paradigm.

Disassembly guidelines partly overlap with adaptability, but consider a smaller level of detail. Topics such as connection details, prefabrication, simplified building systems and infrastructure to facilitate remodeling are touched upon.

**Material banks and managers**

This allows buildings to become material banks, or as stated in the introduction, material managers. Of great importance is the related information network. Information on adaptability, disassembly and materials should be widely available to the different relevant actors to improve the relation and resonation between building and user.

**Shearing Layers**

Stuart Brand’s theory of Shearing Layers is an effective framework to facilitate design for disassembly, user change, functional change, material change and sustainable development. It could be seen as a tool that supports both design for disassembly, design for adaptability and the resonation of use change, material change and ecological impact. It adds an extra distinction to the division between structure and infill of the principle of Open Building. It divides a building into separate layers that are characterized by their distinct properties in lifespan, material use, ecological impact and function. These layers are: site, structure, skin, services, space plan, stuff. The concept stimulates a frictionless interface between these different layers to allow different scales of change. The conclusions on the properties and impact of these layers, the materials, components and elements they include, are discussed in the next paragraph.

### 10.2 Material and Product Perspective

The section on materials consisted of three parts: an overview of material characteristics, the distribution of these characteristics along the shearing layers and a short elaboration on the challenges of material evaluation and appropriation in the design process.
Lastly, all lessons learned are combined in the shearing layers framework that will serve as a design tool (appendix A).

**Different material and product variables**

As already discussed in the introduction, we are to move from a linear process with resource depletion at one end and waste creation at the other, towards a circular system with the only input from renewable energies and in resonation with nature (chapter 8.1.1 – figure 13).

In a beyond sustainable paradigm, a material or a product cycles through the built environment in different steps: from resource collection, through manufacturing, through construction, through use phase, through reuse phase, through disassembly to return to resource collection for a renewed cycle. The cycle is generally dividable in two: the biosphere and the technosphere. The biosphere is open in connection with nature and consists of all natural materials that are compostable. The technosphere is a closed loop, that recycles all other materials, such as plastics and glass.

Within these cycles, different methods exist to renew or extend life of a material or product, being: maintenance, reuse, manufactured reuse, recycling and composting. The last two effectively renew lifecycles, the first three efficiently extend lifecycles.

Within a project a hierarchy of reuse and recycling is needed to allow for different levels of connecting circularity. Preferably all is recycled or composted, but in some cases recycling is not possible, or the value of a product assembly is significantly higher than the value of its separated materials (chapter 8.1.8 – table 5). These products of higher quality could be given a level of genericity, to stimulate reuse. Nevertheless, most value for specific use is created by returning a product to its pure materials and customize it for a new project.

Some products or materials are very hard to recycle, as they cannot be separated: composites. They require big amounts of energy or toxic chemical processes to be recycled. Although, the future may hold solutions for recycling of composites, as long this is not feasible, they should be avoided.
As it is not possible to have all materials closed loop recycled in the technosphere or composted in the biosphere develop a hierarchy of reuse.

1) (Maintenance)
2) Recycling and composting
3) Reuse
   a. Find upgrade: economic, social and cultural, technical, functional
4) Manufactured reuse
5) Downcycling
6) Waste

However, as long as there are materials that are not designed for recycling or reuse, specific solutions are needed to avoid the filling up of landfills. Only if reuse or recycling of these products would actually increase the total lifecycle impact, new products should be considered.

**Hazardous materials**

Many materials and products that have been used in buildings for long times consist of hazardous materials that affect occupant’s health and the environment. Use of these materials should be avoided. In terms of the Shearing Layers of Stuart Brand, they are most commonly referenced to the space plan and the services.

**Material functionality**

Primarily, materials are used because they fulfill a function, mostly protective against the elements or weight bearing. However, some functions add a considerate value to their environment, for example, properties of thermal insulation, carbon capturing but also qualitative values, such as cultural value. These attributes can significantly lower the total lifecycle impact. In this sense, trade-offs sometimes have to be made.

**Embodied and Use energy**

This specifically relates to the balance between embodied and use energy. Improving thermal properties of the façade, will raise the embodied energy of a building, but will more significantly reduce the use energy – and the total lifecycle impact – but only until a certain point. Once the use phase energy approaches the embodied impact, increase of the embodied will increase the total lifecycle impact.
Impact distributed in Shearing Layers

The distributed impacts per layer were mostly been based on LCA studies that were dominated by embodied energy and less so by factors of recycling, toxicity levels, waste, resource depletion and material and product functionality.

Nevertheless, due to the complexity and the custom character of the built environment it will always be too complex to take all factors, trade-offs, variables and benefits in account. For now, it is most important to be aware of the general relations between different components and variables to make the adequate decisions.

The impact distribution amplifies the previously learnt lesson that design should focus on the use stage, as this is a prominent area with large impact on ecology, both in material consumption and in energy use.

Design strategies should effectively manage the service lives of building materials and take in account renovation and maintenance schedules.

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>25 years</th>
<th>50 years</th>
<th>100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>25% to 60%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Skin</td>
<td>25%</td>
<td>16% (+65%)</td>
<td>38% (+150%)</td>
<td>85% (+340%)</td>
</tr>
<tr>
<td>Services</td>
<td>25%</td>
<td>16% (+65%)</td>
<td>48% (+190%)</td>
<td>110% (+440%)</td>
</tr>
<tr>
<td>Space plan</td>
<td>13%</td>
<td>18% (+135%)</td>
<td>42% (+325%)</td>
<td>94% (+725%)</td>
</tr>
</tbody>
</table>

*Percentages of total initial embodied impact and between brackets the percentages of increase per specific layer.*

While initially the structure might have the largest impact, due to renovations and maintenance the impact of the more fluent layers can be significantly higher over the course of use. This, in combination with the fact the relative impact of these layers is much higher, creates a priority for material sustainability for the cycles of these layers. These concepts correspond with the
conclusions from the previous section: a permanent structure that facilitates the connection of material cycles of more fluent layers.

Material selection in the design process

A focus on materials in the design process requires a renewed reciprocal relation where form and material inform each other. Material strategies should be applied at different stages of the building life: design, construction, operation and end-of-life.

Challenges of material selection

> Too many Sustainable Variables (as described in the previous chapter);
> Illegitimate Claims of Green;
> Lack of Transparency and Information;
> Lack of Green and Certified Products;
> Lack of Recycling Infrastructure;
> Too many different Certificates and Standards;

The biggest challenge for material selection is its intransparency in ingredients and tools for certification and databases. To improve this, more information is needed on the manufacturing processes of materials, materials in buildings and the quantification of different green material characteristics. However, even if this is technically possible and all data is available, there are too many variables to take into account.

Extending on the many different characteristics of materials and their different impacts on ecology and sustainability, different building elements have different priorities. When evaluating materials and building components, it is important to take the main priority in account to make effective decisions. For example, an energy efficient operation for HVAC, electrical appliances and plumbing is top priority.

It is important to combine quantitative data and qualitative inspiration. LCA’s in combination with the registry for sustainable building elements, by C2C, not only to bridge the gap between product and architecture, but more importantly, to show possibilities and inspire. In the complexity and, more importantly, the uniqueness of the built environment, many different sustainable solutions might be of equal positive (or negative) impact, each within their own categories.
Conclusion

Further research

> A full comparative LCA on the impact of different Shearing Layers.

> Post-occupancy evaluation of the appropriation of facilities of adaptability by user and building owner and how it can be improved.

> Stimulating material circularity and selection in particular and sustainability in general of the infill in an open building framework.
11 Literature


## Appendix A: Table of Impacts per Shearing Layer

<table>
<thead>
<tr>
<th>Weight</th>
<th>Average Primary Embodied Energy (1)</th>
<th>Potential Recurring Embodied Energy (2)</th>
<th>Recurrence / average lifecycle</th>
<th>Beyond Sustainability Top Priorities</th>
<th>Reuse / recycling priority</th>
<th>Value difference product and material</th>
<th>Toxicity / Health hazards</th>
<th>Ecological Impacts/weight unit</th>
<th>Owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>none</td>
<td></td>
<td>none</td>
<td>- Destruction fertile grounds;</td>
<td>- Removing fertile grounds;</td>
<td>High</td>
<td>Low;</td>
<td>Low;</td>
<td>Investor</td>
</tr>
<tr>
<td>Structure</td>
<td>High</td>
<td>23% to 60%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>30-300 years</td>
<td>- Embodied Energy; - Adaptable;</td>
<td>High;</td>
<td>Low;</td>
</tr>
<tr>
<td>Skin</td>
<td>Medium</td>
<td>23%</td>
<td>16% (+65%)</td>
<td>38% (+150%)</td>
<td>89% (+340%)</td>
<td>20 years</td>
<td>- Thermal protection; - Effective moisture; - Energy harvesting;</td>
<td>Priority;</td>
<td>Medium;</td>
</tr>
<tr>
<td>Services</td>
<td>Low</td>
<td>23%</td>
<td>16% (+65%)</td>
<td>48% (+190%)</td>
<td>110% (+440%)</td>
<td>7-15 years</td>
<td>- Efficient operation;</td>
<td>High priority;</td>
<td>Low;</td>
</tr>
<tr>
<td>Space plan</td>
<td>Low</td>
<td>13%</td>
<td>18% (+138%)</td>
<td>42% (+320%)</td>
<td>94% (+725%)</td>
<td>3-30 years</td>
<td>- Indoor emissions; - Interior climate; - User friendly;</td>
<td>High priority;</td>
<td>Medium;</td>
</tr>
<tr>
<td>Stuff</td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1-10 years</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Embodied impact per layer as percentage of the initial total embodied energy, between brackets the growth percentage per layer.
Appendix B: Collected Design Strategies

Design Strategies Collected

The research thesis resulted in the following design strategies. They are divided in two parts: those related to the built assembly and those related to the building components, products and materials themselves.

Building Perspective

→ [Design Strategies]: Focus on Use Phase

Focus on the use period and allow for future changes facilitated by a division between more permanent and more temporal building elements.

→ [Design Strategy]: Variables of Change

> Design the building for future clients;
> Design the building for future functions;
> Design the building for future technical innovation, guided by a roadmap;

→ [Design Strategy]: Scenarios

> Develop a scenario, along lines inspired by Brand’s scenario design process. Indicate within this scenario how variables such as users, functions, technology and the sustainable development can evolve.
> Allow change of separate parts of the building, without harming other parts.

→ [Design Strategy]: Qualities of Buildings that stay

> Find a balance between durable materials and maintenance, in line with earlier mentioned permanence and temporality. Allow easy maintenance, if needed.

→ [Design Strategies]: Dealing with future uncertainty

> Allow for future changes facilitated by a division between more permanent (adaptability) and more temporal (disassembly) building elements to create a building that can deal with future uncertainty
> Find a balance between durable materials and maintenance, in line with the above mentioned permanence and temporality.
> Construction nuisance in dense urban contexts can temporally result in reduced profits and building and land value, this can be an extra incentive for adaptive construction.

→ [Design Strategies]: Lifetime of a building

> Define the end-of-life of a building, or of building components, to secure a plan for material recycling. However, allow future uncertainty to change these plans.

→ [Design Strategies]: Design for Disassembly

> Design for prefabrication, preassembly and modular construction
> Simplify and standardize connection details
> Simplify and separate building systems
> Consider worker safety during deconstruction & construction
> Reduce building complexity

→ [Design Strategies]: Buildings as Material Managers

> Develop a framework for information management in materials, adaptability and disassembly to serve the goal of material pooling, connecting material cycles, but also improved maintenance and improved management of adaptability.

[Design Strategies]: Open Building

> Resonate ownership and use with the division between more permanent building systems and more temporal building systems as advocated by John Habraken.

→ [Design Strategies]: Structure and infill

> Define the border of structure, infill and ownership ideal for researched scenarios, functions and clients.
> Find an appropriate level of adaptability ideal for the to be refurbished building, researched scenarios, functions and clients.
→ [Design Strategies]: Open Buildings and Material Circularity

> Secure material circularity of the infill by having a material infill subcontractor or consultant to manage material flows and secure scalability of reuse and recycling.
> Define guidelines and specifics for infill to stimulate material performance, interior comfort and material circularity.

→ [Design Strategies]: Shearing Layers

> Using the defined roadmap and scenarios identify the importance of different layers for potential material circularity, performance and impact.
> Create frictionless interfaces between different shearing layers.
> Indicate material performance and material conditions for each layer to be used for material selection.

→ [Design Strategies]: Design for Adaptability

> Increase future options, but limit the balance between initial needed investments and allowed adaptability;
> Facilitate growth
> Create oversize
> Create diversity in space sizes
> Allow changes at different impact levels
> Create different configurations of routings, fragmentations and divisions should be possible to allow different sizes of functions

Material Perspective

→ [Design Strategy:] Hierarchy of Connecting Cycles

As it is not possible to have all materials closed loop recycled in the technosphere or composted in the biosphere develop a hierarchy of reuse.

7) (Maintenance)
8) Recycling and composting
9) Reuse
   a. Find upgrade: economic, social and cultural, technical, functional
10) Manufactured reuse
11) Downcycling
12) Waste

⇒ [Design Strategy:] Application of Material and Product

⇒ Match material and product characteristics with functional requirements of the related building systems;
⇒ High grade products with a big value difference between assembly and original pure materials: modularity and genericity can be beneficial.
⇒ Low grade products with a small value difference between between assembly and original pure materials: customization is preferred.
⇒ Use materials that can easily be disassembled and returned to pure material state

⇒ [Design Strategy:] Biosphere and Technosphere

⇒ Use biodegradable materials for short time use periods where it is unsure if there is a clear recycling or reuse possibility.
⇒ Make sure for disassembly between biosphere and technosphere.
⇒ Avoid bio-based products that lack certification that secures a sustainable harvest.
⇒ If possible, use by-products of other agricultural activities, such as straw.

⇒ [Design Strategy:] Composites

⇒ Avoid composites, use building products that have been made out of one type of material.
⇒ If composites appear to have a significant advantage in terms of ecological impact over regular building products and no alternatives are available – they are an option.

⇒ [Design Strategy:] Recycled Content

⇒ If there are no clear risks for hazardous ingredients, prioritize products and materials with recycled content;
⇒ Avoid reusing or recycling products that might be energy intensive in non-renewable resources;
[Design Strategy:] Minimize Material Use?

- Avoid or minimize material use of materials that are toxic, contain hazardous materials or have limited possibilities for reuse.
- Carefully weigh the minimization of materials when in conflict with the shearing layers, or the increase of material use for creating oversize for adaptability.

[Design Strategy:] Responsible sourcing

- Recycled content
- Renewable content
- Agricultural waste
- Minimal newly sourced materials

[Design Strategy:] Hazardous Content

- Hazardous content and toxic ingredients should by all means be avoided. In case there are no other possibilities, they should be completely recoverable in close technosphere cycles with minimized pollution or harm to the environment.
- Hazardous content is mainly a topic to be included in the Shearing Layers of services and space plan.

[Design Strategy:] Materials that do good

- Identify materials for secondary benefits, such as excellent insulation values, purification of air, carbon capture, etc.
- Prioritize materials used in the interior on their abilities to improve the climate.
- Building or interior elements that have generic dimensions and generic adaptability can be manufactured with high durability and craftsmanship (either new or reused) to add life, culture and meaning to place and facilitate future further reuse. As inspired by the freestanding English bathtub and the beams and columns of American barns.

[Design Strategy:] Embodied Energy

- Prioritize products that are of local origin.
- Prioritize products that have been produced using renewable energy sources.
[Design Considerations:] Impact per Shearing Layer

> Impact of different Shearing Layers does not follow the amount of mass. Structure, services and skin all contribute to about a quarter of the initial impact, over time, due to recurrence, this can be taken over by the space plan changes.

[Design Considerations:] Trade-offs between different sustainable characteristics

> Trade-offs are often necessary in a material strategy. Total Life Cycle Impact should be taken in consideration as well as the main project sustainability goal.
> To improve evaluation of different material characteristics: top priorities are indicated for each building element or Shearing Layer.

[Design Strategies]: Materials as part of the design process

> Inform the design in teamwork of both shape and material;
> Indicate material characteristics for each building layer and find appropriate materials;
> Indicate reuse and recycling of existing materials;
> Indicate a plan for recurrent maintenance and replacement over the course of life, informed by improved sustainability or changing users and functions;
> Indicate a plan for adaptable reuse and deconstruction;

[Design Strategies]: Collaborations with product manufacturers

> Improved relationships between manufacturers and architects to secure material sustainability and circularity. Alternative business models with take back guarantee and service plans instead of product purchasing can be frameworks of these relationships.