Circular housing envelope elements
from residual materials

Jesse Emmelot

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Author
Jesse Emmelot

Mentors

Ir. A.C. Bergsma	AE+T - Facade & Product Design
Dr. R.J. (Bob) Geldermans	AE+T - Climate Design

Delegate of the Board of Examiners
Dr. H.D. Ploeger

Abstract

As of today, the Netherlands experiences a housing shortage of around 300,000. Taking into account population growth and an increasing percentage in single-person households, around 80,000 houses should be built every year for the next 10 years to respond to the projected demand, which is high in most parts of the country. At the same time, the Dutch government has had ambitions and plans towards a circular economy by 2050. These plans were first released in 2016, after which concise reports were made on how to transition certain sectors of the economy towards circularity by 2030. These reports were called 'Transition Agendas', of which five have been written: Biomass & food, Plastics, Manufacturing industry, Built environment and Consumer goods. This project attempts to merge the challenge of solving the housing shortage with the challenge of realizing the circular ambitions of the Dutch government for the Built Environment, with input from all five Transition Agendas to start.

The Built Environment is one of the largest consumers of resources and energy of any industry, both for buildings and for infrastructure like roads and bridges. As it stands, this industry relies heavily on primary materials, as the materials used and conventional ways of construction and demolition are not tailored to reuse or recycling of resources. The other sectors covered by the Transition agendas also highlight a general reliance on primary materials and lack of application of reused or recycled materials by product manufacturers. This may be because the product is not designed to facilitate these processes or since some manufacturers are reluctant to use non-primary resources due to pricing or quality concerns. Pollution and contamination of used products is also a common issue for recycling. Finally, interests and ambitions may vary between parties when it comes to circularity or waste management. There may be clashes in priority between government, manufacturers and the waste processing industry.

The goals for this project is three fold. The first is to connect ambitions and material streams from different resource sectors, the second is to increase the circularity of conventional housing elements and the third is to apply resources from linear material streams in a circular way. The focus of the goals is on the envelope of houses, i.e. the facade and roof. This leads to the main research question: *How can the circularity of conventional Dutch housing envelope elements be increased, through the application of residual resources from linear material streams?* Answering this question involves first studying how circularity can be defined and measured, so that conventional materials and potential alternatives can be compared as objectively as possible. Then, contemporary Dutch houses are analysed to distinguish all common envelope elements and the conventional materials used. It is then speculated what circular improvements can be made on these elements and materials, either by using the original material in a different way or by using alternative (preferably linear) materials. The results are compiled in a catalogue, which provides examples of how each improvement could work and look. From this catalogue, a handful of the most promising examples of using linear residual materials as an alternative building material are picked for comparative calculations. Based off the steps taken to solve the main research question, an advisory framework is created, intended for use by those seeking to apply residual materials into new building elements, or simply develop new building elements based on circular principles.

Preface

This thesis is the result of a graduation project within the Building Technology Master track, at the faculty of Architecture and the Built Environment of the Delft University of Technology. It is written in a time when the Netherlands, as many other countries, faces the challenges of combating climate change and becoming a more sustainable economy. It is also a time in which there is a severe shortage of availability on the housing market, sparking a high need for mass housing in the coming decade. Incidentally, it is also a time of a global pandemic, which makes neither of these high-priority challenges any easier. This thesis attempts to address both the national ambitions to reach for a more circular economy in the coming decades, as well as achieve the construction of a million new houses by 2030.

I would like to thank my mentors, Arie Bergsma and Bob Geldermans, for helping me find a way through the large project scope and always providing useful suggestions for how to proceed.

I would also like to thank Martin Bos of Renewi for answering some questions on barriers in waste processing; his answers and suggestions for further sources gave a more focused direction to the project.

Finally, I would like to thank my family and my fellow BT graduation students, Joost and Christianne, for giving support along the way.

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1. Introduction

1.1 Background

1.1.1 Housing shortage in the Netherlands

As of 2019, the Netherlands has a housing shortage of over 300,000 houses (ABF Research, 2019). Due to scarcity and high prices, buying a house has become increasingly harder for the middle class population. In the largest cities, applicants for social housing are put on a waiting list for up to ten years. One result of this is a doubling of the homeless population in the last ten years. In the meantime, the overall population is also growing fast, with 132,000 new residents in 2019, while the average amount of persons per household has decreased (CBS, 2019). Figure 1 shows the expected severity of housing shortages across individual regions in 2025, which may run up to 8%.

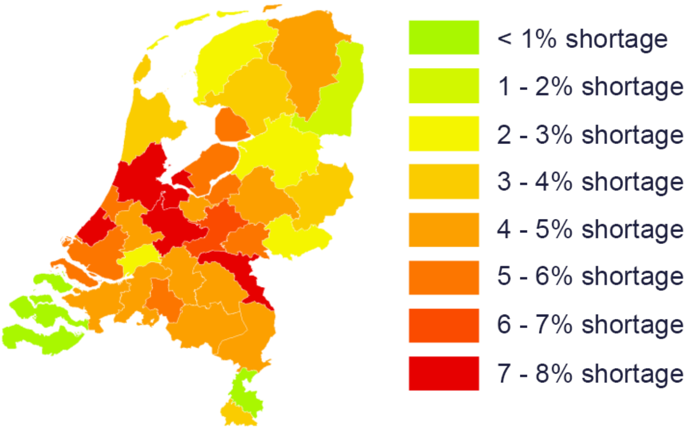


Figure 1: Expected severity of housing shortages in 2025 (ABF Research, 2020)

To respond to the large- and increasing housing demand, 80,000 houses should be built annually for the next ten years (Hulsman & de Voogt, 2020). However, in 2019 only 71,000 new houses were built. This low result can partly be attributed to the nitrogen- and PFAS crisis that started in 2019, which slowed down many building projects and will affect the coming years as well (ABN AMRO, 2020). In 2020, the Built Environment has also been impacted by the coronavirus pandemic which, while allowing projects to continue under safe circumstances, has led to economic decline that could affect investments in new projects (Centraal Planbureau, 2020). A more general reason for the slow annual building progress is that more rules have been introduced to building companies and developers in the last few years, for instance towards sustainability (Hulsman & de Voogt, 2020). While a lot of these additional rules are fair, they do slow down projects and increase costs.

1.1.2 Circularity ambitions

The Dutch government strives for the economy to be fully circular by 2050, as documented in their publication 'Nederland Circulair in 2050' (Rijksoverheid, 2016). According to the publication, this would mean to gather resources in a sustainable way, minimise damage to social- and physical environments, and design products and materials so that they can be re-used with as little value loss as possible, without harmful emissions. As an intermediate step, a 50% reduction in use of primary resources (i.e. minerals, fossils and metals) is intended for 2030. It is stated that the urge to pursue the circular goal comes from three main developments:

1. Increasing demand in resources, due to a global increase in population, economic growth and new technologies.
2. Dependency on other countries, with the Netherlands importing 68% of its resources and depletion of resources leading to geopolitical tensions and price increases.
3. Climate change, with high emissions of CO_2 from gathering and using resources.

In the publication, the idea of five different 'transition agendas' is also mentioned, each of which would cover the planned transition towards circularity of a particular resource-using sector of the economy. These transition agendas were finished and published in 2018, with one of them dedicated to the Built Environment, which includes both the Civilian & Utility ('B&U') sector and the Ground-, Road-, and Water ('GWW') sector. Infrastructure such as roads and bridges is thus also included. The transition agenda highlights that the Built Environment is one of the biggest consumers of primary resources out of any industry. It is responsible for:

- 50% of material resource use
- 40% of energy use
- 30% of water use
- 35% of CO_2 emissions

Besides these figures, it also makes insufficient use of circular design and materials, meaning only 3% of all building materials is reused for new buildings and the remaining 97% is mostly downcycled for infrastructure use. One of the reasons for this is that a large part of building materials is concrete and bricks, which are useful for making asphalt for example, but difficult to reuse as they usually have to be demolished to even remove them from a building. As a result of the aforementioned numbers, the amount of resources needed for building the required amount of houses in the Netherlands, following current building methods, is 2.5 times higher than the amount of available secondary building resources (Rijksoverheid, 2020).

Another issue in the Built Environment is that, while the circular transition is happening, the energy transition has been too. This can be a problem when measures to reduce the energy consumption of a house require more material use, for example thicker insulation and glazing, both of which commonly have circularity issues. Some of the common insulation materials are practically never recycled, and windows often end up on landfill. Solar panels use critical metals, which are also only gathered from select places in the world, causing dependency on other countries.

1.1.3 Linear products

The other four government transition agendas cover biomass- and food, plastics, manufacturing, and consumer goods. Across the different agendas, certain kinds of common material or product can be found that are problematic in becoming circular. Perhaps the most well-known example of this is plastic. There are many kinds of plastic with different properties, not all are equally reusable or recyclable. Industrial processes are nowadays fairly efficient however, and scraps such as shown in figure 2 can be recycled to a fairly high grade again.

Figure 2: Excess plastic scraps and recycled plastic (De Monitor, 2020)

The issue in practice is that scraps are difficult to sell to businesses, meaning that the processing plant may have to rent additional land simply for storing their excess material. The main reason for plastic being hard to sell is that new virgin plastic is currently cheaper than it has been in the last few decades. While volatile, where the value of the most common plastic (PET) used to lie around €1.20/kg, it became €0.85/kg in early 2020, while recycled plastic goes for €0.95/kg (S&P Global, 2020). As a result, a lot of manufacturers would rather use virgin plastic. Even though their finished product is then most likely recyclable later on, it's probably not made from recycled materials itself. Some businesses may also claim that there are negative qualities to recycled plastic compared to virgin - that it is weaker, leaks faster, carries bad odours or that it is hard to get the colour exactly right. While these claims don't always have to be true, many products (especially household items) have fairly strict quality specifications, so virgin plastic would still be preferred if it was the same price as recycled.

Another circularity issue across different sectors comes with products that, for the sake of better performance, are made of combined or mixed materials. Examples of this are food bags, plasticised paper or laminate foils, see figure 3. These are items that are hard to efficiently deal with for the waste processing industry after they are thrown away. For instance, the different materials could have different melting temperatures, meaning one of them may be turned to ash by the time the other reaches its melting temperature. Most mixed materials currently belong with residual waste, which is mostly incinerated for energy recovery. For these kinds of products, the problem already lies in the nature of the design.

Figure 3: Combined/mixed materials

Another kind of product that is hard to deal with for waste processing businesses are those that are polluted or contaminated. For instance, a mattress is already not the easiest thing to recycle even if it's clean (since it is made from combined materials); when contaminated, extra issues come up, as does with products like used vacuum cleaner bags and dirty cardboard. Not only does removing pollution from products require extra effort, processing businesses are also taxed for the residue they create with it (DRIFT, 2019). On top of that, the mass of the pollution within the product counts towards minimum mass norms for recycling, as long as certain limits of toxicity and contamination aren't crossed. Therefore, businesses have to make a choice between saving money through lower grade recycling, incineration or dumping, or spending money on high grade recycling. Also, sometimes recycling is not possible at all, so the problem lies in the use and the disposal of the product.

1.1.4 Perspectives on circularity

Definitions, interests and ambitions may vary between parties when it comes to circularity or waste management. For waste, a collection site may think of waste as whatever comes in, even if some of it could be easily repaired or refurbished. A processing company likes to be able to easily recycle things, so they are content with getting a lot of clean and well-separated material streams, again even if some of that material may not need to be recycled yet.

Figure 4: Several parties consulted for this report

When it comes to circularity, government publications highlight that it's important to think about how a whole product can be reused as long as possible, through things like repair or refurbishment. On the other hand, parties like the national waste processing association ('Vereniging Afvalbedrijven') say they would like to see more products being designed to be easily taken apart into separate streams for high grade recycling. It is also worth stating that, because the Netherlands has always relied heavily on waste incineration and still has a high capacity, incineration is still an appealing option over recycling for example.

1.2 Problem statement

Main problem statement

The Netherlands strives to have a fully circular economy in 2050 but also has a high demand for new houses, requiring a high amount of building resources, many of which are not designed - or utilised - to be fully circular.

Sub-problems

1. Definitions, interests and ambitions towards circularity vary.
2. Across different sectors, there is a lack of ambition to make resource chains circular.
3. Increased measures towards energy-saving may lack in circularity.

1.3 Objectives

Three main objectives will be followed to tackle the problems posed above:

1. Connect ambitions and material streams from different resource sectors.
2. Increase the circularity of conventional housing elements.
3. Apply resources from linear material streams in a circular way.

1.4 Scope

Timespan

The scope of the objectives is between 2020 and 2030. This is a time period in which the (international) economy and resource use are still linear for a significant part. The following reasons are also important for this choice:

- This project relates to the current Dutch housing shortage, which requires a large number of houses being built annually between 2020 and 2030.
- Circular design solutions and business models for now still have to compete in a market that for a large part is built on long-standing-, international- and linear trading relationships which are highly cost effective.
- More accurate predictions can be made for how developments will manifest, using current knowledge and data.

Objective boundaries

1. **Focus on envelope (facade and roof) elements.**
   This is partially a personal preference, since facade design (and the climate design related to it) are the topics of highest personal interest and knowledge when it comes to buildings, compared to structural design for example. Also however, there is a lot of variety in how one can design and construct a housing envelope, thus it would be ideal to dedicate as much time to that as possible.

2. **Focus on reuse from linear (i.e. non-circular) streams.**
   This angle aims to find residual materials or products that, while linear in their current application, may be suitable for a more circular building application. For example, recycled plastics as mentioned in paragraph 1.1.3 - which manufactures might not find of high enough quality - could be useful in housing construction. For instance, one could make interesting looking panels from recycled plastic with slightly different colour shades or use it in applications where any potential odours aren’t noticeable.

3. **No preselection of materials.**
   A bias should be avoided, otherwise there wouldn't be much of a point in doing a broad material search. In the end, it's more valuable to objectively find out what material streams are problematic and why, even if those materials are not the ones that are easiest to work with.

4. **Only look for materials in products used within the Netherlands.**
   They could still be made somewhere else and their materials could come from somewhere else. The Netherlands imports a lot of products and semi-manufactures (Rijksoverheid, 2018). This would still be the case in a circular economy, as it's simply more efficient for some materials or products to come from abroad rather than make factories for everything inside the country. For some product- or material chains it will also always be more efficient to design them in a certain way, where it's hard to deal with afterwards; in other words, some products come into the Netherlands and don't really have valuable end-of-life options (such as those mentioned in chapter 1.1.3). Also, some products are routinely thrown away before their end-of-life, meaning some products can still easily be reused at their end-of-use but just aren't in the current system. Within the scope of this project, what matters is not where a product comes from, but what can be done with it once it's in the Netherlands. That is also why the scope only looks within the next 10 years: currently, lots of product- and material streams are either international- and linear, or only circular through inefficient international cycles with long-distance transport of end-of-life (or end-of-use) products and materials. Over time, product design worldwide should hopefully become more aimed towards circularity. As of today though, the Netherlands has fairly elaborate ambitions for a circular economy, yet still relies heavily on import from parts of the world that may not be as far in pursuing this idea. Until that time, it's best to look at how current linear chains, international or not, that end in the Netherlands can get a circular 'tail' at the end by using their residual materials for more than they were designed for. While linear products made in the Netherlands are of course also plentiful, the point is that this project only looks at solving linear material streams within the Netherlands, i.e. those that are downcycled, incinerated or dumped here.

1.5 Research questions

Main question

How can the circularity of conventional Dutch housing envelope elements be increased, through the application of residual resources from linear material streams?

Sub-questions

1. How can circularity be defined and measured?
2. What materials are conventional in contemporary Dutch housing envelope elements and which elements have high potential for circular improvement?
3. What linear residual materials can be found, which may be applicable to the chosen housing envelope elements in a circular way?
4. How might the market around residual materials change in the near future?

1.6 Design criteria

For the design of any element in this project, the following broad criteria apply:

1. They should be circular as defined by the research.
2. They should be a standardizable application in Dutch housing construction, with the need for efficient mass housing construction in mind.
3. They should be competitive with existing building elements, in terms of costs, functionality and aesthetics.
4. Their materials should be available in significant volumes, i.e. no scarce materials like critical metals for example.
5. Their production should have minimal negative side effects on people and the planet.

1.7 Design goals

Primary end goal

Testing the feasibility and implications of increasing the circularity of conventional housing envelope elements, since:

- The element design criteria can then be satisfied with more certainty.
- It becomes more a test of feasibility through product design, than designing for the sake of a new product.
- Confidence in feasibility and competitiveness is more important than in-depth- or advanced design.

Secondary end goal

Designing or referencing alternative building elements.

1.8 Design approach & final products

Design approach

Using materials that provide increased circularity for existing envelope applications, not necessarily designing new applications or elements altogether. If a material is found with unique and useful properties, experimentation with new possible applications can be done.

Final products

The final product is an advisory framework for those seeking to apply residual materials into new building elements, or simply develop new building elements based on circular principles. This framework will be based on the experience of finding- and creating ways to solve the main research question. The pros and cons of the framework will also be highlighted and improvements will be suggested for future research.

Besides the framework, this report also intends to offer a large numbers of ideas on ways to improve the circularity of conventional housing envelope elements, based on references and personal ideas. Improvements may either a more circular application of the conventional material, or the application of alternative materials. While this project focusses on the use of residual materials from linear streams, this doesn’t constitute all ideas presented in the report.

1.9 Methodology

The full step-based methodology scheme can be found in appendix 1.

Research by design

Design and research go hand in hand for this topic. On the one hand, the research questions aim to establish a clear design brief, listing out which building elements are preferred for the design task and which criteria are important for these elements and possible materials. On the other hand, design possibilities should be considered from the start, by exploring case studies and innovations in both the Built Environment and other industries, as well as through sketching. The exploration guides the decision making process for the building elements and materials. Thus, the order of answering the research questions is not linear from start to finish, rather back and forth of increasing knowledge. To evaluate materials, a set of indicators will be made based on literature research.

Literature review

Throughout the research- and design process, literature serves as an important foundation for decision making. This includes academic sources, developments by government publications and information from different industries. Given the scale of the topic of circularity in the Built Environment and its inherent relation to societal and economical questions, it’s important to gather information from different angles.

2. Perspectives on circularity

2.1 Introduction

This chapter is concerned with sub-question 1: How can circular building be defined and measured? This is important to establish circularity for building products, as it helps to set criteria for using a certain material for a certain application. A building product can only be called ‘circular’ when it can be explained why. It’s important to establish which definitions and perspectives to take on this - and from which parties. For instance, the concept of ‘circular economy’ had already sparked over a hundred peer-reviewed articles back in 2016 (Geissdoerfer et al., 2017), each with their own definition on the topic. Given the scope of this project, the following sides will be considered in this chapter:

- Dutch government
- Waste collecting- and processing organisations
- Scientific research

For the sake of clarity and distinction, the term ‘linear’ shall then mean any material or product that does not fall under the definition of ‘circular’.

2.2 Different parties

2.2.1 Government

The Dutch government describes the circular economy as one that foresees in needs without unacceptable environmental pressure (Rijksoverheid, 2016). In this system, preservation of natural capital is the centre point, making as much use of renewable and commonly available resources as possible. With that, resources are employed optimally and (re)used without risks for health and environment, and primary resources are sourced sustainably. Three strategic goals are presented to work towards this system:

1. High grade utilization of resources in existing chains
2. Replace fossil-, critical- and non-sustainably produced resources by sustainably produced, renewable and commonly available resources.
3. Develop new production methods, design new products, rethink area planning and stimulate new ways of consuming.

The Transition agenda for the Built Environment (Rijksoverheid, 2018) goes into further detail on what a circular economy means for this sector. Here, circular building is defined as developing, using and reusing buildings, areas and infrastructure without unnecessary depletion of natural sources or environmental pollution. Ways in which this can be stimulated are smart demolition or demounting for reuse or using biobased materials. It is emphasized that the challenge for ‘sustainable building’ does not just entail using ‘endless’ sources but also preventing the harming of ecosystems and contamination of soil, water and air. This is important since, for example, production of biobased materials is not by definition good for the environment. Three central ‘pillars’ are key in this transition agenda:

1. Optimal material use for all phases of the building cycle
2. As much use of ‘undepletable’ sources as possible
3. As efficient use of finite resources as possible

These pillars can lead to a variety of circular design strategies, for example:

- Optimising for long lifespan through design and materialization.
- Optimising for reuse through design for disassembly, exchangeability of parts and materials, adaptability for future needs or focused on movability
- Use of existing materials, through reuse of objects, elements or materials
- Use of less materials
- Use of renewable materials, with a low environmental impact.

Which design strategy is used depends on the circumstances in which a project is realised. For instance, a building in the inner city, which might get multiple functions in a few decades, may be optimised for long lifespan using high grade materials. Another instance could be a rural house, which may be built to be fully demounted after several decades to leave the site as natural as possible.

Another transition agenda worth looking at for perspective is that for consumer goods (Rijksoverheid, 2018). Here, circularity is considered as an continuous, cyclical (closed) process in which as little loss of products and materials. In general, it is stated that the R-ladder should be used for any product. The R-ladder is a hierarchy of possible actions to take to minimise the use of primary resources and energy in a product lifecycle. Figure 5 shows the steps on the ladder, including the optimal steps for short cycle products (green) and long cycle products (blue). For consumer goods, a distinction is made between products with short cycles and those with long cycles. For short cycle products, preventing the use of unnecessary products is key. For long cycle products, producer responsibility is key; a producer can strive towards optimal lifespan and high grade reuse of the product, material or resource, which in turn also saves them money. Appendix 2 includes a version of the R-ladder made by the national advisory council for environment and infrastructure (RLI), later edited by the national Environmental Assessment Agency (PBL), which defines what each step on the ladder entails.

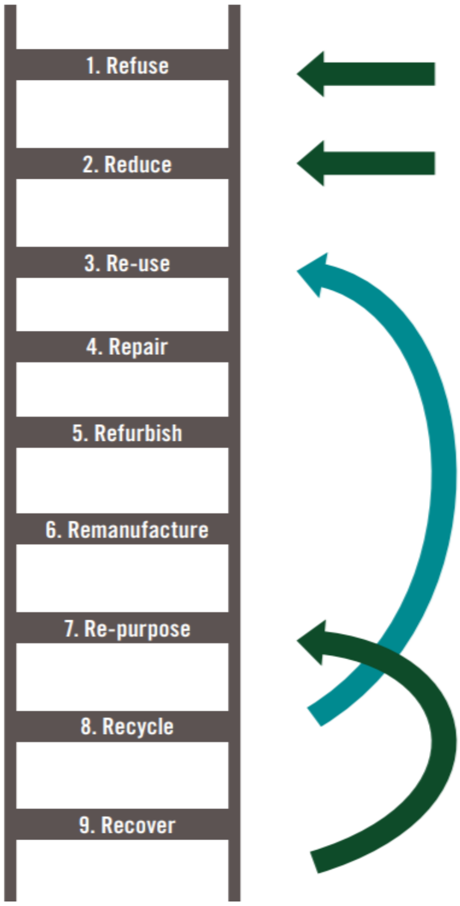


Figure 5: R-ladder (Rijksoverheid, 2018)

Defining waste

The topic of 'waste' is important in discussing circularity, given how many suggestions of either preventing or dealing with created waste can be found in publications. Several of the transition agendas call for a clearer distinction between 'waste' and 'non-waste'. Certain administrative and financial obligations come with waste; if it is not waste, other obligations arise. For processing, applying and transporting waste, there are specific rules and permit procedures. The Ministry of Infrastructure and Water Management (2019) defines 'waste substances' as substances or objects which the keeper (intends to / must) get rid of. For this project, this definition is actually fairly well applicable. This is because the objective boundaries focus on linear material streams which in their current state all end up with waste processing companies; whether these materials are 'waste' in the sense of 'beyond use' does not really matter for these products in current practice. Effectively, these materials are treated – either from their design, quality specs or business model – as 'waste' following the aforementioned definition. Processing companies likely don't mind this either. Although they are working on increased sustainability, they won't quickly refuse to process a load of material because it 'not broken enough'. While as mentioned different obligation come with 'waste' materials, regulations can always be subject to change given the right reasons, e.g. showing that a material can be reused for something useful.

2.2.2 Waste collecting- and processing organisations

Circularity is a topic that has kept waste processing organisations busy in the last few years. While 'waste' is an ambiguous term, waste collecting- and processing organisations will here be considered as those that take products and materials that have been thrown away and process them in a certain way. The easiest way to look at how this sector views circularity is through the national waste processing association ('Vereniging Afvalbedrijven'). This association includes over 50 companies involved with waste across the country. It is stated that 80% of waste is already recycled and 20% of renewable energy comes from the waste sector. They do also highlight the need for prevention, designing and producing differently, use and waste less, and repair more; it is admitted that a lot of progress can still be made here. The biggest potential points of profit are seen as making industrial production processes, as well as consumer behaviour, more sustainable. Like the Transition agendas, they also mention added value of processed waste. Two factors are highlighted that require extra attention:

1. **Quality of collected materials.** This requires a clean input stream, through more- and better separated collection. Through this, contamination can be reduced and purity improved. This can lead to production of more high quality products, where the market demand for recycled materials is leading.
2. **Sales market for resources.** The market longs for quality of resources, continuity, sufficient scale and competitive tariffs.

Contrary to government ambitions, 100% circular is stated to not be possible, since there will always be residual streams. During recycling and sorting, residue streams also get created that cannot be recycled anymore. They therefore state that energy recovery plants and dumping sites will remain indispensable links in the recycling- and waste infrastructure. This importance on existing infrastructure has sparked a government commissioned research into which stimuli drive waste processing business towards dumping, incinerating or recycling (DRIFT BV, 2019). This research found that the current waste system is mostly guided towards reducing dumped waste as well as a shift away from incineration to more recycling, which has been successful in the past few decades. However, it is stated that there is generally little motivation to do better than the minimum norm, leading to a large gap between circular ideals and those of the cost-competitive waste sector. Currently, dumping and incinerating waste are also still cheaper than recycling. In fact, there has even been an increase in waste dumping in recent years (see figure 6), with financial stimuli being seen as an important reason.

Figure 6: Trends in specific types of non-renewable waste processing (Rijkswaterstaat, 2020)

There also seems to be waste imported from abroad to incinerate in the Netherlands. The abundance of incineration in the Netherlands is the result of several decades of increasing capacity, as a way to prevent the need for dumping. This need was high due to economic growth (more production of products) and an increasing variety of different waste compositions from the 1970s onwards. In 1979, a motion for an order of processing steps was proposed by member of parliament Ad Lansink, dubbed the 'Lansink-ladder', see figure 7.

Figure 7: Lansink Ladder (Korse, 2015)

Since then, the amount of dumpsites has reduced, from 450 to less than 20. The existing dumps have advanced systems for soil protection and gas extraction. The market is controlled by a few large parties who operate internationally. Citizens have been adjusting their behaviour during the years and picked up new routines for separating and recycling. Many municipalities provide residences with different bins for separating household waste and there is likely a public collection point for separated waste collection nearby, such as in figure 8.

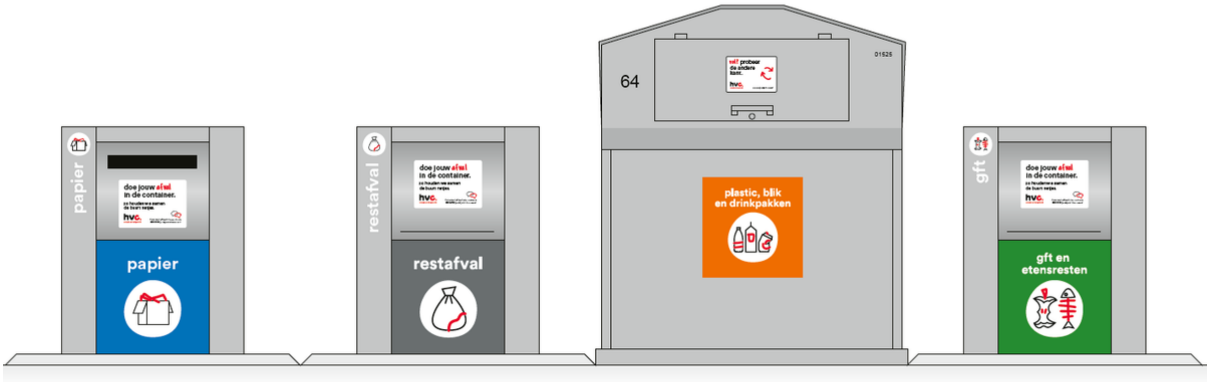


Figure 8: Example of a public separated waste collection point (HVC, n.d.)

There seems to be a good balance in the high amount of waste and high amount of separation and efficient management. There has also been a frame of policy around the Lansink Ladder (commonly also referred to as the 'waste hierarchy'). Nowadays, the majority of waste is recycled, otherwise incinerated with energy recovery. Given the current infrastructure of waste processing in the Netherlands, characterised by its high capacity of incineration and otherwise preference for recycling, it is understandable that the waste processing sector wants to be able to keep using this infrastructure. After all, waste processing is a business and these companies have a profit model which might not be fully compatible in a circular economy. That is why it is also understandable that they mostly cover ways to process waste in a circular way (e.g. 'how can waste be reused after it has been processed?'), rather than preventing waste being created in the first place; if there wasn't any waste, they wouldn't have business. Traditionally, recycling is the highest step on the R-ladder that they are really involved in, as practically all other (higher) steps revolve around preventing the creation of waste. This is also why, when talking about designing products in a more circular way, they talk about designing around better separation and recycling of a product's materials (i.e. easier waste processing), rather than designing for optimal lifespan, reuse or repair of a product.

Despite certain differences in ambition between frontrunners of the circular economy and the waste processing industry, both sides still have a lot to offer each other. It is therefore best to look at common interests between the more ambitious parties in the field of circularity, and the waste processing industry. In particular, it is useful to look at the different waste streams that waste processing organisations distinguish, what products or materials fall under these streams and what generally happens with them (e.g. recycling or incineration). This way, it can be found what kinds of material are most problematic in the waste they create. An example of how waste streams are distinguished in practice can be found by HVC group, a company that mostly operates in the provinces of Flevoland, Noord- and Zuid-Holland. They are also a member of the national waste processing association. Table 1 and figure 9 show the material types between which HVC makes a distinction for collecting and processing.

Waste stream	Materials	General treatment
Bulk waste	Anything not belonging in a household bin (e.g. ironing boards, carpeting, old smartphones, broken appliances, furniture, mattresses, Styrofoam, metals, paint cans, batteries, plastic buckets, toys, sails, tents)	Recycled (up to 70%) or incinerated.
Plastic	All plastic, with some exceptions (e.g. packaging with an aluminium inner layer, hard plastics like buckets and toys, or large pieces of plastics like farm sail or party tents)	Recycled (up to 95%) or incinerated.
GFT and food	All green- and food waste, with some exceptions (e.g. biodegradable plastic, soil-, turf-, wood- or thick branches (bulk waste), manure from hobby animals (residual waste), plant pots (from hard plastics)	Processed into green gas or compost.
Paper and cardboard	All paper and cardboard, with some exceptions (e.g. wallpaper or vinyl, receipts-, plastic coated paper-, sanitary paper- or contaminated paper and drinking packs.	Recycled up to six times (making up 75% of all paper) given it's clean and dry.
Textile	All textile, with some exceptions (e.g. bed sheets, pillows, contaminated textile (residual waste)	Reused (over 50%) or recycled, given it's clean and dry.
Frying fat	Frying fat	Mostly processed into biofuel.
Residual waste	All household waste outside of the other categories. Examples include corks, ash, dirty paper/cardboard, and most mixed materials (e.g.	Incinerated

Table 1: Distinguished material types for collected and processing by HVC group.

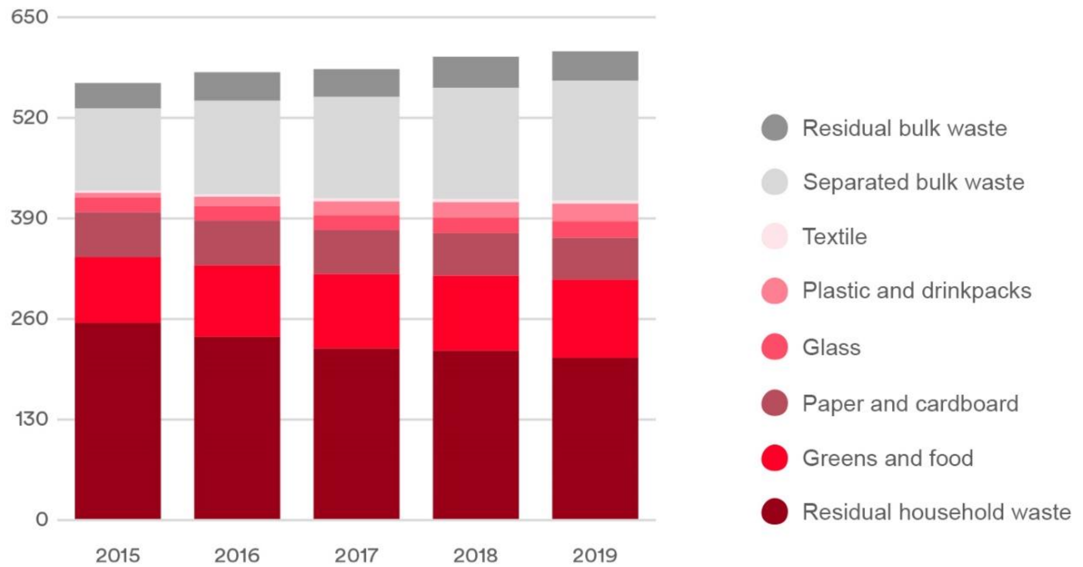


Figure 9: Amounts of collected waste streams per year in kton (HVC group, 2019)

The rightmost column of table 1 shows that most categories have high potential for recycling, given the right conditions. This involves most pure, clean and dry materials. The most problematic materials for reuse or recycling are those which are contaminated or made from mixed materials. In either case, it is either impossible or not efficient to separate the waste streams, meaning the material can only be treated as residual (bulk) waste and incinerated.

As figure 9 shows, residual household waste is decreasing, though still a significant portion of the total. Also important to consider is that the term ‘recycling’ may also be used for when a material is effectively downcycled for another use. Examples of this include breaking down building demolition waste to granulates for asphalt, and breaking down rubber from tires into ground surfaces and mats. Many improvements could therefore also be made in bulk waste.

Recycling challenges for waste processing businesses

To get a better understanding of the challenges that waste processing businesses face in recycling certain material streams, several major Dutch waste collection/processing companies were contacted and asked the following questions:

1. How are recycled materials redistributed back into the market?
2. Which material types receive little demand from the market for reuse or recycling?
3. Which material types are difficult to (efficiently) process at a high quality grade?
4. What are current developments/innovations in the high grade processing of waste materials (e.g. chemical recycling techniques)?

This enquiry yielded a response from a representative of Renewi, one of the largest waste processing companies in the Netherlands. Their responses and references were helpful in discovering problematic material streams and interesting developments, such as those described in chapter 1.1.3. Their annual ‘MVO’-report (Renewi, 2019) offered additional useful information. The answers are summarised below:

1. After being collected and sorted, sorted waste streams are sent to recycling firms for processing. The recycled material is then sold to manufacturers based on demand. This can sometimes lead to shortages or excess in available recyclates.
2. Generally, mixed materials (within the same product) are less desirable to recycle, for examples mattresses or mixed insulation. Polluted streams are also problematic. The way a material is brought in for collection is important too; if the earlier mentioned mattresses were disposed on the street, they likely contain too much moisture and pollution for being worth the effort to recycle.
3. Even when clean, a lot of mixed materials are hard to recycle. This includes both materials which are layered together (e.g. laminate foils) and those that are combined into a single substance. Materials that contain toxic substances are also problematic, such as asbestos, steel grit and sulphur-containing products.
4. There is a variety of initiatives to optimise recycling processes, such as chemical recycling techniques like pyrolysis and chemolysis for breaking down polymer. Techniques have also been developed to tackle toxic waste streams like asbestos and chrome-6 paint.

2.2.3 Scientific literature

The topic of the circular economy has been discussed plenty in scientific literature. Kirchherr et al. (2017) analysed 114 individual definitions of the circular economy, which offers a comprehensive start for scientific references for this project. Definitions were gathered from both peer-reviewed journal papers and non-peer-reviewed sources. A well-known example of a definition is that of the Ellen MacArthur Foundation:

> *"[CE] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."*

The main framework used to measure all definitions was the 4R framework, which consists of four of the R-ladder steps: reduce, reuse, recycle and recover. Also gauged was how well definitions kept in mind the three aims of 'sustainable development', a concept of which the circular economy can be seen as a practical operationalisation. These three aims are: Environmental quality, economic prosperity and social equality. The analysis produced several interesting findings.

Firstly, recycling was found to be the most commonly used R-principle of the four, followed by reuse and reduce. With this, it was found that practitioners relatively speaking feature 'reduce' less than average; this is understandable since reduction of production would likely reduce consumption - therefore also economic growth. One way to increase interest of this party for the 'reduce'-principle would be the widespread implementation of the product-as-a-service model; this business model has also been promoted in the Transition agendas from the Dutch government (all except for the Biomass agenda).

Secondly, there is a lack of mention of waste hierarchies. While, as mentioned in chapter 2.2.2, this hierarchy may not produce ideal results, it does prioritise 'reduce' over the other principles. As also mentioned in that chapter, production companies and waste processing businesses would, under their current model of operation, likely suffer from having to prioritise 'reduce' and 'reuse' over recycling, incinerating or dumping. The danger of not prioritising 'reduce' is a continuation of the current day 'business-as-usual', rather than progress towards a circular economy.

Thirdly, social equity is also not represented often enough given its significance in the 'sustainable development' concept. As will be shown in chapter 2.3, measuring tools for circularity may also leave out this factor. Because of this, the impact that social equity has in a circular economy is also not well-known. For this graduation project, it would also be a challenge to include social equity, for two main reasons:

1. Compared to certain other resource consuming sectors, such as consumer goods or biomass- and food, it is hard to predict the social benefit of circular interventions in the Built Environment, particularly for housing envelope construction as opposed to, say, the interior or services.
2. Given the scope of this project to only look at products used - not necessarily produced - in the Netherlands, there is little control over the production of the products. Thus, even though products which reach their end-of-use in the Netherlands may lead to social benefits through reuse in building elements, they may still be produced somewhere else under suboptimal conditions.

While it is stated that the circular economy cannot be defined undisputed by a single party, it is encouraged for scholars to “critically engage with concepts frequently found in various CE definitions”. The methodology used in chapter 2.2 matches that advice, by gathering information from different sources and attempting to form a definition which is most applicable to the project. The authors note which single one of their analysed sources they would recommend as a singular definition. This concerns a paper by van Buren et al. (2017), who see reducing the unnecessary destruction of resources as the main point of the circular economy, along with the following points:

> *“Reducing the consumption of raw materials, designing products in such a manner that they can easily be taken apart and reused after use (eco-design), prolonging the lifespan of products through maintenance and repair, and the use of recyclables in products and recovering raw materials from waste flows. A circular economy aims for the creation of economic value (the economic value of materials or products increases), the creation of social value (minimization of social value destruction throughout the entire system, such as the prevention of unhealthy working conditions in the extraction of raw materials and reuse) as well as value creation in terms of the environment (resilience of natural resources).”*

It is argued that the following changes are needed to make a circular economy function:

1. **Consumer behaviour.**
   The effectiveness of a circular economy strongly depends on the behaviour of society. Spreading awareness on the value of reused material over new material, and people setting examples for others, may stimulate a chain reaction.
2. **Governmental policies.**
   The government has shown willingness to support circular business solutions through policy- and regulation changes. For instance, certain production residue materials have been labelled as a by-product rather than waste. Distinctions like this are important, since ‘waste’ is legally speaking not a resource. Generally, marking waste as a non-resource helps to protect the environment and public health through making it have specific treatment. Allowing certain materials to have a different status opens up opportunities, as has also been done in the Built Environment with recycled aggregates from construction and demolition waste.
3. **Business practices.**
   New business models (e.g. nearsourcing, product sharing, leasing, outsourcing functionalities), value chains and product-service delivery models.
4. **Guidance and monitoring.**

Several barriers are mentioned in the way towards a circular economy. One is the difficulty for a company to change up their production chain from a linear to a circular model. This would likely mean having to make products with longer lifespans, dealing with longer contracts between partners, and stronger integration of external costs into lifecycle costs. Companies also tend to plan for the shorter term (a few years with quarterly budgets); circular business models require planning further ahead, increasing management costs. Additionally, some raw materials are currently cheaper than recycled material. According to the authors, one reason for this is the exclusion of external costs (social, environmental) into the raw material price.

Ultimate circularity
Potting et al. (2017) describe the concept of *ultimate circularity*, in which materials from discarded products retain their quality going into another product, effectively making discarded materials a ‘resource’ rather than ‘waste’. In practice, this is highly difficult to achieve due to things like degradation, mixing and contamination, as well as potential negative side effects to look out for. For one, increased circularity of a chain may actually require more resource- or energy use, such as chemical recycling of contaminated plastic requiring high energy for decomposing and reconstructing the material. Another side effect is that increased use of recycled materials in one chain results in fewer available secondary resources in other chains.

Product-as-a-service models

Many of the publications on circular economy referenced in this report mention the product-as-a-service model. For certain consumer products, this model may be preferred over extending a products lifespan, since more people being able to use it in a relatively shorter lifespan is more effective than the product having one function for a relatively longer time. This would work best for products that are only at certain times of the day or for relatively short periods, like vehicles, appliances, clothes, etc. The model may not be as ideal when it comes to housing envelope products, as most of the components always do their job when installed (e.g. structure, insulation, seals). For interior building walls, or envelopes of other building types (such as schools or offices) the model may be more applicable to facilitate potential changes in function during the building’s use. An example of this is a pilot project by the TU Delft, installing different façade modules on the EWI faculty building in 2016, see figure 10.

Figure 10: TU Delft façade leasing pilot project (Architectuur.nl, 2016)

Circular building
Chapter 2.2.3 has so far referenced and discussed ways in which a circular economy can be described and implemented effectively, as well as how this applies to this graduation project specifically. This gathering of information has been fairly general (i.e. applicable to pretty much all resource consuming sectors of the economy). It is however also useful to gather information on circular building specifically; this will also provide a better setup into chapter 2.3, where it is discussed how one can measure the circularity of a building part. When it comes to circular building, there are different ways to go about it. As with other sectors, strategies such as those from the R-ladder can be applied when designing a building element, for example optimising for lifespan, recyclability, purity, etc.

Geldermans (2016) organised a number of workshops which involved researchers, architects and consultants, to discuss how circular resources flows and adaptable building can be combined. It was found that a circularity-values can be found in the cross-over between two types of building(element) properties:

- *Intrinsic*: material and product characteristics, including:
    - High quality (functional performance)
    - Of sustainable origin, able to 'reincarnate' sustainable (after every iteration)
    - Non-toxic (only healthy materials are used)
    - Consistent with biological cycle and cascade, or one or more technical cycles
- *Relational*: building design and use-characteristics, including:
    - Dimensions (overdimensioning may be worth the extra resources for flexibility)
    - Connections (dry and logical, likely standardised)
    - Performance time (defining the lifespan)

It is stated that homogeneous pure products with high recyclability are not necessarily preferred over more complex products with high maintenance. This depends on additional parameters. Important to think about when using a certain material for making a circular building element is determining the possible use- and reuse paths. Geldermans (2020) elaborates further on this idea, through six different 'pathways':

1. *Maintenance*: an upgrading intervention on-site, without relocation of the part.
2. *Redistribution*: utilisation of the part 'as is' after relocation to another site, possibly including a period of storage.
3. *Remanufacturing*: the rebuilding of a product to original specifications, potentially using a combination of reused, repaired and new parts.
4. *Recycling*: breaking a product down to separate raw materials that can be used again in product iterations of a similar quality, that is, retaining value rather than destructing value (this thus excludes 'downcycling').
5. *Bio-cascades*: applying biological materials in one or more product(ion) iterations, representing gradually decreasing grades, until they are ultimately used up and can safely return to the biosphere in the form of nutrients.
6. *Bio-feedstock*: direct application of materials as biological feedstock for the production of materials that can be used in high-grade and renewable iterations. This can be referred to as a form of 'upcycling'.

Leising et al. (2017) performed three case studies in the Built Environment: a newly built project, a renovation project and a demolition project. From this, a collection of innovations in sustainable business models were identified:

1. Create value from waste, through methods like design for disassembly, material banks, C2C materials, closing waste loops, high rates or reuse and recycling, and take back management via material passports.
2. Deliver functionality without ownership, through methods like product-as-a-service.
3. Optimise material efficiency, through methods like reduction of special needs.
4. Substitute with renewables.
5. Repurpose for society, through providing a healthy environment for users
6. Inclusive value creation**,** through alternative ownership (e.g. the producer owns the product)

Lastly, this chapter references a study performed by Nußholz et al. (2019), covering ways to achieve carbon saving through more efficient use of (secondary) materials in the Built Environment. Firstly, it is noted that one should keep in mind the consequences of transport to the environmental impact, which in some cases can outweigh the savings of using alternative materials. Secondly it is argued that companies can be encouraged to apply circular principles more readily if it is shown how value is created through that; this includes both economic and environmental value. There are however barriers to creating value from reuse or recovery of secondary materials:

- Unclear financial case
- Low value of material at the end of life
- Lack of market mechanisms to aid separate collection and recovery
- Warranty issues of using reused materials
- Limited access to sufficient quantity and quality of secondary materials
- Increasing market share and sales through it is difficult
- Market domination by actors with low incentive for high value recovery

Some of these barriers have also been highlighted throughout this report, and helped to guide into the direction of where issues need to be solved. The paper does also offer ways in which production of building materials with secondary resources can be stimulated. For instance, standards for secondary materials can be (or already have been) developed to provide technical- and safety specifications. Another incentive is to simply tax primary materials more heavily, though solutions like this fall outside the scope of this project. In terms of carbon savings through use of secondary materials on a product level, these mostly depend on process-related factors (e.g. transport energy and production energy).

2.3 Measuring circularity

2.3.1 Introduction

Several of the publications referenced in chapter 2.2 included either their own method for 'measuring' circularity or otherwise called for its need. Measuring circularity is a way in which the effects of designing and using a certain product (e.g. resource depletion, emissions, value creation, etc.) can be established and compared to the effects of another product. This idea is relevant to any sector that uses resources for creating something, whether this is a small consumer product or an entire building. It is hard to determine a single appropriate method however, especially when crossing through multiple sectors as this project does. This chapter covers a few methods which reoccur frequently in literature, to draw knowledge from and create a method that can be used for judging materials and designs.

2.3.2 Separate indicators

There are already certain indicators that can be used to register resource use (Rijksoverheid, 2020), such as the MCI (Material Circularity Indicator), DMI (Domestic Material Input) and RMC (Raw Material Consumption). There are also indicators for environmental pressure, such as carbon footprints. The challenge in combining indicators such as those into a single number is that it means having to weigh the importance of each indicator relative to others. This requires making assumptions and solving conflicts of interest. A single 'objective' score is still preferred over separate indicators however, as it is more reliable than having to make a subjective judgement based on those indicators; see MPG scoring below as an example.

2.3.3 MPG

One existing method that reoccurs in government publications and discussions is the MPG, The method is used since 2013 for gauging the environmental effects of buildings and infrastructure based on life cycle analysis (LCA). Recently, the Dutch government has announced interest in expanding the method by including circular performance (Rijksoverheid, 2019). In the current MPG, the effect of renewable- and secondary resources and products is also included, leading to a better (i.e. lower) score than a building with all primary resources. Additional indicators are intended to be developed, such as high grade reuse and recycling.

The current MPG is calculated as the sum of shadow costs per used material, over total floor area [€/m^2]. According to the Handbook Environmental Prices (CE Delft, 2017), shadow prices "indicate the loss of economic welfare that occurs when one additional kilogram of the pollutant finds its way into the environment". As of 2018, new houses should not have an MPG exceeding 1.0. This value was found to be achieved too easily however (Sira Consulting, 2019). The consequence of this is that the MPG calculation often is not done until the last possible moment, since there is little worry about exceeding the maximum. The Dutch cabinet therefore sharpened the maximum to 0.8 at the start of 2021, so that the MPG calculation will be done earlier in projects and thereby force more conscious decisions to be made about things like material choices and building shape. The lower maximum will also make it harder for buildings with high ambitions for energy saving to achieve a low enough MPG. This may cause conflicts in relation to the recent BENG indicators, used for determining energy use of a building, which are compulsory since January 1st 2021.

Life Cycle Analysis (LCA)

LCA has become an integral part of the most prominent calculation methods for sustainable resource use in the Netherlands and is used globally. LCA is defined by the ISO 14044 as “the compiling and evaluation of the input and output and the potential environmental impacts of a product system during its lifetime”. By the same standards, LCA consists of four phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

Phase 1: Goal and scope definition

To start, the analysis is to be specified. This includes specifying the reasons for doing an LCA, stating whether it is comparative, what assumptions are made and what are the system boundaries. Of course, the product subjected to the LCA must also be specified. This includes its intended function, as well as demand. The intended product function can be quantified through a *functional unit*. The functional unit can be made up of several indicators that define its performance, such as purity, toxicity, durability, etc. In turn, this functional unit influences how a product is made to realise the desired performance.

After specifying the products’ function and functional unit, the *system boundaries* of the product system must be drawn. A project system includes all possible steps between gathering the base resources, and the manufacturing-, use- and end-of-life options. System boundaries include the following:

- **Cut off criteria:**
  These define which parts and materials of the product’s system are included. For example, it may be chosen to only include materials that contribute more than 5% to the total mass of the product. This step also includes cutting out processes that are identical between two compared products, as the impact would be the same.
- **Boundary type:**
  The boundary type determines which system steps are included, for example:
  - Cradle to Grave: from raw material up to the product’s end of life.
  - Cradle to Gate: from raw material up to the finished product at the factory.
  - Gate to Gate: the manufacturing process of the product.
  - Gate to Grave: from the finished product up to the product’s end of life.
  - Cradle to Cradle: An alteration of Cradle to Grave, where the end of life constitutes a circular strategy like reuse or recycling.
- **Allocation:**
  It may happen that a certain base resource is used for multiple products. In this case, it can be hard to know how much of the input contributes to one or several of the outputs. It is advised to therefore avoid allocation if possible, otherwise ratio the output impacts based on a known physical distribution between outputs, e.g. weights.

Phase 2: Inventory phase

After specifying the analysis, the next step is to make an overview of all processes that are relevant to the covered system, within the chosen boundary type. Processes include things like resource extraction, transportation, smelting, shredding, washing, assembly, etc. Once the processes are known, data can be collected for each process. The result of this collection is a *Life Cycle Inventory* (LCI), which includes all material- and energy inputs and outputs of the system. See figure 11 as an example.

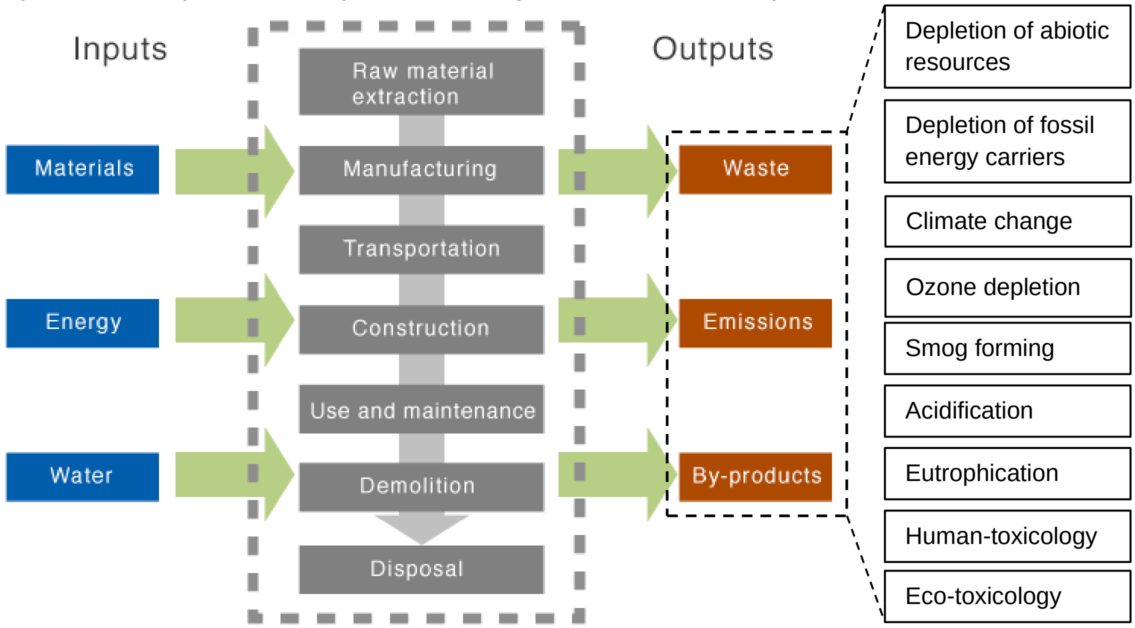


Figure 11: Schematic of a Life Cycle Inventory (Greenspec, n.d.)

When all processes in a product system are known, data can be collected on the inputs and outputs. There are many databases for LCA data and even more calculation tools to perform the LCA. The most prominent Dutch database for LCA data is the 'Nationale Milieudatabase' (NMD in short, meaning 'National environmental database').

Phase 3: Inventory phase

With the LCI from phase 2, a *Life Cycle Impact Assessment* (LCIA) can be performed. This assessment reveals the severity of the environmental impacts that happen in the product system. The two most important steps for LCIA are:

1. **Classification:**
   Assigning resources and emissions to 'impact categories'. An example of an impact category is the Global Warming Potential (GWP); emissions that contribute to global warming, such as CO_2 and methane, are part of the GWP.
2. **Characterisation:**
   Converting the results of the LCI into the 'reference unit' of the corresponding impact categories. For example, the GWP has the reference unit *kg* CO_2*-eq*. Conversion factors are used, based on an established methodology.

Phase 4: Interpretation

After the impact assessment, the results can be interpreted.

2.3.4 CB'23

Introduction

Platform CB'23 is an organization set up by several parties, including the Dutch Ministry of Infrastructure and the NEN (institute for normalisation), with the goal of establishing national agreements on circular building in the entire Built Environment by 2023. Since their formation in 2018, they have released multiple versions of documents in which a new 'core measuring method for circularity' is brought to life. This was done through feedback from outside parties (including market players, policy makers and scientists). Through this feedback, three main goals were established for circular building:

1. Protecting material supplies: preventing exhaustion, so they can remain being used.
2. Protecting the environment: preserving quality of human and animal
3. Protecting existing value: preservation through high quality and use.

The creators of the core method considered including 'social fairness' as a goal, though this in practice was found not to be as important of a stimulus for project parties to want to build circular. CB'23 does acknowledge its importance and have therefore included some methods to measure social fairness, which could be used for this report as well. As of the writing of this report, the core method is in version 2.0; some parts are still lacking from this version, intended to be added in the future. The general workings of the core method are shown in figure 12.

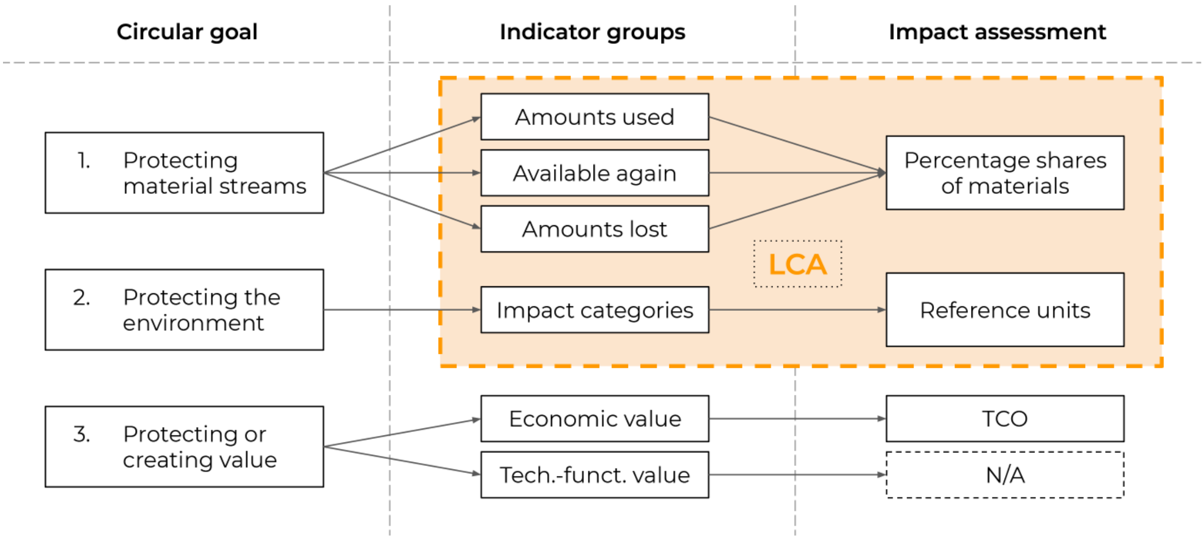


Figure 12: CB'23 new core method general workings (own image)

Adaptiveness

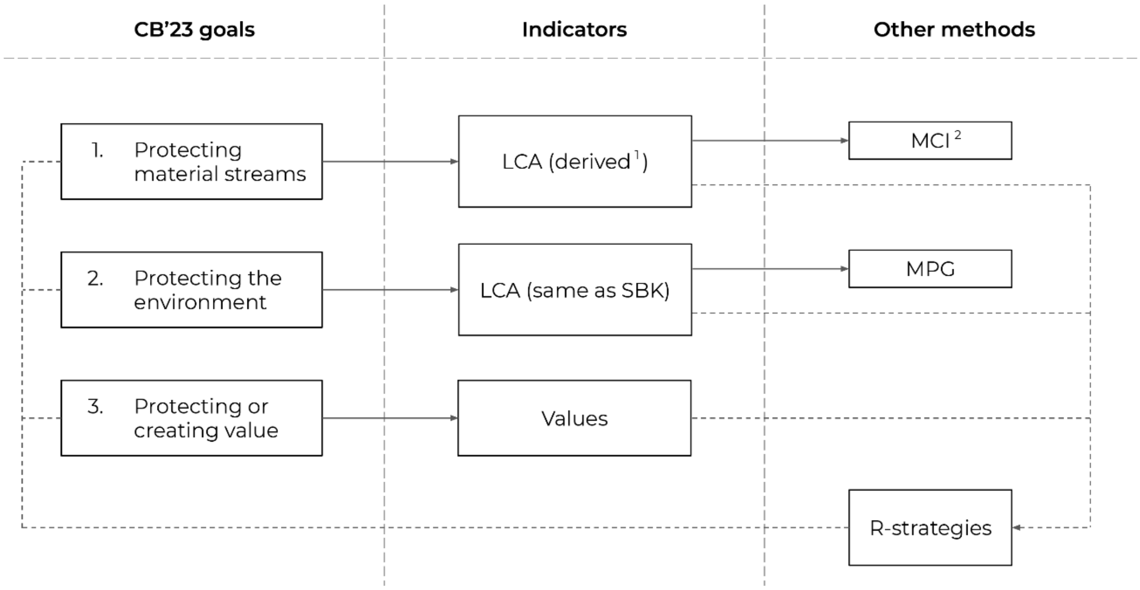
Besides the three sets of indicators, users of the core method should also report on the 'adaptiveness' of their building(part), of which two types are distinguished:

1. *Spatial-functional adaptiveness*: the building(part) can handle changes in functions and spatial needs.
2. *Technical adaptiveness*: connections are separable, elements are reachable and physically independent.

Given that the focus of this project lies on the scale level of building parts, technical adaptiveness is most important, since spatial-functional needs for envelope elements usually don't change over their lifespan. It would be more important to ensure separable connections, to safely remove elements from buildings for reuse or other uses.

Relation between CB’23 and common methods

The approach that CB’23 takes could be considered a meta-analysis of common existing methods and their shortcomings, to build upon them while applying improvements. The diagram below covers the relationship between prominent methods and CB’23.



[1] The core method uses its own set of indicators, which can mostly be derived from the LCA inventory phase.

[2] There are slight differences between the MCI and core method indicators, though similar in direction.

2.4 Decisions based on literature findings

2.4.1 Introduction

The literature review has shown the depth to which circularity can be discussed and how much research is already available on it. From these findings, several important conclusions can be made on the definition of circular building and how to measure it, to apply further in the report.

2.4.2 Defining circular building

Chapter 2.2 cited angles from the Dutch government, the waste processing industry and scientific research. Compiling all findings from chapter 2 results in the following list of prominent circularity topics (no particular order), all of which can be found in at least several of the references publications:

- Applying R-strategies, as high as possible on the ladder
- Thinking of high-grade utilisation paths within resource chains
- Optimising material efficiency in a product
- Designing for demountability and reuse
- Preventing the harming of ecosystems and the environment
- Preventing contamination and degradation of products
- Preventing unnecessary mixing of materials in products
- Preventing the use of toxic materials
- Crafting policies around preventing and qualitative handling of waste
- Considering new methods of material processing and product design
- Using new business practices, e.g. extended producer responsibility, nearsourcing
- Stimulating socio-institutional change
- Creating and protecting value: economic, technical, functional, social

The most relevant singular definition found is that by Van Buren et al. (2017), which is centred around applying R-strategies and creating value. The R-ladder is one of the most commonly reoccurring principles in literature on circularity, as well as being comprehensive to use. Value creation- and protection may also be deemed essential when discussing circularity, as they gauge the effects of applying circular strategies within a resource stream. Additionally, companies may be encouraged to apply circular principles more readily if it is shown how value is created through that, making it worthwhile to alter production lines or business models.

Baseline circularity criteria

Similar to how design criteria for new products are put up in chapter 1.6, several circularity criteria have been derived from the list which will apply to every suggested envelope product:

1. The product should use the minimal amount of materials to achieve its desired functionality and lifespan, thereby preventing excess and maximising on possible units.
2. The product should be installable and demountable as a separate unit, thereby increasing its reusability and adaptiveness.
3. The product should be pure, i.e. made of a single material, unless directly reused from a former application. This reduces risk of contamination and making it easier to recycle.
4. The product should contain no toxic substances, thereby reducing potential harm to humans and the environment.

2.4.3 Measuring circular building

Chapter 2.3 covered several methods which are commonly used for calculations related to circularity. The goal was to help construct a method through which a judgement can be made on the circularity of different options for housing envelope elements (e.g. applications, materials, connections).

The most promising singular method found was the new core method by CB'23, as it is elaborate in terms of the included indicators, which it attempts to tie to more established methods like the MPG and LCA. It also works well for testing out the effects of R-strategies and puts an inherent importance on product value. Most importantly, the method can be used on any scale of a building, down to individual elements, whereas the MPG is meant for whole buildings. The new core method does have its shortcomings however:

1. As of version 2.0, there are not yet indicators for base technical-functional value. The addition of technical-functional value indicators is planned for the next version.
2. Social value indicators are not included, nor planned, as it is noted to not be a significant enough stimulus for most parties to consider circular measures. If social value were to be considered in this project, indicators would have to be specified here.
3. The method does not yet provide a way to conclude scores from the collections of indicators. This would be most useful for assessing environmental impact, as kilogram equivalents of different impacts are difficult to judge in relation to each other. One way to solve this is to use shadow costs, as is done in the MPG method.

In this project, the new core method could be used to measure two housing envelope options and compare their results together, as an objective means to assess circular 'improvement'. The steps and assessment for this measurement would be as shown in figure 13. This scheme is largely identical to the general workings of the official core method, with the addition of shadow prices for comparing environmental impacts and custom indicators for technical-functional- and social value. Appendix 8 shows how the custom method could be applied, in the form of an Excel. Such a worksheet can be made to automatically calculate certain results based on inputs, such as percentage shares of different resources in a product based on mass, and shadow prices based on environmental impact results.

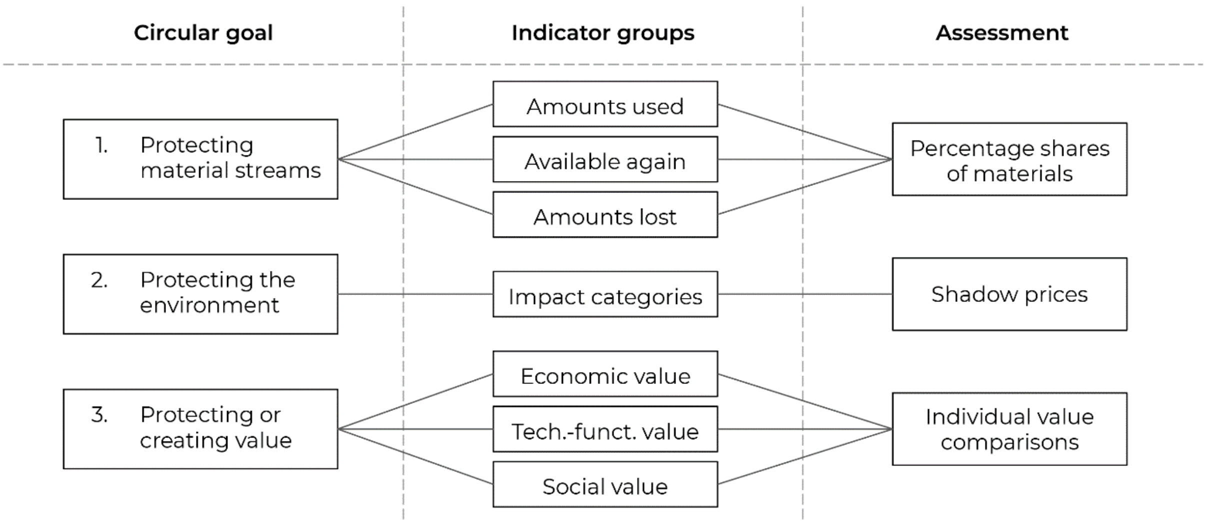


Figure 13: Possible implementation of the CB'23 core method in this project

As mentioned previously, the indicators for goal 1 and 2 of the new core method are either derived- or taken from standardised LCA. For goal 3 (protecting value) only economic value is yet included in version 2.0 of the method. The mock-up Excel sheet in Appendix 8, shows what possible technical-functional- and social values might be applicable to a comparison between two building products. Given that the goal here is value preservation, it would be sensible to gauge these values over at least two lifecycles, to find out how much can be preserved between cycles.

Measurement challenges

Initially, it was intended to use the above described custom version of the new core method and the corresponding Excel sheet later in this report. However, attempting to execute the method highlighted some challenges, both specific to the method and to circularity calculations in general. Table 2 lists out these challenges.

Topic	**Challenges**
Life Cycle Analysis	LCA works best when the entire product system is known. When testing out unconventional materials (or designing an unconventional building element) assumptions have to be made during the inventory phase, about where and how the material is gathered, what processes are used to make the product, etc.
	When comparing two different materials, a lot of real-life variable are out of the methods control, for example the possible end-of-use paths for the different materials.
	Quantifying different circularity indicators by the same metric (e.g. shadow costs, or a general score) may lead to less accurate results, as conversion factors add an extra step of uncertainty.
	Comparing the lifespan of a conventional element with a suggested alternative may mean they have different boundary types (e.g. cradle-to-grave as the conventional treatment, with the alternative being cradle-to-cradle). This makes the comparison less relevant.
Value calculations	For economic value, many assumptions have to be made to calculate a TCO, given the unknowns of unconventional materials or elements.
	Measuring value loss over multiple life cycles can only be accurately done through empirical testing, given the many variables during use (e.g. cracking, discolouration) and after use (e.g. recycling quality).
Data collection	When using unconventional materials for a product, there may be little to no available LCA data on that material.
	While there are high quality software tools for automating the LCA process, there may be a lack of transparency into the exact data used for gathering resources, transportation, manufacturing, etc. This is a problem when applying materials in unconventional products.

Table 2: Challenges faced in planned circularity measurements

Adjusting goals for measurements

The challenges with using the new core method by CB'23 for this project mostly stem from the unknowns of using unconventional materials and element designs. When the product system isn't well-known, there are too many out-of-control variables, as well as a lack of data for LCA- and value calculations. This means having to take too many assumptions – or even predictions – to accurately quantify the circularity of a new building product.

Since the use of the aforementioned method would be suboptimal for this project, the goals for the measurements were adjusted towards crafting a more suitable method. Given that the project revolves around the testing and implications of new housing envelope solutions, it was decided to focus more on circular *potential* of these solutions, such as:

1. Potential for applying residual materials from outside the Built Environment.
2. Potential for designing entirely new building products by unique material properties.

Circular potential can be based on a combination of the more certain numerical values from the new core method (e.g. technical-functional values) and the possibilities for the product to create a sustainable product system (e.g. use of different R-strategies). This way, a judgement on circularity can still be made in an objective way, whilst not falling victim as strongly to numeral assumptions.

Creating a final method

The main goal for creating a new method was for it to have a strong connection with:

- The broad design criteria, as defined in chapter 1.6.
- The main definition for circularity, as decided in chapter 2.4.2.
- The baseline circularity criteria, as defined in chapter 2.4.2.

The result is a method based on three categories, see table 3.

Category	Purpose
Product design	Specify what the product idea would actually entail
Product feasibility	Gauge the potential of the product idea to be a well-functioning housing envelope element for its initial lifecycle.
R-paths	Think of all R-strategies that can be used throughout the product system, from its base materials to after its first lifecycle.

Table 3: New method categories and their purpose

Figure 14 shows the indicator types- and assessment for each category. Appendix 9 shows custom-made Excel sheet for executing the method, highlighting the specific indicators used in each of the three categories. The method and its results are assessed in chapter 4.3.

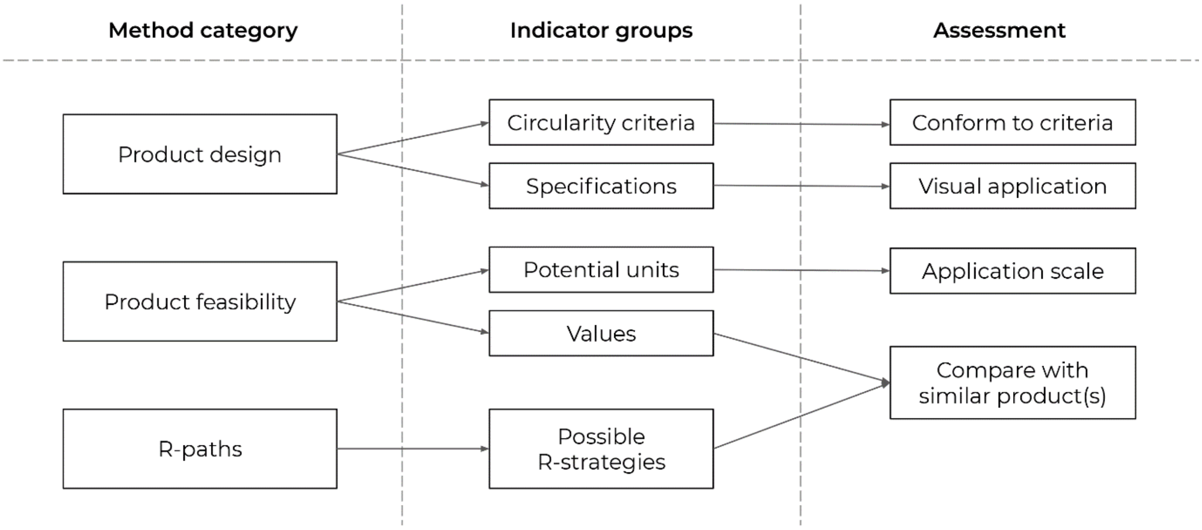


Figure 14: Method structure for assessing circular potential

2.5 Summary of defining and measuring circularity

Defining circularity

Literature review of different angles on circularity was performed. The chosen angles were the Dutch government, the waste processing industry and scientific research. This resulted in a list of prominent topics, all of which can be found in at least several of the references publications. From this list, several circularity criteria have been derived from the list which will apply to every suggested envelope product:

1. The product should use the minimal amount of materials to achieve its desired functionality and lifespan, thereby preventing excess and maximising on possible units.
2. The product should be installable and demountable as a separate unit, thereby increasing its reusability and adaptiveness.
3. The product should be pure, i.e. made of a single material, unless directly reused from a former application. This reduces risk of contamination and making it easier to recycle.
4. The product should contain no toxic substances, thereby reducing potential harm to humans and the environment.

The most relevant singular definition for circularity is deemed that by Van Buren et al. (2017), which is centred around applying R-strategies and creating value; these two topics are chosen as the guiding principles for circular actions in this project. Accordingly, ‘linear’ materials or products are here seen as those which do not apply R-strategies as high as possible, if at all, nor preserve or create value for multiple lifecycles.

Measuring circularity

Assessing new product ideas for housing envelopes will be done based on their circular *potential*, which is gauged through a custom method of three categories:

1. Product design: specifying and visualizing the product idea.
2. Product feasibility: gauge how well-functioning the product idea could be.
3. R-paths: apply R-strategies over the entire product system.

3. Contemporary housing envelope materials

3.1 Introduction

This chapter is concerned with sub-question 2: What materials are used for contemporary Dutch housing envelope elements and which elements have high potential for circular improvement? First, an overview is made of conventional envelope elements based on references. Then, the current state of circularity is gauged for every found element and the materials commonly used for it. Finally, a selection of materials is made which are most interesting to continue with.

Figure 15: Examples of contemporary Dutch housing

3.2 Analysing references

As a start to answering sub-question 2, many reference images of contemporary Dutch houses were simply looked up and analysed for as many different elements or applications as possible, combined with existing knowledge on facade- and roof sections. This approach is also necessary, as there were no complete sources to be found which dissected housing envelopes to such an extent.

After distinguishing as many different elements as possible, all conventional materials used for each element were documented. This started with noting the obvious combinations (e.g. bricks for cladding) and going into progressively more detail (e.g. specific plastic types for gutters). For this process information was widely available, as practically every common envelope element is made by a variety of companies and sold by multiple retailers, making it easy to find specifications. For some elements, such as insulation, articles comparing different material types were also useful for getting overviews. The end result is a colour matrix, shown in appendix 3.1. Some general material groups, such as composites and plastics, have been broken down into more specific materials in appendix 3.2.

3.3 Hierarchy of significance

Not every element in the matrix has the same amount of 'significance' for every house. Since it would not be feasible to cover every element from the matrix in the later design phase, a hierarchy has been made, putting each element into one of three 'significance' categories, see table 4. Also included here are five different 'colour groups', described later.

High significance	**Medium significance**	**Low significance**
Door (frame)	Curtain	Balcony platform
Facade cladding	Dormer cladding	Chimney
Facade insulation	Dormer insulation	Door awning
Facade structure	Dormer structure	Louvers
Roofing	Facade interior finish	Railing
Roof insulation	Gutter (drain)	Rolling shutter
Roof structure	Rolling shade	Vapor barrier / Waterproof
Window (glass)	Roof interior finish	Ventilation grilles
Window (frame)	Sunshade	Window sill

Table 4: Element hierarchy (alphabetical order per category)

Each element was ranked based on a culmination of the following criteria:

1. **Frequency of houses in which the element is included.** All elements in the 'high significance' category are principal to any contemporary house, while elements that may not be part of every house (e.g. balconies or chimneys) are placed lower.
2. **Amount of material used in the element.** This mostly helped with dividing elements between the 'medium' and 'low' significance categories. For example, a gutter typically requires less material to make than a dormer or railing. Additionally, it emphasises the high significance of elements like insulation, cladding and windows.
3. **Type of material used in the element.** This point was used to finalise rankings on certain elements, based on how high the potential is for material innovation. For example, elements like curtains, dormers or interior finishes could potentially be made from many different materials, while there is less potential in elements like chimneys and vapor barriers.

For the sake of relevance, the priority in the continued research lies on elements of medium and high significance. In the matrix and hierarchy table, there may be strong similarities between different elements in terms of materials commonly used. In the table, elements generally made from (most of) the same materials are marked with the same color. This results in five distinct groups within the high- and medium significance category, each marked with a different color, see table 5. Now it is easier to approximate the current state of circularity for a material within multiple possible elements.

Doors Windows Dormers	• Wood • Polymer (sometimes layered with steel for higher strength) • Aluminium (sometimes layered with steel for higher strength)	
Insulation	• Polymer, incl. EPS, XPS, PUR and PIR • Mineral, incl. glass wool and rockwool • Natural, incl. wood fibre and cellulose	
Structural components	• Concrete (reinforced) • Steel • Wood	For just facade structures, limestone or brick are also common
Cladding Roofing	• Aluminium • Bitumen • Ceramics (bricks, tiles) • Composite, e.g. HPL • Copper • Natural stone, e.g. slates	• Polymer, e.g. PVC • Reed • Steel • Wood-based, e.g. MDF • Zinc
Curtains Sun shading	• Acrylic • Polyester	

Table 5: Groups of elements sharing common materials

Going forward, it was decided to exclude structural components from further assessment of conventional elements. This is due to the increased complexity in performance requirements of structural components compared to other envelope elements, which become more complex when considering use of non-primary (unconventional) materials. In addition, personal preference does not lie within structural design as much as other building aspects.

3.4 Approximate circular potential of found materials

In chapter 2.4.3, a custom method has been devised to gauge circular potential of new building product ideas. For answering sub-question 2, this method could be applied on all selected conventional elements and materials too. This would however be too intensive of a task, given the large amount of indicators and required data. Therefore, a simplification on the method is used for approximating the circular potential of each conventional element/material, focussing on their lifespan and highest common R-paths to find where improvement opportunities lie.

Element group	Material type	Material	Lifespan	Highest common end-of-use
Doors, windows & dormers	Wood		30 – 60	Reuse, repurpose, downcycling, biomass
Doors, windows & dormers	Polymer		20 – 30	Reuse, recycling
Doors, windows & dormers	Aluminium		20 – 40	Reuse, recycling
Insulation	Polymer	EPS	35 – 50	Reuse, ground up for use in new EPS or XPS
Insulation	Polymer	XPS	50	Reuse, crushed into granulates for new XPS
Insulation	Polymer	PUR	50	Sheets: reuse Foam/sheets: repair, ground up and bonded to new PUR
Insulation	Polymer	PIR	50	Reuse, recovery
Insulation	Mineral	Glass wool	50	Reuse, repurpose, recycling
Insulation	Mineral	Rockwool	75	Reuse, repurpose, recycling
Insulation	Natural	Wood fibre	50	Reuse, repurpose, recycling
Insulation	Natural	Cellulose	20 – 30	Repurpose, recycling
Cladding & roofing	Aluminium		75	Reuse, recycling
Cladding & roofing	Bitumen		25	Recycling, downcycling, recovery
Cladding & roofing	Ceramics	Brick	100	Downcycling – grinding up for infrastructure use
Cladding & roofing	Ceramics	Clay tiles	50	Downcycling – grinding up for infrastructure use
Cladding & roofing	Composite	Al. sandwich	40	Reuse, recycling (difficult), recovery
Cladding & roofing	Composite	Wood-plastic	25 – 50	Reuse, recycling (difficult), recovery
Cladding & roofing	Composite	HPL	30 – 40	Reuse, recovery
Cladding & roofing	Copper		80	Reuse, recycling
Cladding & roofing	Natural stone	Slates	30 – 60	Reuse, repurpose (through downcycling)
Cladding & roofing	Natural stone	Granite	50	Reuse, repurpose (through downcycling)
Cladding & roofing	Natural stone	Limestone	50	Reuse, repurpose (through downcycling)
Cladding & roofing	Polymer	PVC	30	Reuse, recycling
Cladding & roofing	Polymer	FRP	30	Reuse, recycling (differs)
Cladding & roofing	Reed		25 – 40	Composting, biomass
Cladding & roofing	Steel		40 – 50	Reuse, recycling
Cladding & roofing	Wood	Tropical hardwoods	25	Reuse, repurpose, downcycling, biomass
Cladding & roofing	Wood	Cedar, oak, treated pine	15 – 25	Reuse, repurpose, downcycling, biomass
Cladding & roofing	Wood	Impreg. pine	10 – 15	Reuse, repurpose, downcycling, biomass
Cladding & roofing	Wood	Untreat. pine	5 – 10	Reuse, repurpose, downcycling, biomass
Cladding & roofing	Wood	Birch, poplar	< 5	Reuse, repurpose, downcycling, biomass
Cladding & roofing	Wood	MDF / HDF	50	Reuse, recovery
Cladding & roofing	Zinc		50	Reuse, recycling
Curtains & shading	Acrylic		10 – 20	Repurpose, recovery
Curtains & shading	Polyester		10 – 20	Repurpose, recycling

Table 6: Lifespan and highest common end-of-use strategies for housing envelope materials

The lifespan of every material/element in table 6 is the minimal expected lifespan as suggested by either the manufacturer of that material/element (taken from several manufacturers) or independent sources for building information (see catalogue). This is why there may be a range of years, as different sources give different figures. It should also be noted that for certain materials the lifespan heavily depends on how well it is maintained over the years, for example wood. The same kinds of sources were used for finding out the common end-of-use strategies. A material/element is considered eligible for 'reuse' if it can be removed and reinstalled without breaking or damage; for instance, brick is considered ineligible for this. Sources were reviewed critically, as it is not uncommon for manufacturers to either overestimate the lifespan and sustainability of their element, or to talk down on other materials used for that element. It is also common to find wording which makes a product seem more sustainable than it actually is, for example using 'thermal recycling' to mean 'heat recovery'.

3.5 Selection of elements and materials

Table 6 shows, as briefly as possible, the lifespan and common end-of-use strategies for conventional Dutch housing envelope elements. Paragraph 3.5 is used to decide which of these elements are most worth continuing with, both from a point of relevance (i.e. which elements/materials can potentially be improved on most in terms of circularity) and personal interest. As found in chapter 2, improvement in circularity may not just mean higher R-strategies but also comparable values (economic, technical, functional, social). Appendix 4 goes through all elements and materials from table 6, marking which have been selected (blue) and not (orange). Table 7 shows the final selection of elements and materials to continue with for finding circular improvements.

Element group	Materials
Insulation	EPS, XPS, PUR, PIR, glass wool, wood fibre, cellulose
Cladding and roofing	Brick, bitumen, clay tiles, stone, polymer, reed, steel, wood
Curtains and sun shading	Acrylic, polyester

Table 7: Final selection of materials and elements to continue with

4. Circular improvements for chosen materials

4.1 Introduction

Chapter 4 is concerned with sub-question 3: What linear material streams can be found, which may be applicable to the chosen housing envelope elements in a more circular way? Towards the final product as stated in chapter 1.8, chapter 4 should result in a large collection of ideas – either personal or by reference – on possible circular improvements for every selected element/material from chapter 3. As concluded in chapter 2, R-strategies form the guiding principle for circular improvements. For applying R-strategies, two directions are possible:

1. **Improve the circularity of the conventional material for the element.** This may be achieved through more circular design of the element (e.g. different connections, increased purity, lowered toxicity) or finding ways to increase the quality of the secondary material (e.g. better recycling methods).
2. **Look for a more circular alternative material, from a linear stream.** The aim is to find materials with which similar values can be achieved compared to what is conventional, while having higher R-paths.

4.2 Creating a catalogue of ideas

4.2.1 Applying R-strategies

Chapter 3 provides a selection of elements with high potential for circular improvement. Accordingly, for each element of the main selection, R-strategies for improving circularity have been devised and written down in a large table, which is shown in appendix 5. For every R-strategy for a certain element/material, the foreseen improvement is specified and the main benefits are noted. Besides providing set results on how certain linear materials can be used to make a circular building product, the goal of this report is also to inspire the reader on the general variety of options to make housing envelope elements more circular. This is reflected in the idea of making a catalogue full of ideas, both personal and by reference. These ideas could then be integrated into the table from appendix 5, as examples of how the suggested R-strategies for an element/material could be realised. For example, the table includes two R-strategies for using brick in a more circular way: one of designing for reuse through more adaptive connections (see figure 16) and one of reuse/recycling of brick rubble (see figure 17).

Figure 16: Facadeclick system (source: Bativox.be)

Figure 17: Brick rubble reuse (source: Bureau SLA)

4.2.2 Catalogue presentation

The table in appendix 5 was made in an online Excel spreadsheet. In the appendix, a link is provided to the sheet is provided. The sheet includes a column on the far right, which for every material and its different suggested R-strategies includes a dropdown list of links to ideas and real world examples of articles or products related to that R-strategy. These examples complete the foundation of the catalogue. The idea behind a catalogue is to show off how circular improvements to conventional building elements -and materials would work. Coming up with R-strategies and finding examples of it went in both directions; some strategies were devised and then assisted by examples, in other cases a found example inspired a strategy. Inspiration was gathered from a myriad of online- and literary sources, including most notably:

- ‘Imagine series’ published by Knaack, Klein and Bilow (2008 – 2016), providing creative ideas and sketches for construction.
- ‘Building from waste’ by Hebel, Wisniewska and Heisel (2014), providing real world examples of buildings and products made from secondary material, see figure 18.
- MaterialDistrict, a large collection of innovative materials inside and outside the Built Environment, see examples in figure 19.

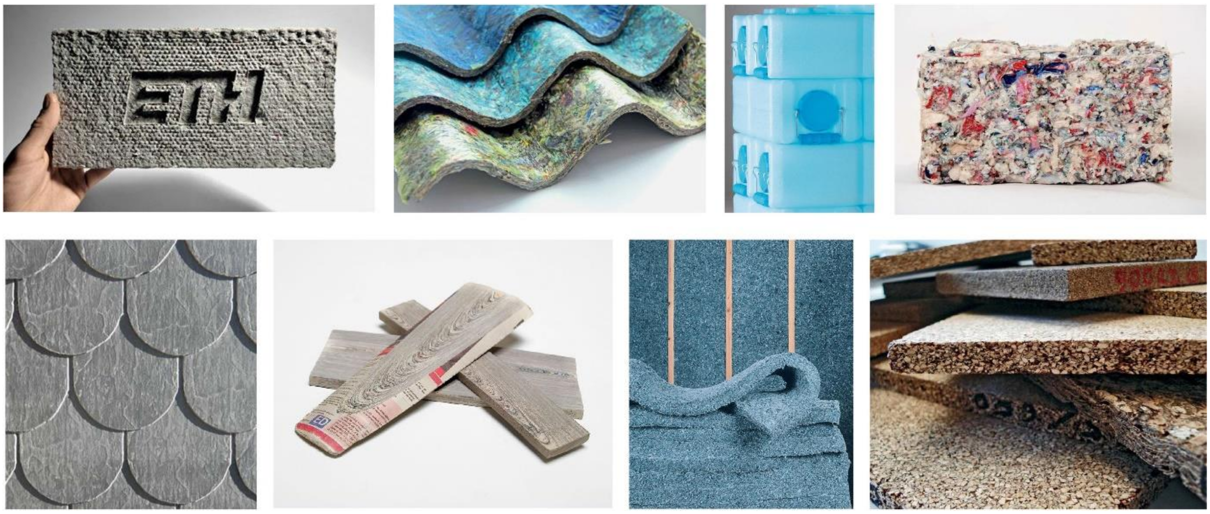


Figure 18: Examples from ‘Building from waste’ (Hebel et al., 2014)


Figure 19: Examples from MaterialDistrict

Besides online- and literary sources, a collection of personal ideas – some based on found inspiration – has been sketched out. Figure 20 shows an example of one of these sketches, the other sketches can be found in appendix 6.

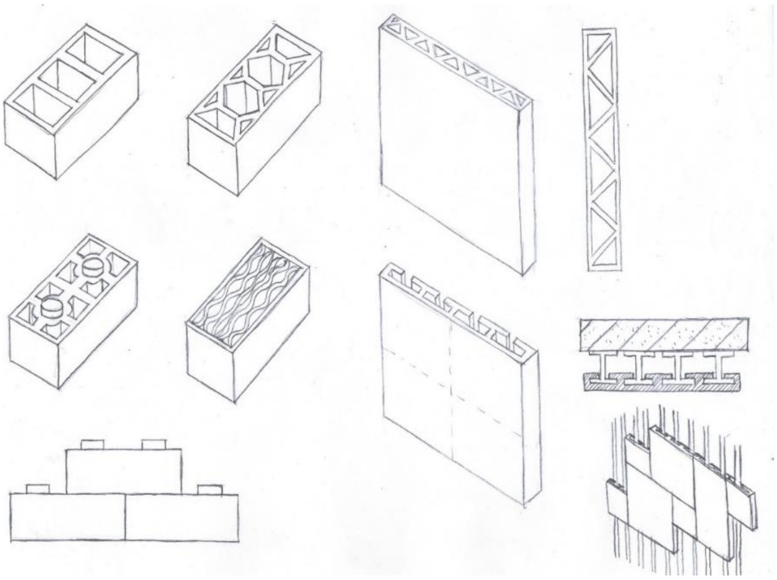


Figure 20: Sketch ideas for plastic bricks and panels

To present the catalogue, the idea came up to create an interactive website. Figure 21 shows a rough concept of how it would work. The idea behind a website is that users can 'try on' different materials for an element. The example shows how one may click on a brick façade, after which a popup shows which R-strategies may be applied on that material, as taken from the catalogue. Example images of each R-strategy (e.g. different connections or materials) are also shown in the popup. Clicking on one of the alternatives replaces the appearance of the brick in the model, giving an impression of how the change would look.

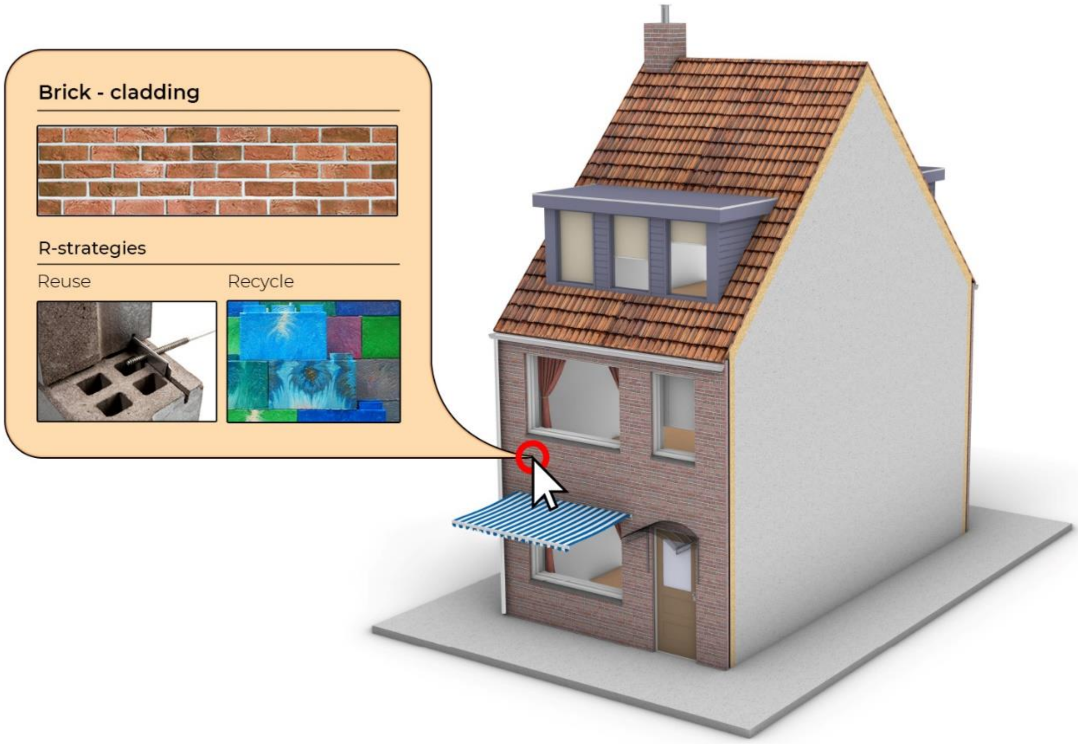


Figure 21: Website concept for catalogue presentation

4.2.3 Selecting catalogue ideas for testing

The catalogue provides examples of how R-strategies can be used on conventional elements, with the intention of increasing their circular potential. In order to test this, several cases from the catalogue are to be picked and subjected to the custom method from chapter 2.4.3. This number will be limited to a handful of the most relevant ideas towards the project's goals, as to give proper attention to each direction.

First, a selection of R-strategies and corresponding improvements was made from the options in the catalogue, with a priority on improvements based on residual materials (rather than renewables for example); this priority stems from the main goals of this project. The resulting selection is shown in table 8 below, with 8a being improvements to the original material in a conventional element and 8b being improvements through the use of alternative materials. All rows marked blue also have the potential to be used for a different application (such as reusing an alternative material back into its former function after use in a building).

ORIGINAL MATERIAL IMPROVEMENT			
Element (group)	**Material**	**R-strategy**	**Improvement**
Insulation	EPS / XPS	Reuse	Reuse from former applications
	PUR	Reuse	Reuse from former applications
	Wood fibre	Reuse	Reuse from former applications
	Cellulose	Reuse	Reuse from former applications
Cladding / roofing	Brick (both may be combined)	Reuse	Using more adaptive connections
		Reuse / Recycle	Utilising old bricks and rubble
	Ceramic / Stone (strats may be combined)	Reuse	Using more adaptive connections
		Reuse / Recycle	Utilising old tiles / slabs / rubble
	Polymer	Reuse / Repurp.	Reuse from former applications
		Recycle	Using lower grade sec. polymer
	Steel	Reuse	Reuse from former applications
	Wood (both may be combined)	Reuse	Using more adaptive connections
		Reuse	Reuse from former applications
Curtains / shading	Polyester/ Acrylic	Reuse / Repair / Refurb. / Repurp.	Reuse from former applications

Table 8a: Favourite improvements to original conventional materials

ALTERNATIVE MATERIAL			
Element (group)	**Material**	**R-strategy**	**Alternative material**
Insulation	General	Recycle	Textile (e.g. denim)
		Repurpose	Mattresses
		Recycle	Cork
		Recycle	Polymer (e.g. PE, PET)
Cladding / roofing	General	Repurp. / Recycle	Aluminium
		Recycle	Paper / cardboard
		Repurp. / Recycle	Rubber
		Reuse	Bark
		Refurb. / Repurp.	Textile
		Recycle	Cork
	Brick	Recycle	Polymer (e.g. PE, PET, PVC)
	Ceramic / Stone	Recycle	Polymer (e.g. PE, PET, PVC)

Table 8b: Favourites from improvements through alternative materials

After making a list of favourites from the catalogue, each option was considered more critically. For this final selection, the goal was to be left with a handful of materials and R-strategies that were most relevant to the goals of this project, i.e. making use of residuals from linear streams. Table 9 shows the final selection of materials and their residual treatment, as well as a shortened elaboration. Appendix 7 includes a separate table for the selected materials, as well as one for the rest of the materials which were left out. For each material in both tables, an elaboration is given as to why being selected or not.

Material	**Residual treatment**	**Elaboration**
Polymer	Reused / Recycled	Versatile in applications, current market issues
Rubber	Reused / Repurposed	Danger in reuse, inherently hard to recycle
Ceramic / stone	Reused / Recycled	Large part of total waste, usually downcycled
Wood	Reused / Repurposed	Often premature end-of-life in other uses

Table 9: Selection of residual materials for testing

4.3 Case study testing

The material selection from chapter 4.2.3 is subjected to the custom measuring method for circular potential, as described in chapter 2. The goal of these case studies is two-fold. Firstly, the materials can be tested on their real-life applicability and circular potential. Secondly, the testing method can be assessed on its strengths and weaknesses, based on use experience.

4.3.1 Product design

Following the first category of the method, the materials have to be applied in a full housing envelope product. For the specification of the product, the exact material has to be chosen. For the selected materials from chapter 4.2, this means selecting what kind of polymer, rubber, ceramic/stone and wood is used. Table 10 breaks down the materials into their most commonly found types. In the case of polymer and wood, only a few types are considered for testing, based on their cause of linearity and conformance to the baseline circularity criteria. Materials marked blue have been selected, materials marked orange are left out.

Polymer		
Type	Application	Cause of linearity
PET	Bottles	1. The majority of recycling (85%) is effectively downcycling, into polyester fibres for textile. 2. Recycled PET (R-PET) is currently at a premium compared to virgin, in part due to pandemic
HDPE	Fluid containers (shampoo, cleaners, paint, etc.)	Manufacturers are reluctant to make their products from recycled HDPE, stating concerns about polish, colour, smell and potential leaking. Because of that, they often prefer using virgin plastic.
PVC	• Pipes • Cables • Windows • Flooring • Foils	Varying levels of (sometimes hazardous) additives are used to achieve desired properties, yet mechanical recycling only works well for well sorted streams. Mixed- or unsorted recycling, commonly done, leads to unwanted results such as lower strength. The price of feedstock (i.e. chemical) recycling, a possible solution for purer secondary PVC, is higher than landfilling. For this project, an option could be to design products made from mechanically recycled mixed PVC, which would mean minimizing costs of sorting and thereby making a more competitive product. The problem with this is that this not only creates a mixed product (which goes against the criteria) but also likely a lower quality one; this may have way lower durability than a pure PVC product, while also be even harder to recycle than before. There are better options for improving the circularity of PVC, such as better separation during building demolition, stricter regulations for PVC additives (and simply its general use) and improved recycling techniques.

Rubber		
Type	Application	Cause of linearity
Mixed	Tires	Since rubber is made through vulcanisation, its structure is irreversible without destruction of the molecular bonds. Common 'recycling' techniques for rubber therefore involve grinding it up into granulates, which are either used for new applications (e.g. playground floors, which is really downcycling) or mixed in with new rubber (in limited amounts, as to maintain sufficient quality).

Brick / Ceramic / Stone		
Type	Application	Cause of linearity
Brick	Masonry	1. Bricks are usually fixed in place with mortar. While this makes for easy and durable cladding, it also makes it hard to remove the bricks separately later. 2. During demolition of a building, brick rubble often gets piled up with other waste and not collected fully separately. A lot of this mixed rubble can only be downcycled, e.g. for infrastructure applications.

Wood		
Type	Application	Cause of linearity
A-wood	• Pallets • Packaging	A-wood is untreated wood. While recycling of this wood (and of course reuse) are well possible, it is speculated that recycling is actually declining, compared to the more common option of incineration as biofuel. A big reason for this is a limited capacity of recycling, which drives up the cost compared to biological incineration. Untreated wood is also preferred for incineration over treated wood.
B-wood	• Doors • Windows • Laminate • Furniture • Painted wood • Particleboards	B-wood includes wood that is painted, coated, glued or pressed. This type accounts for the vast majority of waste wood collected in the Netherlands. The possible processing depends heavily on the quality and treatment of the wood, though the majority of B-wood is used as biofuel. A big reason for this is a limited capacity of recycling, which drives up the cost compared to biological incineration.
C-wood	• Fences • Sleepers	C-wood is wood that is impregnated under high pressure. Useful applications of this wood as a secondary resource are explicitly not allowed by regulations, except as a fuel source.

Table 10a: Selecting secondary materials and representative former applications

Material	**PET**	**HDPE**	**Rubber**	**Brick**	**A/B wood**
Application	Bottles	Fluid containers	Tires	Masonry	Various
					

Table 10b: Selecting secondary materials and representative former applications

With specific material types selected, ideas can be crafted on how to apply them in a housing envelope product. Figure 22 shows the sketches made in this process. From these ideas, three have been selected for further design, see figure 23.

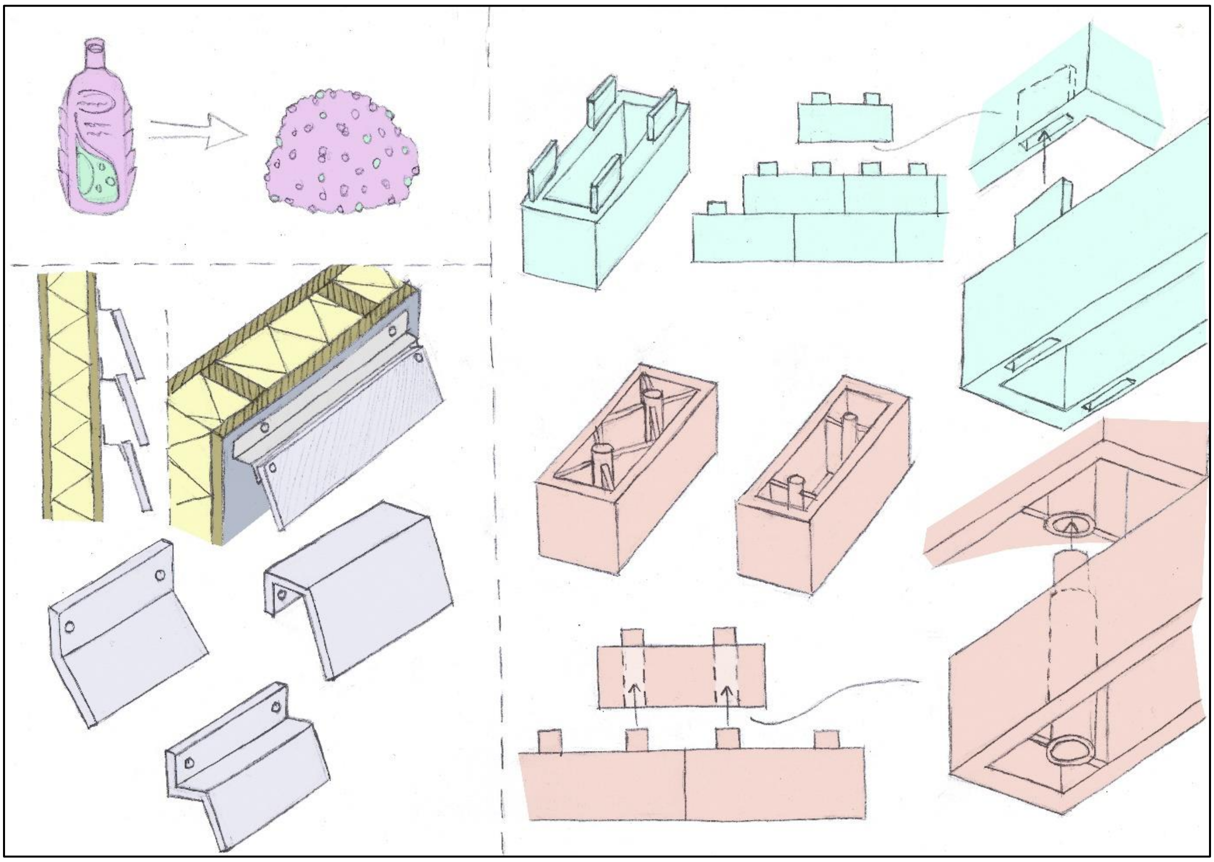


Figure 22a: HDPE cladding applications

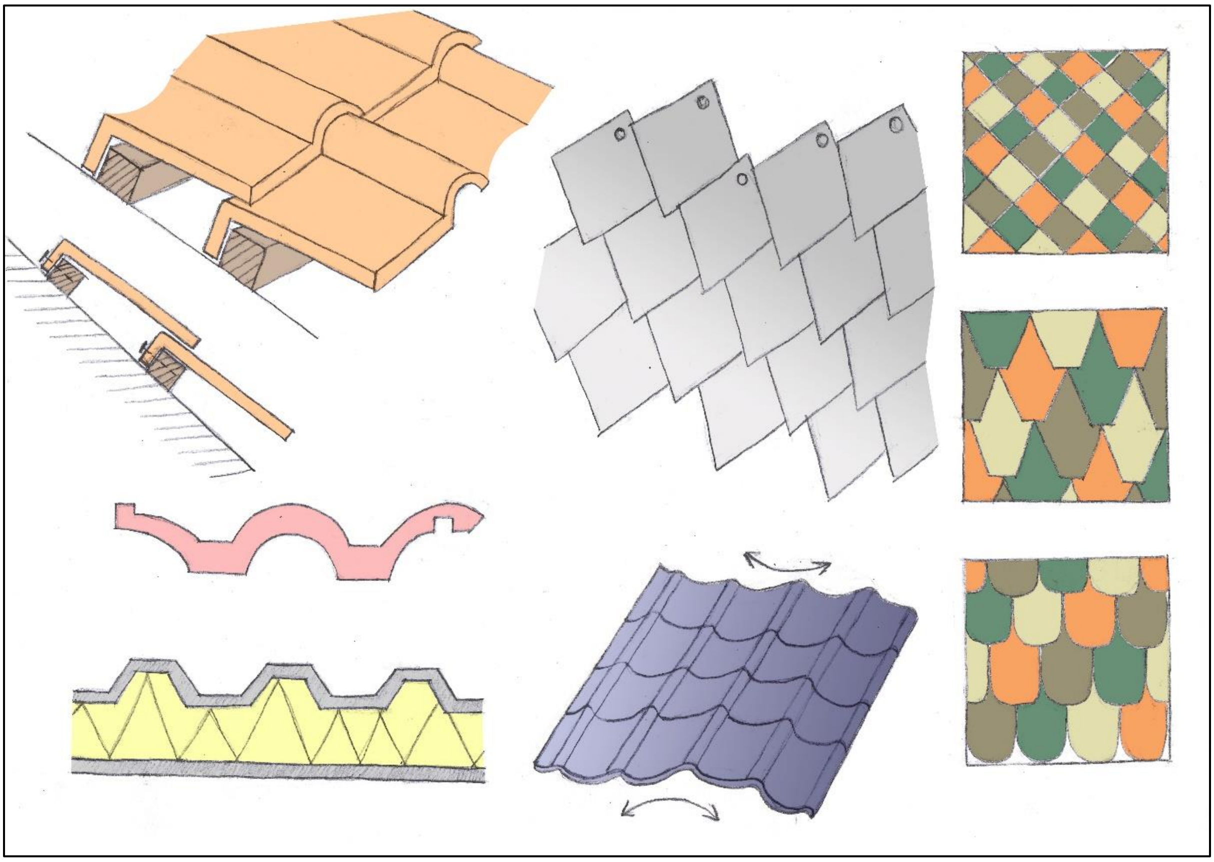


Figure 22b: PET/HDPE roofing applications

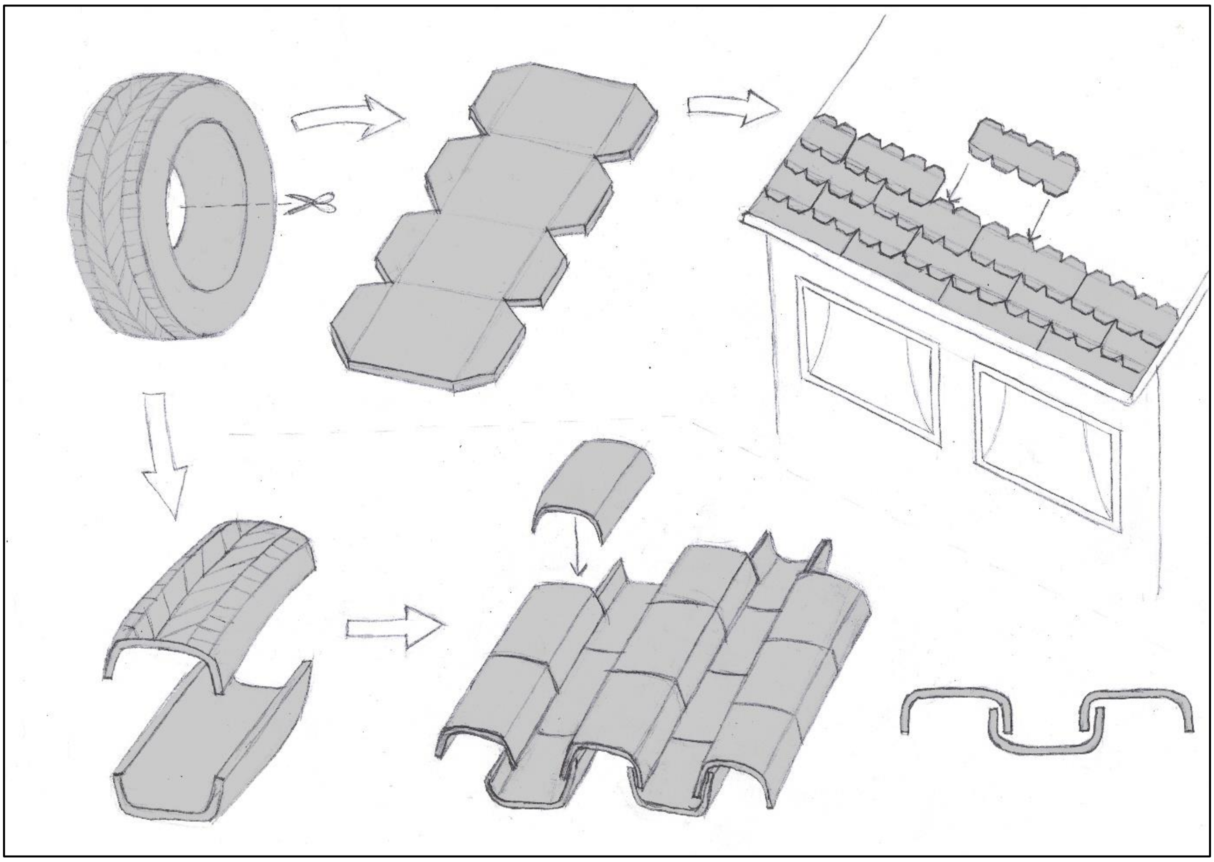


Figure 22c: Rubber roofing applications

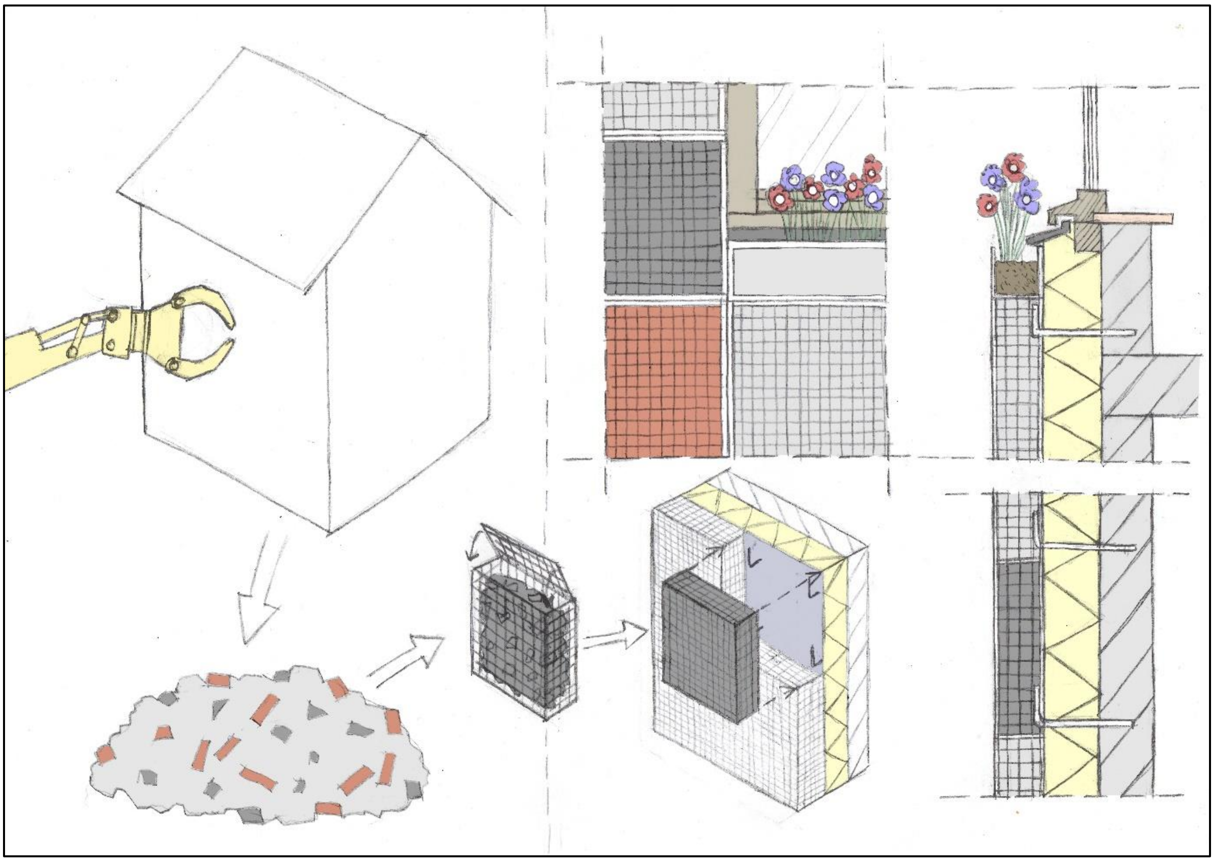


Figure 22d: Demolition rubble cladding applications

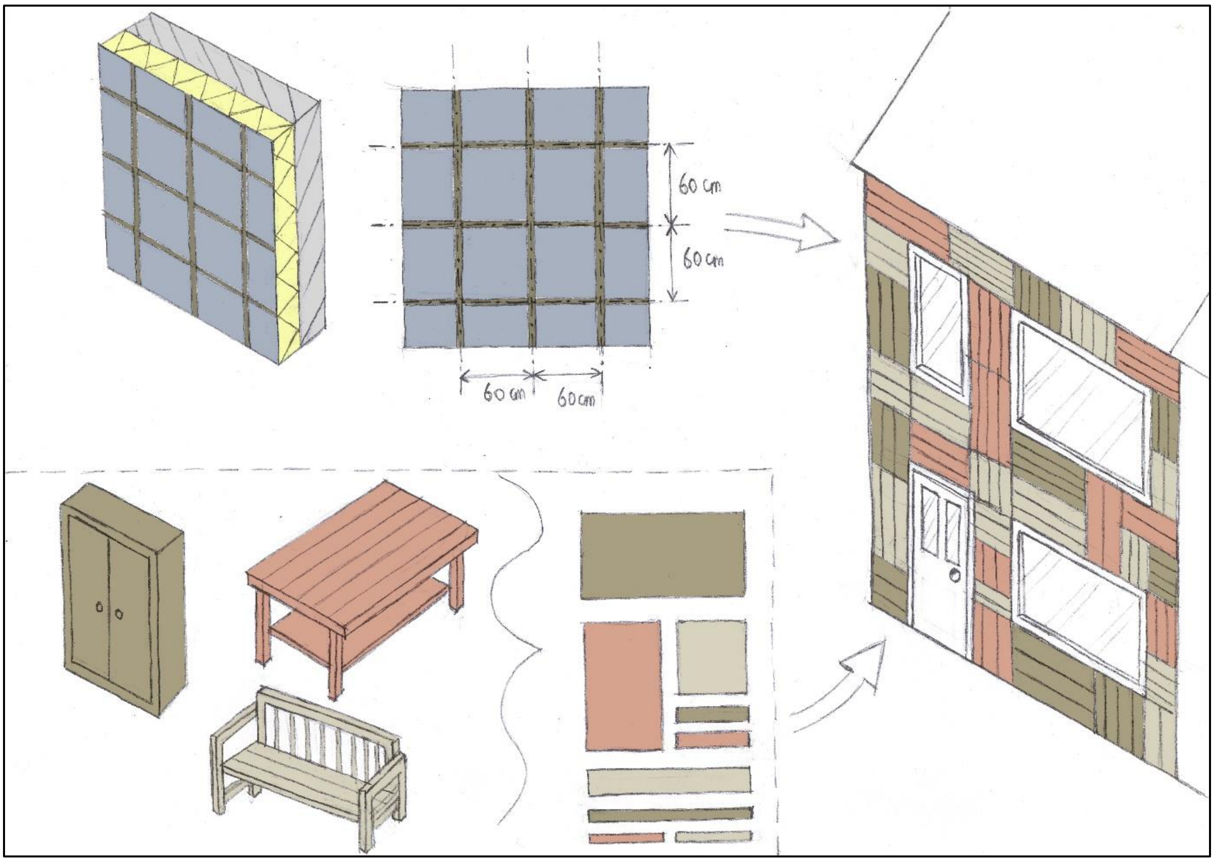


Figure 22e: Wooden cladding applications

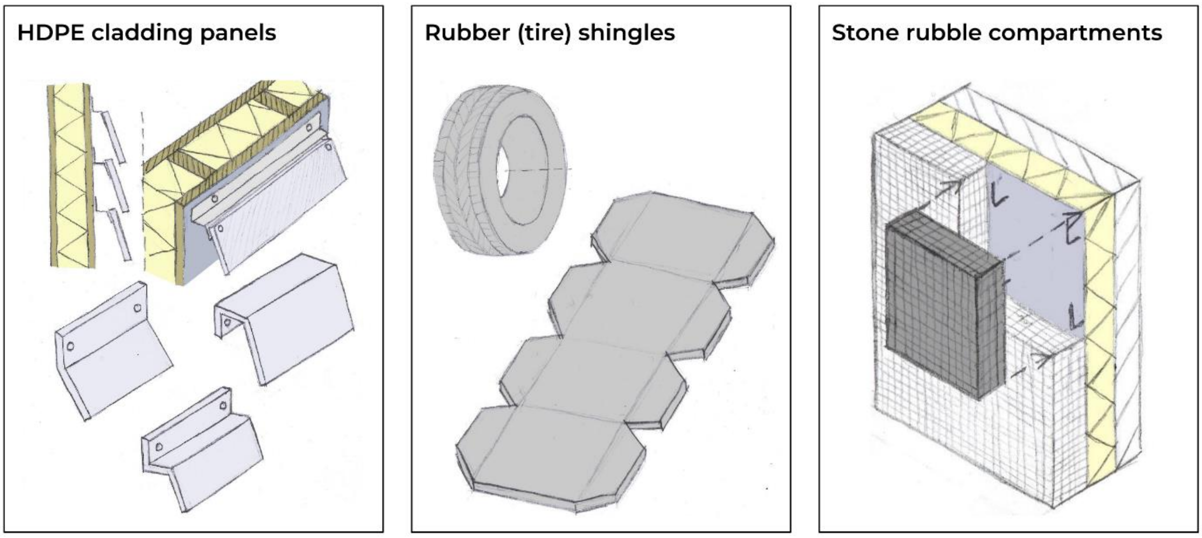


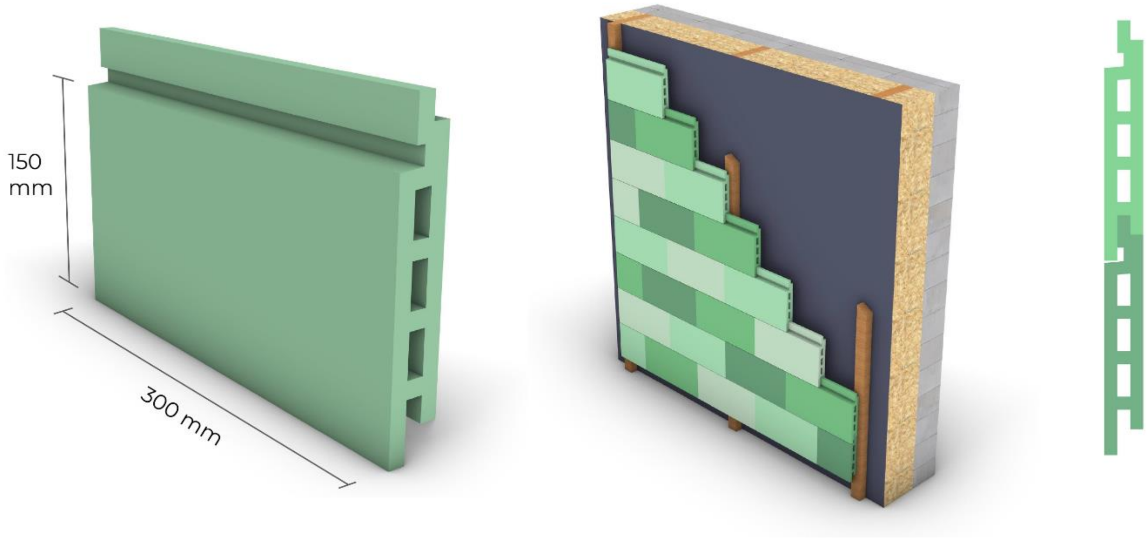
Figure 23: Selected ideas for further product design

The three chosen product ideas can be designed in more detail, to establish the exact dimensions, connections and means of production. The product's mass can then be derived from the resulting volume. It can then also be checked how well the product conforms to the four baseline circularity criteria.

Case study 1 – HDPE cladding panels

Polymers are commonly used for building cladding, usually in the form of planks or panels which either interconnect or overlap. Commonly, uPVC is used for this application, though other (mixes of) polymers are also used. In some cases, these products are fibre-reinforced for increased strength.

HDPE is not commonly used for building envelope applications, except for foils such as water barriers. Outside the Built Environment though, it is used for many applications, such as fluid containers, beer crates and playground equipment. It is a relatively soft plastic compared to uPVC, which is likely why it is uncommon for exposed building uses.

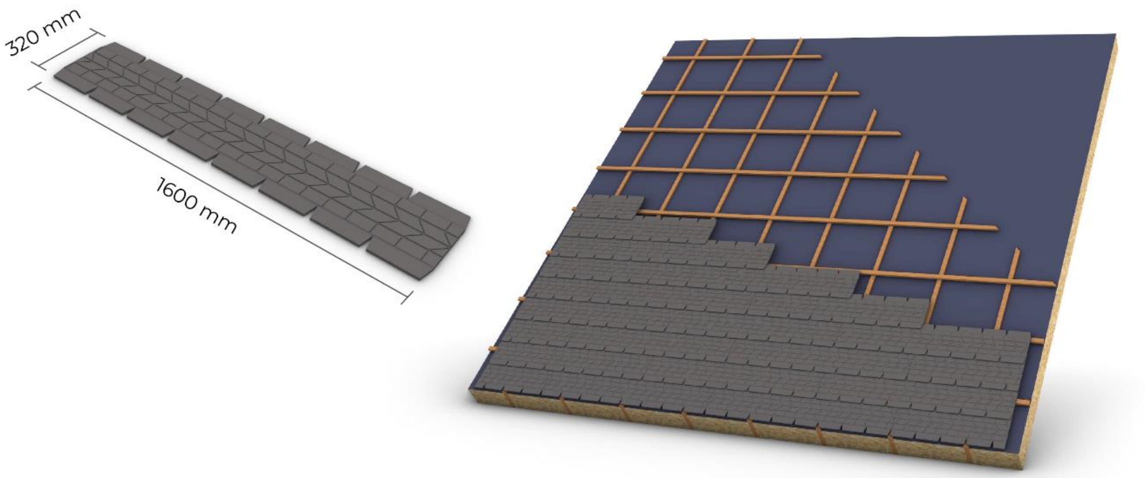


Case study 2 – Rubber (tire) shingles

Rubber tires are made with a certain depth of thread, between 7 – 9.5 mm depending on type and manufacturer (Kwik-fit, n.d.). Over time, this profile is worn away through driving. For summer tires, it is recommended to replace them below 2 mm thread depth, with 4 mm for winter tires. Tires in general may not have a thread depth of less than 1.6 mm. Besides wear from use, it is advised to replace tires every ten years (Michelin, n.d.). As discussed previously, tires are usually recycled after use, though this does not offer high grades given the inherent properties of the material.

This case study explores the possibility of repurposing tires which have either aged or been worn down to a point of being unsuitable for use on a car, yet still holding together well with little surface damage. Whole tires would be cut up in a way to be folded flat into shingles, which can be installed with nails similar to bitumen shingles. Potential difficulty lies in cutting the sidewalls of the tire, as these usually contain steel wire bundles for increased edge rigidity, see figure 24. If cutting the sidewalls is not possible, only the running section could be cut out. The dimensions below are based on common width, height and circumference of 15-16 inch car tires.

Figure 24: tire half section (popularmechanics.com, 2014)

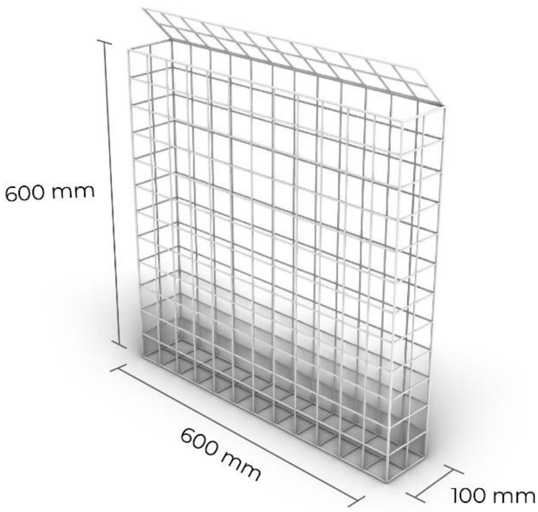


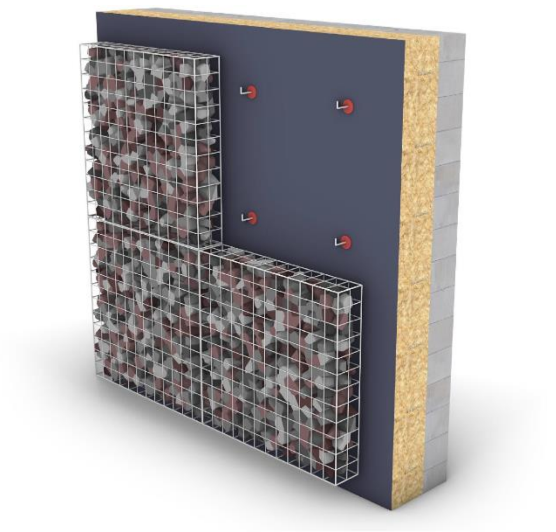
Case study 3 – Demolition rubble compartments

Building waste accounts for 50% of all waste created in the Netherlands annually. A large part of this comes from concrete and bricks, given their prevalence in building construction. Up to 97% of this rubble can be used for other application, primarily infrastructure like roads. This requires breaking the rubble down to small particles however, and asphalt (a common use for the granulate) is not highly circular. There are multiple ways to reduce demolition waste, such as using more demountable connections or demolishing more carefully as to preserve larger elements; such tactics are currently not the norm however.

This case study is inspired by gabions, which can be commonly found on road sides or gardens, see figure 25. In this concept, large rubble pieces can be put into a thin steel cage, which can be opened and closed. The thickness is the same as common brick, meaning weight is comparable to brick and mortar cladding. The compartments are stacked on top of each other and connected laterally to the façade structure by hooks. Making use rubble that is still partially intact opens up more opportunities for end-of-use strategies, as will be shown later in this chapter.

Figure 25: gabion example (bigbagsiergrind.nl, n.d.)





4.3.2 Product feasibility

The second category of the custom measuring method involves gauging a product's feasibility. This is done by comparing a few of its estimates values to those of similar conventional building products, as well as estimating the maximum amount of units that could be produced annually. Table 11 shows which values are gauged. By comparing estimated values for the product with those of similar established products, it can be found what aspects may be troublesome if it were to be used.

Indicator type	Value	Unit
Potential units made annually	Amount of product units	-
	Area	m^2
	Amount of houses	-
Economic value	Raw material market value	€/m^2
Technical-functional value	Lifespan (expected)	years
	Density	kg/m^2
	Stiffness	MPa
	Thermal resistance	m·K/W
	Flammability	-
	Tolerances (per product unit)	mm
	Thermal expansion	m/(m·K)
	Resistance to UV	-
	Resistance to water	-
	Resistance to oxidation	-
Social value	Circumstances around production and transportation	-
	Aesthetic qualities	Colour, texture, feel

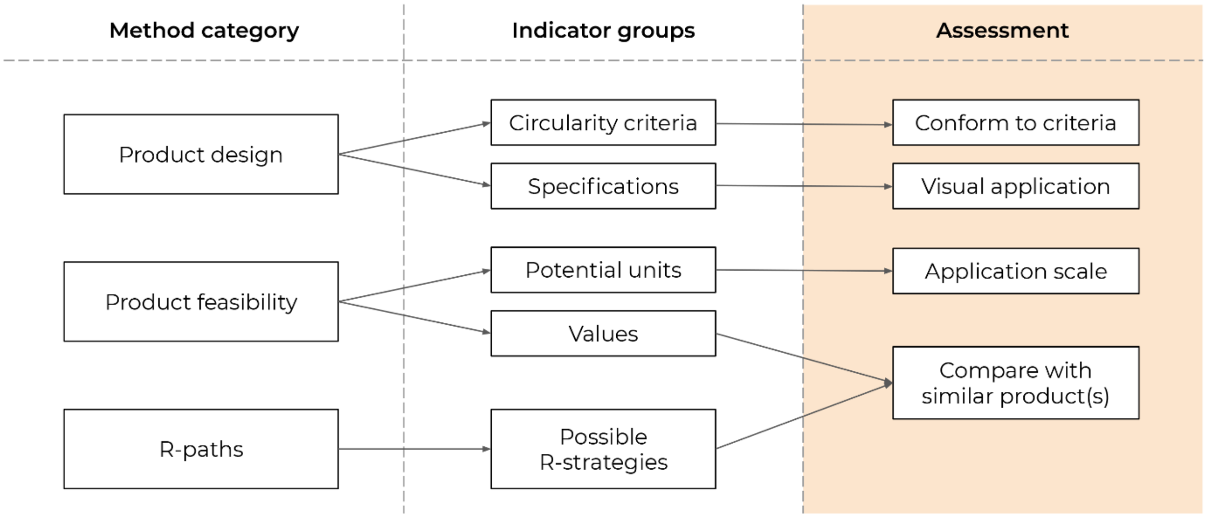
Table 11: Product feasibility indicators

4.3.3 R-paths

The third category of the method is most relevant to the circular aspect of the product's potential. It involves considering all strategies from the R-ladder which may be applied over the entire product system, from raw resource to after the product's initial lifecycle. This way, options can not only be conceived for what to do with the product after its initial end-of-life, but also how to make the former application(s) of the products materials more circular. The result is a list of R-strategies, which can be visualised in a flow diagram, see appendix 10. For assessment, these flow diagrams can be compared to those of the same existing products they were compared to for feasibility measurements, see chapter 4.3.4.

4.3.4 Assessment

To assess all indicators of the custom measuring method, an Excel sheet has been made. As shown, besides the results of the indicators, there are also column with notes on the results, as well as a column highlighting any potential shortcomings of the method for each indicator. The former column is there to highlight any required additional info on the result, as well as uncertainties. The latter column is there to also be able to assess the method itself.



For assessing the product design indicators, only the case study product is looked at. For the other two categories, the product is compared to similar existing building products. After comparing results and adding possible notes in the Excel sheet, conclusions can be drawn on the shortcomings of the case studies and how to potentially solve them, see below.

Case study 1 – HDPE feasibility

Points of attention	Potential solution(s)
High sensitivity to UV	Applying a separate UV foil onto the element.
Low stiffness	Increased thickness. Additional foil can also add structural support. Mixing in fibres would compromise on recyclability.
Colour inconsistency	Quality control

Case study 2 – Rubber (tire) shingle feasibility

Rubber (tire) shingle

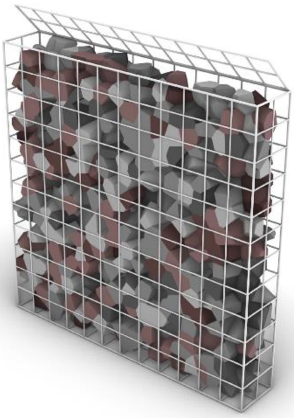
Bitumen shingle (PRECIT)

Ceramic tile (Koramic Madura)

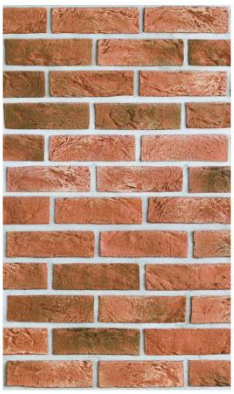
Points of attention	Potential solution(s)
Low breathability	Overlapping shingles may seal each other off; cutting notches or not overlapping them can prevent this.
Toxic flames when ignited	-
Relatively low UV resistance	Periodical check-ups on the condition
May start to leach over time	

Case study 3 – Rubble compartment feasibility

Rubble compartments



Brick and mortar (KnB Keramiek)



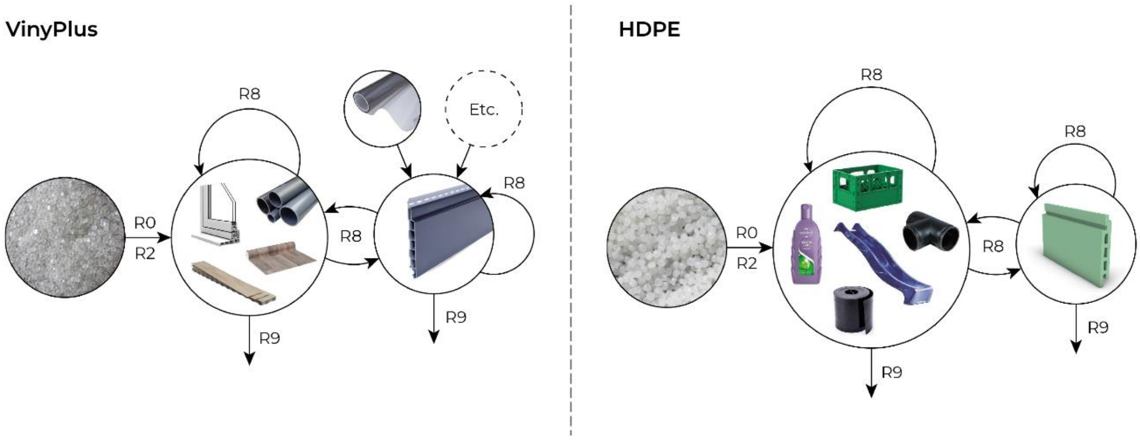
Ceramic panel (Mosa ®)

Points of attention	Potential solution(s)
Difficulty in fitting a full facade due to large size	Proper facade measurements beforehand, to construct custom smaller size cages for edge pieces.
Rubble size inconsistency	Sorting out small rubble before loading the compartments.
Rubble contamination	Inspect rubble on contamination and hazardous materials.

Case study R-paths

The final category to assess are the R-paths, of which the flow diagrams can be found in appendix 10. Given the goal of circular increase compared to conventional products, the idea is also draw out the R-paths for these conventional products and compare them with the case studies. While a higher number of R-paths does not necessarily imply higher circular potential, it does mean more flexibility in optimising the product system. In some cases, a new product may be a way to extent the product system of a conventional product, e.g. rubble compartments as an extra option for old brick use. The comparison for each case study is shown below, with assessment of the result.

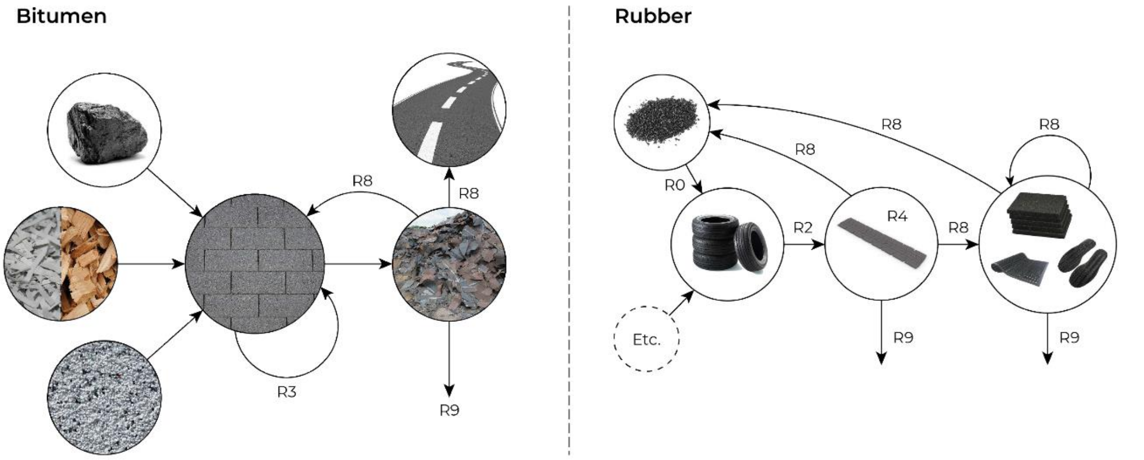
Case study 1 – HDPE cladding panels



The R-HDPE elements are compared to VinyPlus, a commonly used uPVC element. While the exact material mix is not disclosed by the manufacturer, it is claimed to be made from recycled PVC, with the product itself being 100% recyclable even with the added UV layer. In theory, this would lead to similar possible R-paths for both materials in the comparison, despite being made from different polymers from different former applications. This result also gives confidence in the idea of adding foils to the HDPE for protection, while retaining high recyclability.

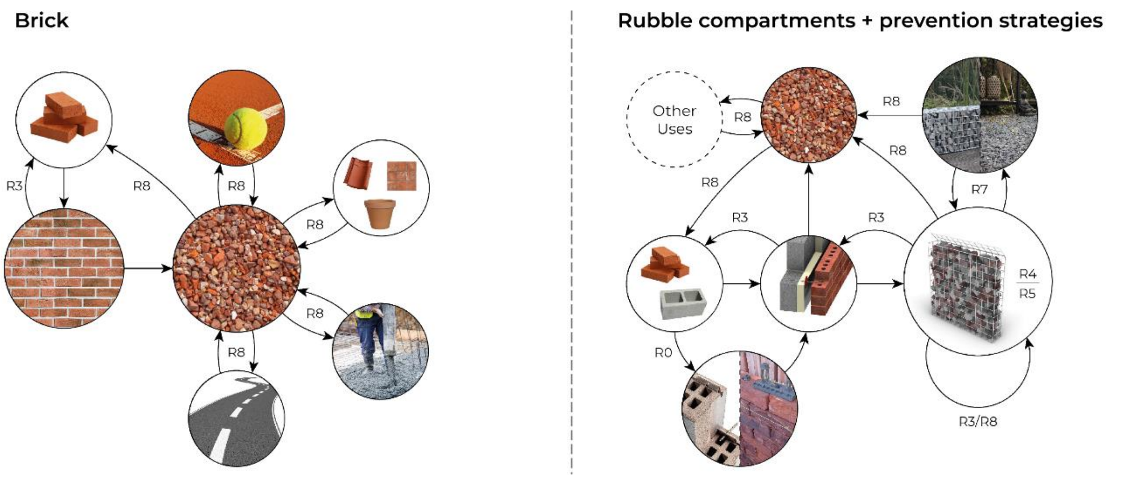
The danger in this comparison lies in a lack of knowledge of the exact compositions of the two products, specifically their additives. Depending on the application certain additives may be mixed in with the polymer to achieve desired properties, for example plasticizers to make it more flexible. Even the pigment used for colouring can influence properties, such as carbon black outperforming most other tints and white being a generally decent choice (Resco Plastics, n.d.). While it is unknown where the recycled PVC for VinyPlus comes from, it certainly won't be sources from any other former application. The same would have to go for selecting former products from which to source recycled HDPE.

Case study 2 – Rubber (tire) shingles



The rubber shingles are compared with bitumen shingles, given their similarity in application. While similar in application, both products are vastly different in their resources and R-paths. The biggest similarity in circularity is the fact that both rubber tires and bitumen are typically downcycled at their end-of-life, albeit for useful applications. Bitumen has the benefit of likely being a better functioning building product, given that it is more stable, durable and fire-safe. Rubber has the benefit of begin usable for a larger number of applications for recycling; with innovations in composition, rubber may get easier to be recycled to a high-grade rather than breaking down with quality loss. As far as repurposing tires for building applications, there are more options besides shingles too; for example, rubber strips could be tried as dry seals for window water tightness.

Case study 3 – Rubble compartments



The rubble compartments are compared with brick and mortar, the most common cladding material for Dutch housing. This comparison is a case where the new product could serve as an expansion of the conventional product’s system, by offering additional end-of-life options. The steel cages are not considered in this comparison, though this is highly durable- and recyclable and can be sourced from many former applications.

5. Future changes in material streams

5.1 Introduction

Chapter 5 covers subquestion 4: How might the market around residual materials change in the near future? Improvements in circularity could be made for practically all of the materials included in the improvement catalogue, both conventional and alternative. The approach to this may differ per material. As discussed in chapter 2.2.2, there are several possible reasons for material streams not being as circular as they could be. Given the increasing push towards a circular economy in the Netherlands and likely internationally in the near future, these barriers may become lifted, or new barriers could come into play. While this project does not cover product design outside the scope of housing envelopes, it does ultimately center around the use of residual materials from former product streams. Therefore, changes along the entire stream of those residual materials impact their potential for later use in buildings.

Chapter 5 both looks at what general changes may occur in the market of secondary materials, and highlights the potential future of the five prominent materials that were selected in chapter 4.2.3. As an example, it may be found that in order to reduce litter issues there will be a push towards the use of biodegradable plastic for bottles in a few years, which also happens to be cheap and sustainable to recycle; this would have the following consequences for the suggested use in buildings:

1. Bottles become inherently more circular, meaning there is less need to apply them in another function.
2. The biodegradability reduces the lifespan in outside conditions, meaning reduced technical-functional value for building envelope purposes.

5.2 General changes

5.2.1 Topics of circular improvement

This paragraph considers changes that are likely to impact all product sectors of the economy, thereby covering the entire final catalogue. Since the basis of this project is built upon the Government Transition agendas, these are consulted for potential circular measures to be implemented. Some measures suggested there may indicate how certain sectors will develop. Table 12 highlights relevant topics of improving circularity which are covered in all five transition agendas - thus likely to impact all resource sectors - as well as specific topics per agenda.

Figure 26: Transition Agendas for five different economic sectors

Transition agenda	Topic of circular improvement (no particular order)
All agendas	Biobased materials
	Extended Producer Responsibility (EPR)
	Product as a service
	Rewarding circular purchasing / taxing non-circular purchasing
	Using the R-ladder
	Internalising external product costs (e.g. emissions, pollution)
	Phasing out non-recyclable products/materials
	Improving recycling quality over quantity
	Standards for quality of secondary resources (i.e. grades)
Plastics	Development of chemical recycling
	Better separation and sorting in waste collection
	Prevention of harmful additives and microplastics
Consumer goods	Working with locally available materials
	Shared economy of products
	Optimising return systems
Built environment	Reuse of components with a long lifespan (e.g. brick)
	Uniformity and standardisation of building elements
	Total Cost of Ownership (TCO) for valuing components
Manufacturing industry	Preventing premature/planned obsolescence of a product
	Standards for compliance and repair/refurbishment
Biomass and food	Cascading of biomass into other materials/products, only use for energy at the end of the cascade.
	Rewarding businesses that invest in preventing CO2 emissions down the product chain/

Table 12: Relevant topics of circular improvement from Transition Agendas

Some of the topics of improvement shown in table 12 have already been integrated into this project, such as the use of the R-ladder, internalising external costs (through shadow prices) and using the TCO-approach for economic value of a product. Regardless, all shown topics would have a definite impact on the way products are manufactured and used. The real question is how likely it is that these measures will be pursued in the near future and what barriers stand in the way; this is discussed in chapter 5.2.2.

5.2.2 Barriers towards effective change

Ideally, implementing the measures from table 12 would work towards ensuring that resources, materials and products retain their value for as long as possible, either over a long lifespan or preserved through multiple cycles. There would be a stronger position of secondary materials on the market. There would be fewer linear resource streams, as businesses would be more incentivised (in some cases mandated) to design, manufacture and treat their product in a circular way. As a result, the problems which this graduation project tackles would be less urgent: resources would be better utilised within the Built Environment, and the amount of linear material streams outside the Built Environment would be smaller. The FEAD (2015) states that “Europe’s economy can only be truly circular if markets are available for the secondary raw materials (SRM) the recycling and reprocessing sector produce.” The SRM market has been a topic of ample research in recent years.

A study by CPB (Netherlands Bureau for Economic Policy Analysis) (2019) provides a list of prominent barriers for secondary materials, that could stand in the way of the measures from table 12 succeeding:

- Lack of pricing policies
- Lack of innovation
- Unexploited economies of scale, i.e. recycling is often done on a smaller scale
- Government policy/failure
- Lack of marketability for reuse of household waste. Products designed to be recycled more easily tend to be more expensive to produce, therefore cost more, yet consumers don’t benefit from the reduced recycling costs after they have used it.
- Markets for secondary materials are supply-driven due to lack of demand, which stems from generally high prices. This in turn leads to insecurity of supply.

Besides individual barriers, a barrier towards any market shift is time. A study by the Ministry of Environment and Food of Denmark (2019) modeled three cases in which a different material (concrete, wood and roof tiles) was analysed for potential to improve its recycling, reuse and creation from secondary resources. While the study found individual market barriers similar to those listed above, it also found that in all modeled scenarios a market transition would take about 15-20 years on average. This is attributed to “the large inertial factors in the system, both in the build-up of processing capacity for handling secondary materials, and not least for the build-up of sufficient market learning and changes in buyer behavior (attitudes)”. These factors would certainly also be present in the Dutch market, as the issues of slow-moving systems and consumer behaviour have been highlighted throughout the Transition Agendas.

5.2.3 Overcoming barriers

To combat the barriers in this chapter, several angles can be taken. An elaborate approach can be found in a study by the Chamber of Commerce of Molise (2018), which lists out its own findings on barriers towards a secondary material market. These barriers are categorised by one of the following types:

1. Regulatory
2. Operational (shortcomings in technology and handling of waste)
3. Economical
4. Awareness

Once again, the barriers found largely share the same underlying issues as those found in chapter 5.2.2. The two most commonly recurring categories throughout the literature on this subject are regulatory (i.e. policy-related) and economical. Most operational- and awareness-related barriers could be solved through policy as well. Because of that, it's worth most to look into ways in which policy and economic systems can stimulate the secondary material market.

For policy, the study by CPB (Netherlands Bureau for Economic Policy Analysis) provides a list meant to resolve their barriers listed in 5.2.2:

- **Pricing policies for environmental damage**
  This would mean enforcing the idea of internalising external costs, for example through shadow prices.
- **Extended producer responsibility (EPR)**
  Being one of the recurring topics in all of the Transition Agendas, this may be an effective tool in ensuring producer innovation. It involves producers designing their products so that they are more environmentally friendly and/or easier to recycle. In theory, this would lead to an increase in quality of secondary materials, although this isn't guaranteed. For example, setting a simple quota on the percentage of products recycled after use does not control the quality of the recycling. Therefore, the incentive needs to be correct.
- **Stimulating innovation**
  This would mean funding development of better mechanical- or chemical recycling, sorting techniques, etc.
- **Deposit-refund system**
  This involves putting a slight premium on the price of certain product types, which the purchaser receives back when they return the product. An example given is plastic products, which are particularly problematic as litter in the environment. This system could also create more homogeneous return flows, as different product groups get collected separately.
- **Regulation**
  There are many ways in which this could be done. Examples include export taxes - or even bans - for waste to countries that dump a large percentage of their waste, limiting or preventing the use of harmful additives in products, or reducing the diversity of materials that are often collected mixed (therefore less efficient to recycle) such as plastics.
- **Information and collection focussed on quality**
  This may involve things like clearer labeling of waste bins for better separation at the source, or launching campaigns which promote the use of products made from recycled materials (eco-labeling).

Besides policy, pricing is perhaps the most important driver of the market, both for producers and consumers. It also appears to be the strongest barrier against the growth of the SRM market. When it comes to pricing of raw materials versus secondary materials, the way in which they are determined differs. As noted in chapter 5.2.2, the SRM market is driven by supply and demand. According to the FEAD (2015) the cost and efficiency of waste collection and processing also have an influence on SRM prices. For virgin materials, pricing often correlates more directly with raw resource prices, which are less volatile. A clear example of this pricing difference is plastics, see figure 27.

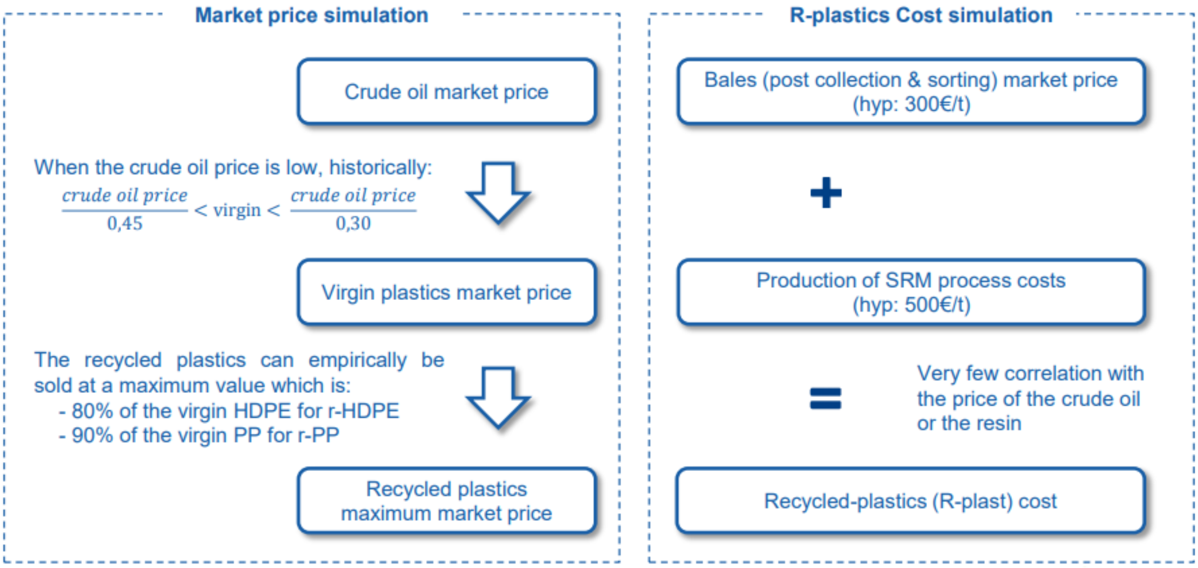


Figure 27: Pricing method for virgin plastics compared to recycled plastics (SUEZ, 2016)

While certain pricing policies, such as internalising external costs from environmental impact, make secondary resource pricing more favorable in theory, this isn't always the case - or even possible. Free trade rules of the European Union forbid the levying of an environmental tax on products imported from abroad (CPB, 2019). The variety of factors going into secondary resource pricing makes it up to five times more volatile than virgin prices (Chamber of Commerce of Molise, 2018); because of that, the article lists several pricing schemes which may give more stability to secondary materials, see table 13. A pricing scheme is defined as "the strategy to define a number of standard prices for a product/service in addition to the default price".

Pricing scheme	**Explanation**
Market pricing	The more conventional approach, where pricing relies on a number of market conditions including supply- and demand, regulations and seasonality. Transport costs are also included.
Tiered/volume pricing	Pricing per unit of material decreases as the ordered quantity increases. This should encourage producers to buy in bulk.
Bundle pricing	Several different types of material together are cheaper than those materials bought separately. This benefits producers who offer a variety of products.
Geographical pricing	Transport costs are taken as the primary factor to determine pricing. This puts more importance on local material sourcing.
Project based pricing	Pricing is set at a flat fee, based on material quantity estimates set by the involved actors. Some flexibility is required here.

Table 13: Pricing schemes for secondary materials

5.3 Material specific changes

This paragraph looks at the potential near future of the five materials that were selected as a prominent option for application in housing envelope elements. Besides speculating on the natural course these materials may take, it will also be considered which of the circular measures from 5.2.1 may be best taken on them, which of the barriers from 5.2.2 stand in the way of those measures, and which methods from 5.2.3 could help lift those barriers. The predicted outcome of a material shows the implications for its use in housing construction, and how necessary this solution would be in the coming years.

5.3.1 PET

The primary reasons why PET is currently less circular than it would like to be is that a large percentage of it is not recycled back into its original purpose - instead used for other purposes or disposed of - as well as virgin plastics currently being cheaper than R-PET (see figure 28).

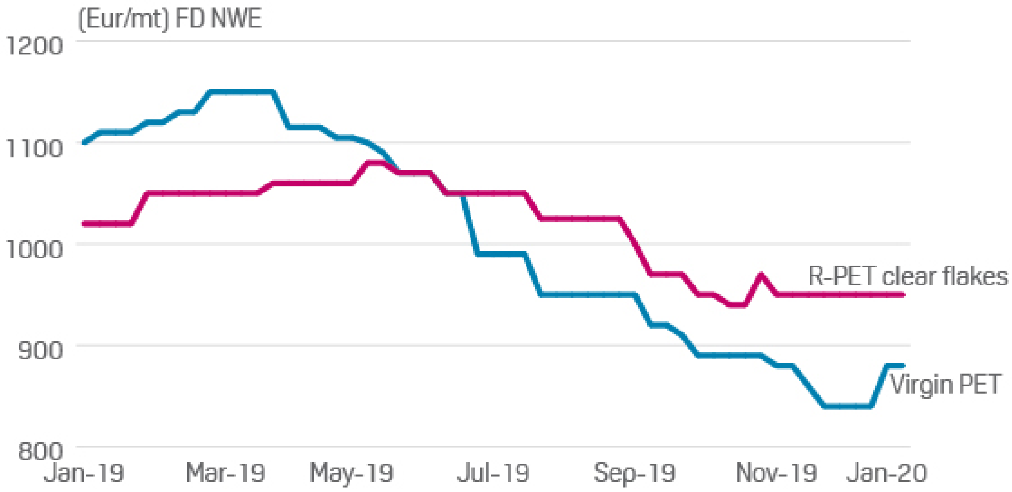


Figure 28: Price of virgin PET compared to R-PET (S&P Global Platts, 2020)

The favourability of R-PET over virgin in the coming decade will depend heavily on shifts in their prices. This balance is hard to predict however. While an increasing number of countries will push towards a circular economy in the near future, it is estimated that global plastic use will actually double by 2030 - compared to 2019 - unless active changes are undertaken (WWF, 2019). While only predictions can be made on the near future of PET, the following assumptions are made based on trends and ambitions towards a circular economy:

1. **Separated collection will increase**, as public awareness increases and incentives are right. For example, from July 1st 2021 people in the Netherlands will receive a deposit when returning small plastic bottles (< 1 litre) where this currently only applies for bottles over 1 litre (Rijksoverheid, 2020).
2. **Technology in sorting and recycling will improve**, as innovation continues to be funded and stricter regulations are put on these actions.
3. **Capacity for recycling will increase,** in order to achieve climate goals set in accordance with both industry parties within the Netherlands - such as those set in the Plastic Pact (Rijksoverheid, 2017) - and the European Union. Besides goals, another stimulus for increasing recycling capacity is the fact that some countries to whom waste was formerly exported may stop accepting it, such as China in 2018; the danger here however is that more will be incinerated here (NOS, 2018).

4. **Use of biobased PET will increase,** given the importance set on biobased materials across all Transition Agendas. While this isn't inherently more circular from a product standpoint - it may for example take more energy or water to produce - it avoids the use of oil for creating primary plastic. As oil should get progressively phased out and global plastic demand continues to grow, the importance of this alternative will rise.

Some of the projected improvements to the circularity of PET bottles are effective quickly, such as the deposit in small bottles. Other developments, such as the increased use of biobased plastics, are longer term goals towards 2030 and will likely happen more progressively. Developing new technologies and implementing them at a national scale is also a process of years. Therefore, it is still seen as a relevant linear stream for use in housing construction between 2020 and 2030; the same goes for HDPE, discussed below.

5.3.2 HDPE

Unlike R-PET, recycled HDPE does not suffer from an unfavourable price relation with virgin, see figure 29. For this plastic, linearity may more often stem from a presumed drop in quality through recycling.

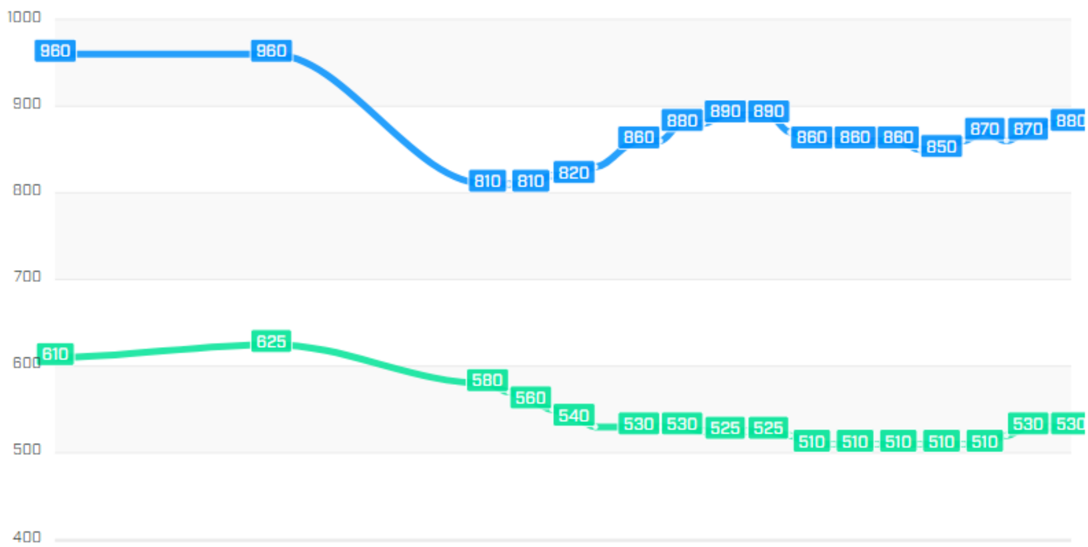


Figure 29: Price of virgin HDPE (blue) compared to recycled HDPE (green) (vraag&aanbod, 2020)

Currently, PE products are too diverse to justify separate collection from other plastics, setting it apart from PET bottles. The following assumptions are made about the near future of HDPE, most of which benefit from the same developments noted for PET, and most other consumer plastics for that matter:

1. Technology in sorting and recycling will improve, see PET.
2. Capacity for recycling will increase, see PET.
3. Use of biobased HDPE will increase, see PET.
4. More standards will be set on the quality of secondary plastics, possibly in the form of grades. Producers and policy makers may look for agreements on which lowest grade is acceptable for certain products, stimulating use of secondary resources.

5.3.3 Rubber tires

When discussing rubber tires, this report mostly considers car tires. These are difficult to make circular, as no R-strategy is ideal. Reuse is limited, as tires are mostly used until they are worn out and not suitable for use on a car anymore. Recycling of wornout tires is difficult due to the way rubber is produced - the process of vulcanisation - which cannot be undone without breaking the molecular bonds; these bonds can then not simply be restored. While mixing in recycled rubber with new rubber is possible, the quality decreases as the recycled content increases. Most recycled rubber applications, such as playground mats, are effectively downcycling.

It is unlikely that road-based transportation will transition to an alternative to rubber in the near future. Meanwhile, car-ownership in the Netherlands is likely to increase; this has been the case between 2015 and 2020 (see figure 30) and will probably continue as the population increases, as well as the average income increasing and car costs decreasing (CPB, 2020).

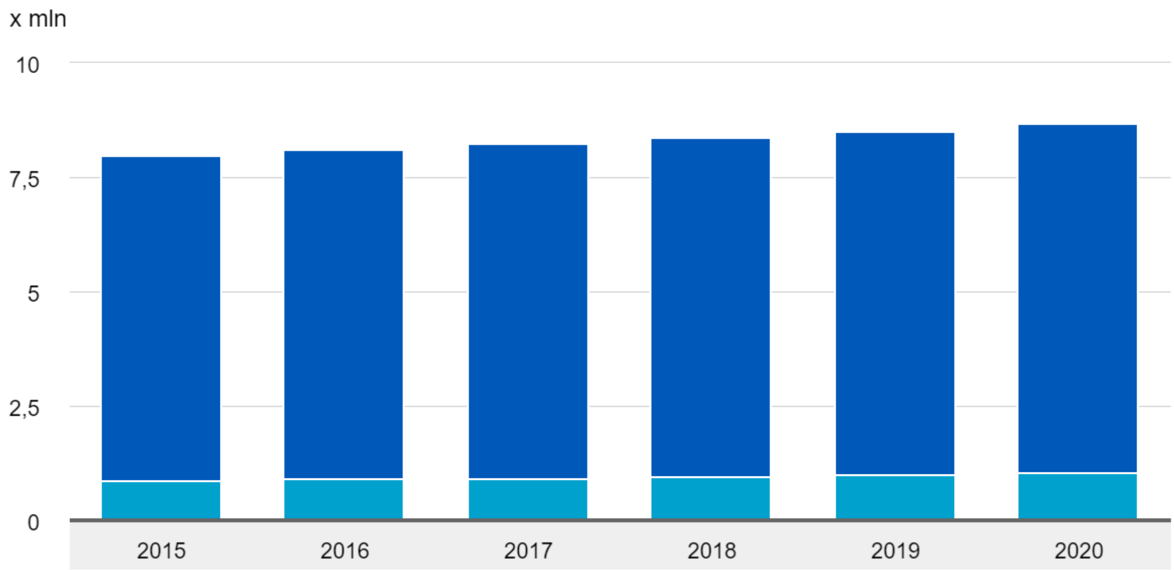


Figure 30: Amount of cars in the Netherlands 2015 - 2020 (CBS, 2020)

Development of more sustainable rubber is an ongoing process. Research is being done on how to make rubber that can be broken down at high temperature without breaking molecular bonds, only the crosslinks between molecular chains. This is not done on a commercial scale yet however, and facilitating such a production process would require manufacturers to change their production line.

Given the circumstances, it is safe to say that rubber will face the same issues for the near future, meaning it is considered a worthy building material by this project. Using rubber for shingles or similar applications allows for the rubber to stay intact (only cutting to size and flattening is required). Unlike for cars, where worn rubber is inefficient and dangerous, wear is less problematic for cladding or roofing, where an element breaking during use is not dangerous to anyone and air-tightness isn't needed. Despite not being a 'pure' product, since tires include other substances besides rubber, the product would not be mixed in with other materials.

5.3.4 Brick masonry

The circular shortcomings of brick (and mortar) are mostly inherent to the material. While it is made to be durable and fairly maintenance free through baking and wet connections, these same processes make it hard to later disassemble and apply R-strategies to it. Disassembling a brick wall can generally only be done through forceful demolition. It is not easy to retrieve whole bricks from this process, nor is it within the best interest of demolition companies to take the extra time and effort for it. Besides, rubble is often put to another use in infrastructure. Given the popularity of brick as a building material though, it is a waste not to use old bricks - even rubble - more towards their full potential. There are a few ways in which brick may become more circular within a short timespan:

1. **Standardising dry connections,** such as ClickBrick and FacadeClick. The problem with methods like these though is lower tolerances, since there is no mortar to compensate for slight size differences and imperfections. Additionally, connectors made of metal will likely not be as durable and possibly need replacement within the lifespan of a building, while plastic connectors aren't as strong without being sizable.
2. **Stricter guidelines on demolition practice,** meaning either more careful demolition or better separation of rubble types. This would be a shorter term solution, as it does not solve the inherent circularity issues of brick with wet connections.
3. **Recycling of rubble,** such as done by StoneCycling. These products have the same potential lifespan as primary brick, meaning high value per recycle. The biggest challenge with this currently is the need for well separated rubble, though regulation may provide better separation during demolition. Another current issue is pricing, which comes out higher than primary brick.

Unlike the previous materials or PET, HDPE and rubber, brick is already a common building material. What will be done to make it more sustainable is hard to predict. As of recent, stone strips are more commonly used to retain the look of brick while saving material. These also do not require as hefty a connection as full size bricks, nor are they directly attached to other strips. One may still wonder how carefully these strips are removed in practice though. This project supports the development and potential standardisation of dry connection to certain specifications, for example brick size range, connector size range, and tolerances. Within these specifications, there is room for competition between producers.

5.3.5 A/B-wood

Unlike the other materials covered in this chapter, wood has a negative carbon footprint to 'produce'. In other words, primary wood production is not too unfavorable compared to secondary wood, especially if the secondary wood needs treatment due to being worn over the years. Therefore, transport distances are relatively more impactful on the total carbon footprint than for the other materials. Also compared to materials like brick, the actual lifespan of wooden elements is relatively closer to the theoretical lifespan, meaning wooden products more often get used to their fullest potential before being replaced and downcycled/incinerated. A-wood has a high inherent potential to be circular, since it can be turned into high grade wood fibres for insulation, then into paper or cellulose which can be recycled many times. This currently happens with about 67% of A-wood, although this percentage is actually expected to drop in favor of incineration due to its high energy production potential (Tauw, 2017). Depending on the treatment, B-wood can't always be used for any high grade application after use, as well as recycling being the more expensive option over mechanical recycling.

Although it is hard to predict how waste wood is treated in the future, a few improvements could be made to the system following ambitions from the Transition Agendas, as well as pushing back on the potential shortcomings of the waste processing industry as covered in chapter 2.2.2:

1. **Increase national recycling capacity,** lowering the cost of recycling and making it more favorable compared to incineration. This transition could go along well with a possible reduction of incineration capacity, which would benefit other material waste streams as well.
2. **Improve sorting and recycling techniques,** as mentioned for some of the other materials as well. This would make wood that is part of a product with less durable materials, like a couch, more likely to be separated in good condition and little to no treatment.
3. **Avoid treatment of wood,** such as painting it. While keeping wooden elements as untreated as possible may lower their lifespan, particularly for species with a poor natural durability class (i.e. most native wood species), they can then at least be turned into a useful product afterwards. Recycling of untreated wood is also generally cheaper and leads to a higher grade secondary material (Tauw, 2017).

6. Advisory framework

6.1 Introduction

The previous chapters involved exploring ways to achieve the project's goals and solve the research questions. The steps taken in this process are now highlighted and compiled into an advisory framework for those seeking to apply residual materials into new building elements, or simply develop new building elements based on circular principles. The pros and cons of the framework will also be highlighted and improvements will be suggested for future research.

6.2 Framework creation

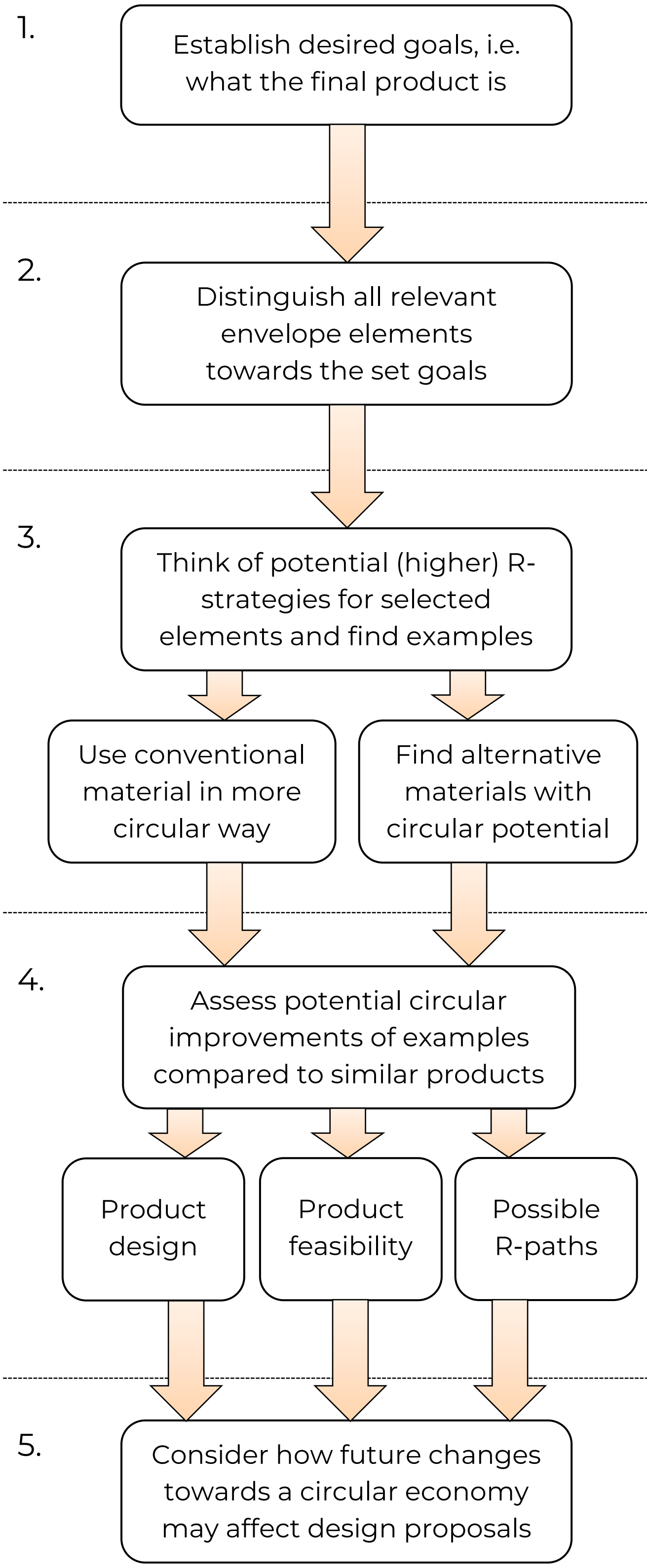
First, an over has been made of all methodological steps taken in this report up until chapter 6, see appendix 11. These steps largely follow the schemed steps from appendix 1. For each step, the decision or result that came from that step is given, as well as what principles guided the result. These principles are usually objective, though some have been influenced by personal preference as to narrow down the research scope. All orange rows in the table involved results strongly influenced by personal reasoning. While this reasoning is deemed justified for the purpose of a more focussed scope, these steps are left out of the framework for the sake of objectivity. The main goal for constructing the framework was for it to be usable in a flexible way. For instance, if a user already knows what element to use a particular material for, some steps may be skipped. The suggested steps are list in table 14.

Advisory framework	
1	Establish the desired goals of answering the research question, i.e. what the final product should be.
2	Distinguish all relevant elements towards the set goals, then: a. Find out which materials are commonly used for each distinguished element. b. Gauge the circularity of each element, for each of its common materials. c. Make a selection of elements and materials with the highest potential for circular improvement.
3	Think of potential (higher) R-strategies for each of the selected elements and materials and find/create examples, towards increasing their circularity either by: a. Utilising the conventional material of an element in a more circular way. b. Finding alternative materials with under-utilised circular potential.
4	Assess the potential circular improvement of the found/created examples compared to their similar conventional elements and materials, through: a. Designing a building product based on the examples. b. Gauging the product's feasibility through comparison with existing products. c. Thinking of all possible R-strategy paths for utilising the product and its materials, across multiple lifecycles, and comparing these to those for conventional building products/materials.
5	Consider how general future changes towards a circular economy may affect the design proposals.

Table 14: Advisory framework steps

6.3 Framework assessment

Lastly, the framework itself is assessed, to find and highlight points of attention for during use. The diagram below shows points of attention for every step.



Points of attention (step 1)

- Goals and criteria can differ from those used in this report, though later measuring indicators for circular potential are based on the goals and criteria of this project.

Points of attention (step 2)

- If one already has certain elements in mind, (parts of) this step may be skipped.
- For a low amount of options, it is recommended to gauge circular potential using R-paths here too.

Points of attention (step 3)

- If one already has certain strategies or examples in mind, this step may be skipped.
- 'Reduce' is considered a default strategy in this report
- This project focusses more on the second direction, specifically use of linear materials. It is recommended to consider this angle as well.

Points of attention (step 4)

- R-strategies by themselves do not always reflect negative side effects (e.g. recycling costing more energy than primary production).
- If the product concept is advanced enough for the product system to be known, LCA can be used to test the effectiveness of the R-paths.
- Comparing R-paths can't be done critically without composition info.
- Some product values may only be found through physical tests.

Points of attention (step 5)

- Economic changes are hard to predict, thus this step is meant for awareness of the larger picture.
- Predicted innovation in technology may support more left-field ideas.

7. Conclusion

7.1 Introduction

This graduation project has attempted to find a solution for the following research question: *How can the circularity of conventional Dutch housing envelope elements be increased, through the application of residual resources from linear streams?* This topic was inspired by the current housing shortage in the Netherlands, with the need for one million new houses between 2020 and 2030. Simultaneously, the Dutch government has also gained increasing ambitions towards a ‘circular economy’ by 2050, with intermediate goals for 2030. It was deemed a worthy effort to attempt to bring these two national ambitions together, in seeing how circular product development can aid in more sustainable mass housing construction.

Given the large scope of the research, objective boundaries were put up early. In this, a focus was decided on the housing envelope, based on personal knowledge and interest on this aspect of buildings. It was also decided to focus on finding resources from linear (i.e. non-circular) material streams, both from inside and outside the Built Environment, for potential use in circular building applications. This was based on the ambitions of the Dutch government for different sectors of the economy to cross over in tackling the circular challenge.

Despite the focus of the main research question on application of resources from linear streams, the final goal of the project was to come up with a more general framework which others can use to develop circular building concepts themselves. The framework is based on the process of approaching the main research question by researching the following topics:

- How to define circularity (applicable to buildings)
- How to measure circularity of building elements in an objective way
- Which elements of conventional housing envelope warrant circular improvement
- What strategies can be used to improve circularity of conventional elements
- What linear residual materials can be found to apply circular building strategies to
- What lessons can be learned from trying to measure circularity of building elements.
- How general changes towards a circular economy may influence product proposals.

7.2 Results

Defining and measuring circular building

From researching the perspective of different parties on circularity, a stance was taken on its most applicable definition, which is centered around R-strategies and value creation as guiding principles for circular improvement. Along with these principles, four baseline circularity were constructed, reflecting important topics from literature:

1. The product should use the minimal amount of materials to achieve its desired functionality and lifespan, thereby preventing excess and maximising on possible units.
2. The product should be installable and demountable as a separate unit, thereby increasing its reusability and adaptiveness.
3. The product should be pure, i.e. made of a single material, unless directly reused from a former application. This reduces risk of contamination and making it easier to recycle.
4. The product should contain no toxic substances, thereby reducing potential harm to humans and the environment.

For finding a suitable method to measure circularity of building products, several commonly used methods were assessed. Most of these make use of certain standardised indicators, such as those used in Life Cycle Analysis (LCA), which lead to quantitative results on material use and environmental impact. None of these methods was considered fully applicable to this project however, as too much knowledge about a product and its material system is needed to accurately make judgements on its circular values. Such methods are more suited for products which are already in full production, as to find ways to improve the sustainability of the established product system. Besides, LCA indicators are revised regularly, indicating that a general consensus on optimal measuring of circularity has not been reached.

Instead, assessing new product ideas for housing envelopes wad done based on their circular *potential*, which is gauged through a custom method of three categories:

1. Product design: specifying and visualizing the product idea.
2. Product feasibility: gauge how well-functioning the product idea could be.
3. R-paths: apply R-strategies over the entire product system.

This method sticks to the core circular principles established from research, while using a combination of quantitative- and qualitative indicators. It was attempted to only include quantitative indicators for which data was fairly readily available, as to avoid excessive assumptions that would significantly skew the results. To test the method, it was needed to create product ideas which may be subjected to it.

Applying circular strategies on conventional housing envelope elements
A collection of conventional housing envelope elements was distinguished, divided up into categories of elements made from the same materials, then gauged by potential for circular improvement, based on its lifespan and common end-of-use strategies. This could be seen as a simplified version of analysing R-paths, which would have been too intensive for the large number of elements. Elements with high potential for improvement were selected for applying circular strategies to. For each selected conventional element, it was considered which R-strategies could be applied to them, higher on the R-ladder than what is common. This was done in two ways:

1. Improve the circularity of the conventional material for the element.
2. Look for a more circular alternative material, from a linear stream

For every conceived improvement, examples of how these could result in a functioning building product were either found by reference or created by sketch design. In the end, a handful of promising ideas was selected, based on relevance towards the projects goals. Additional focus was put on ideas which make use of residual materials from linear streams.

Testing circular potential of product case studies
For the most relevant ideas of the selection, more ideas were created on how to apply the found residual materials. The idea was to create three product case studies, using one of these materials. This resulted in the following three concepts:

1. HDPE cladding panels
2. Rubber (tire) shingles
3. Demolition rubble compartments

The three case studies were subjected to the custom measuring method described previously. By this subjection, points of attention were found for the product and its main material, and possible solutions for these issues were given. By this merit, the method seems adequate for quick testing of the real-life applicability of building product concepts.

R-paths in the form of flow diagrams give a quick overview of the possibilities for applying R-strategies across the entire product system, from base resource to end-of-life options. Comparing them with similar conventional products is challenging though, in cases where the exact composition of a product is not disclosed by the manufacturer. This means lacking information on possible additives or other components that may limit some end-of-life options.

General shifts towards a circular economy

Given the growing ambitions of the Dutch government and many others to achieve a more sustainable economy, general shifts in the economy can be predicted for the coming decade. It was researched what general barriers currently lie in the way of linear streams becoming circular and how these barriers could be lifted. This was done both for general resource streams and five of the most prominent found residual streams in the Netherlands. The result is a fairly elaborate overview on measures to improve circular practice in resource chains, such as pricing schemes, policies and improvements in technology (e.g. sorting, recycling).

Creating an advisory framework

Based on the experience of completing the aforementioned research steps, an advisory framework was created. This framework is intended for those seeking to apply residual materials into new building elements, or simply develop new building elements based on circular principles. It therefore is not limited to only applying residual materials from linear streams, even though this was the focus for the case studies. The framework consists of five main steps, which roughly follow the methodology of the steps described in this conclusion. Lastly, the framework itself has been assessed, to find and highlight points of attention for during use. With the added points of attention, the framework is deemed useful as a first iteration. Of course, improvements can be made, as is discussed in 7.3.

7.3 Future research

Based on the experience of creating and assessing the framework, and all steps leading up to it, some ideas for future research have come up. Besides that, there were some aspects of the project which were unfortunately not able to be fully realized due to lack of time or availability of information. Below, directions for continued or derived research are listed.

- Realising the idea of a visual catalogue of circular improvement ideas, such as through an interactive website. This would also strengthen aesthetic assessment.
- Further development of case studies, to expand measurements through LCA.
- Considering influence from promising developing methods, such as by CB’23.
- Research on how product systems can be made more predictable and transparent, e.g. through the use of material passports.
- More in depth research on predicted changes towards a circular economy. The results could be used to put a stronger emphasis on the use of particular residual streams.
- Trying out the method beyond housing envelopes, e.g. office buildings
- How to optimize on material efficiency in a product, i.e. maximise on its properties

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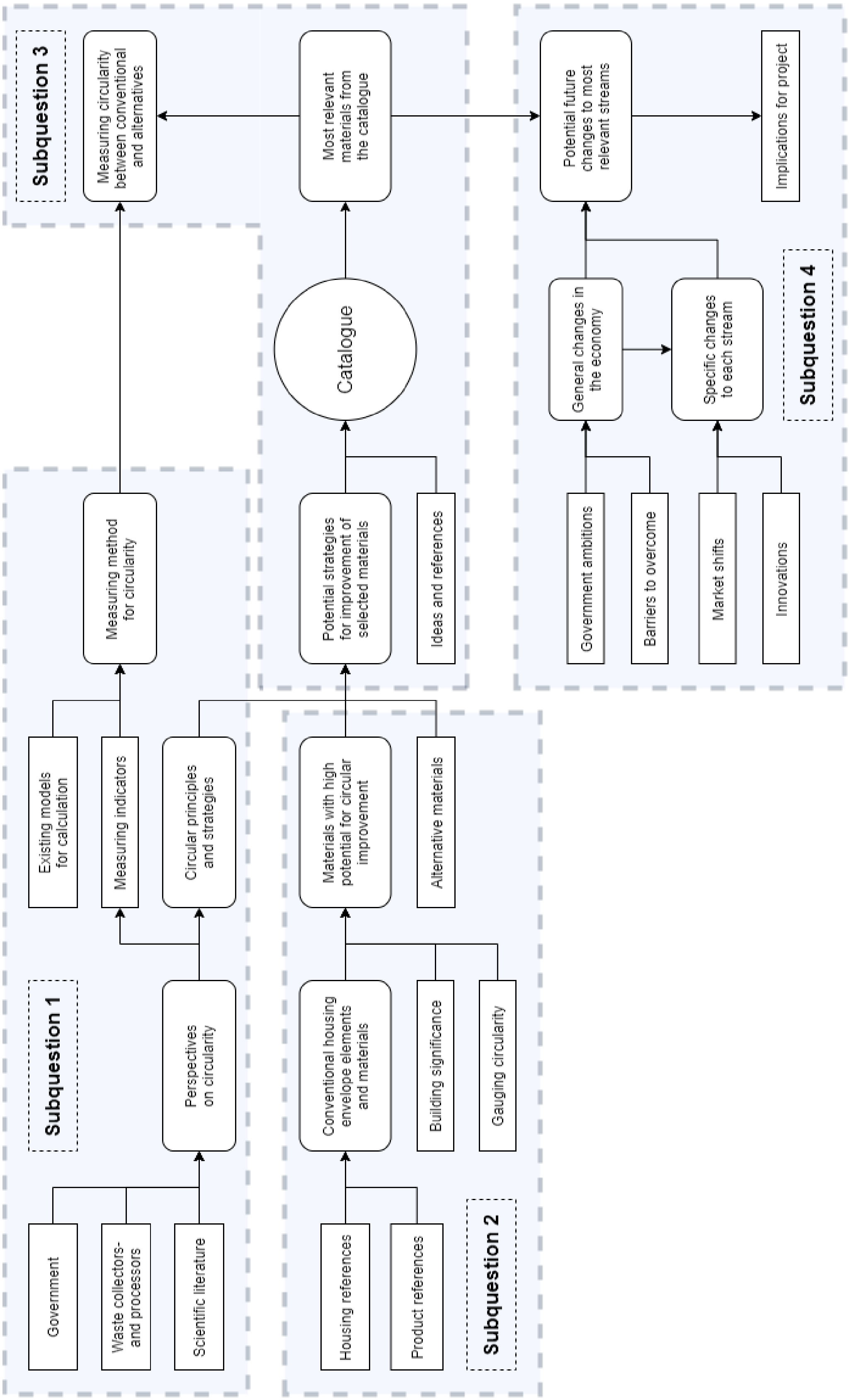
Appendices

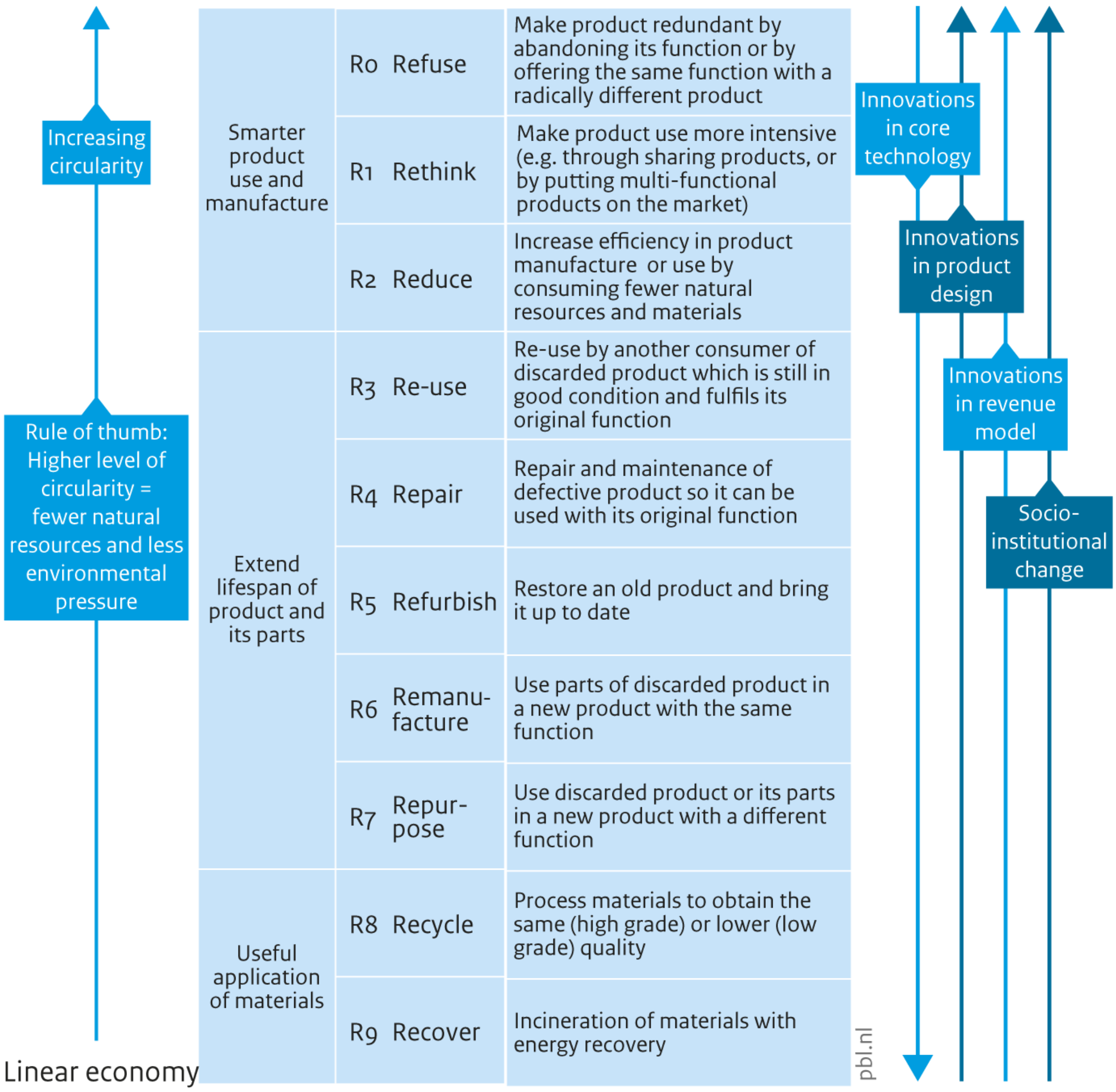
Appendix 1 - Methodology scheme



Appendix 2 – R-ladder

Source: https://www.pbl.nl/en/publications/circular-economy-measuring-innovation-in-product-chains

Circularity strategies within the production chain, in order of priority



Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of materials with energy recovery

Source: RLI 2015; edited by PBL

www.pbl.nl

Appendix 3 - Conventional housing envelope materials

3.1 Conventional elements -and material overview

3.2 General material groups broken down into specific materials

Materials / Applications	Composite	Al. sandwich	Wood-plastic	FRP
Balcony platform				
Chimney				
Curtains				
Door				
Door awning				
Door frame				
Dormer cladding	■	■	■	
Dormer insulation				
Dormer structure				
Facade cladding	■	■	■	
Facade insulation				
Facade interior finish				
Facade structure				
Gutter	■			■
Gutter drain	■			■
Louvers				
Railing	■		■	
Rolling shade				
Rolling shutter				
Roofing	■	■		
Roof insulation				
Roof interior finish	■	■		
Roof structure				
Serre				
Sunshade				
Vapor barrier				
Ventilation grilles				
Waterproof layer				
Window (door)				
Window frame				
Window sill	■			■

Materials / Applications	Natural stone	Limestone	Basalt	Slate
Balcony platform				
Chimney				
Curtains				
Door				
Door awning				
Door frame				
Dormer cladding				
Dormer insulation	■		■	
Dormer structure				
Facade cladding	■			■
Facade insulation	■		■	
Facade interior finish	■			
Facade structure	■	■		
Gutter				
Gutter drain				
Louvers				
Railing				
Rolling shade				
Rolling shutter				
Roofing	■			■
Roof insulation	■		■	
Roof interior finish				
Roof structure				
Serre				
Sunshade				
Vapor barrier				
Ventilation grilles				
Waterproof layer				
Window (door)				
Window frame				
Window sill	■	■		

Materials / Applications	Polymer	PES (also textile)	PVC	PUR	PIR	PC	PE	PS	PMMA
Balcony platform									
Chimney									
Curtains	■	■							
Door	■		■						
Door awning	■	■				■			■
Door frame	■		■						
Dormer cladding	■		■						■
Dormer insulation	■			■	■			■	
Dormer structure	■		■						
Facade cladding	■		■						■
Facade insulation	■			■	■			■	
Facade interior finish	■		■						
Facade structure									
Gutter	■	■	■						
Gutter drain	■	■	■						
Louvers	■		■						
Railing	■	■					■		
Rolling shade	■	■	■						
Rolling shutter	■		■						
Roofing	■		■						
Roof insulation	■			■	■			■	
Roof interior finish	■		■						
Roof structure									
Serre	■		■			■			■
Sunshade	■	■	■						
Vapor barrier	■						■		
Ventilation grilles	■		■						
Waterproof layer	■						■		
Window (door)	■		■			■			
Window frame	■		■						
Window sill	■		■						

Materials / Applications	Textile	Cotton	Acrylic
Balcony platform			
Chimney			
Curtains	■	■	■
Door			
Door awning			
Door frame			
Dormer cladding			
Dormer insulation			
Dormer structure			
Facade cladding			
Facade insulation			
Facade interior finish			
Facade structure			
Gutter			
Gutter drain			
Louvers			
Railing	■	■	■
Rolling shade	■		
Rolling shutter			
Roofing			
Roof insulation			
Roof interior finish			
Roof structure			
Serre			
Sunshade	■		■
Vapor barrier			
Ventilation grilles			
Waterproof layer			
Window (door)			
Window frame			
Window sill			

Appendix 4 – Selection of elements and materials

Blue = selected, orange = not selected

Element group	Material type	Material	Reasoning for (not) selecting
Doors, windows & dormers	Wood		These elements can vary greatly in their construction (profiles, connections, etc.) and use of different materials within the element (e.g. base material, glass, rubber, silicon, insulation). This makes them difficult to cover well, particularly circularity of windows and glass.
	Polymer		
	Aluminium		
Insulation	Polymer	EPS	Potential for value increase (economic and technical-functional) and reduced raw material use through high grade use of secondary polystyrene.
		XPS	
		PUR	Potential for reuse from different former applications, incl. building insulation, furniture and mattresses.
		PIR	Potential for upcycling ground-up PIR into other applications.
	Mineral	Glass wool	Potential for upcycling lower-grade glass wool (which is usually unrecyclable) into other building applications.
		Rockwool	Rockwool has an above average lifespan for insulation and can already be recycled with very little quality loss.
	Natural	Wood fibre	Potential for value increase (economic and technical-functional) and reduced raw material use through reuse of wood fibres from different former applications.
		Cellulose	Potential for value increase (economic and technical-functional) through reuse of cellulose from different applications.
Cladding & roofing	Aluminium		Aluminium has a high expected lifespan and can be recycled to a high grade for many cycles. The biggest sustainability issue with aluminium is in its production, which takes up to ten times more energy than most metals and emits high amounts of CO_2. Demand for secondary aluminium is low, as production and import of raw aluminium is cheaper than recycling it. The most effective solution to this, as of today, may be limiting production capacity of factories, which are mostly in China.

	Bitumen		Bitumen can be recycled fairly well in theory. However, due to a lack of sorting during demolition of buildings, bitumen is often incinerated. Furthermore, one of the most common ways to recycle bitumen is to use it for making asphalt, which may be seen as a form of downcycling. An interesting challenge here would be to look for other materials which can fill their function (both technical and aesthetic) with comparable values and which are more circular.
	Ceramics	Brick	The majority of Dutch houses has ceramic cladding and roof tiles. Neither of these have many end-of-life options besides downcycling however. Besides finding a more circular way of dealing with the ceramic, another interesting challenge with ceramics is to look for other materials which can fill their function with comparable values and which are more circular.
		Clay tiles	
	Composite	Al. sandwich	Besides including aluminium, which by itself is not covered further as mentioned previously, this is a fairly specific product of which the circularity is not well known. Different manufacturers may use different coatings and adhesives.
		Wood-plastic	These products are problematic for circularity from their composition (mixed materials) resulting in high production energy and low recyclability. It is unknown what the exact mix of materials is for these kinds of product, which often is not fully disclosed.
		HPL	
	Copper		In terms of circularity, copper already performs fairly well. It has a long lifespan and can be fully recycled to a high grade. Besides, it is not a widely used material for housing envelopes, due to high costs.
	Natural stone	Slates	These materials face the same circularity issues as ceramics, therefore the challenge could also be the same, i.e. finding other materials which can fill their function (both technical and aesthetic) with comparable values and which are more circular.
		Granite	
		Limestone	

	Polymer	PVC	Potential for value increase (economic and technical-functional) and reduced raw material use through high grade use of secondary polymers.
		FRP	
	Reed		Reed is often replaced before the end of its lifespan due to aesthetical reasons. It is a significant material for this project, as it is widely used for Dutch housing. There may be potential for reusing prematurely removed reed from roofs, which depends less of aesthetics or water tightness.
	Steel		Like aluminium and copper, steel is already fairly circular in its lifespan and recyclability. Since steel is such a widely used material in most manufacturing industries, it is still worth looking at potential for reusing lower grade steel for different applications.
	Wood	Tropical hardwoods	Firstly, there is potential for reusing old wood of a high durability class with aesthetics qualities. Secondly, there is potential to think of ways in which this wood can be used at its end-of-life to create new circular cycles (e.g. turned into fibres or cellulose).
		Cedar, oak, treated pine	
		Impreg. pine	
		Untreat. pine	
		Birch, poplar	
		MDF / HDF	Currently, MDF is difficult to recycle due to adhesives, meaning there won't be a high amount of secondary material available. Like with other bound materials, such as HPL and WPC, improvements may mostly come from different compositions, which is outside the scope of this project.
	Zinc		In terms of circularity, zinc already performs fairly well. It has a long lifespan and can be fully recycled to a high grade. It is also not a highly common material in housing envelopes and costs about 50% more than aluminium or steel.
Curtains & shading	Acrylic		Potential for using old or secondary fabric streams in new building applications, such as sun shading or insulation.

Appendix 5 – Catalogue foundation: circular improvements

https://docs.google.com/spreadsheets/d/1Z2vK6Lnq_Sh8OY-tYAKVTXkh_wnS3uMwITdoyNI97zU/edit?usp=sharing

5.1 Improvements to the original material

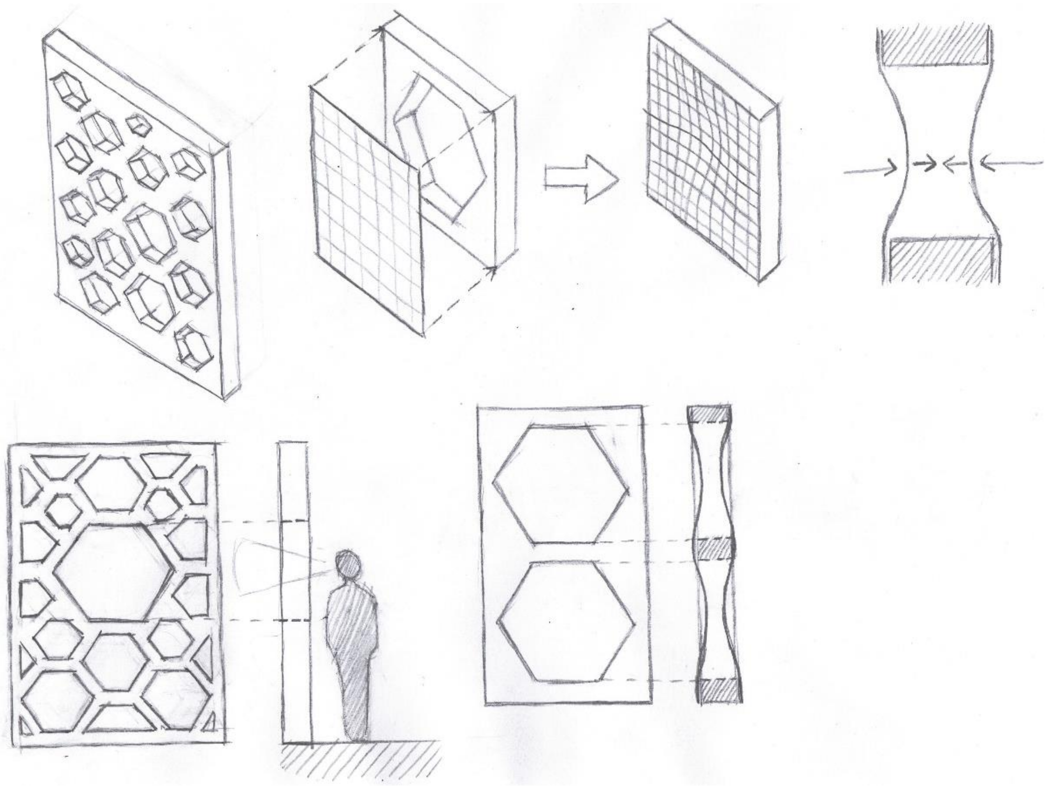
ORIGINAL IMPROVEMENT				
Element (group)	**Materials**	**R-strategy**	**Improvement**	**Benefits from improvement**
Insulation	EPS / XPS	Reuse	Extending the lifespan	The sheets could be removed and reused somewhere else without any damage to the material
		Reuse	Reuse from former applications	Possibilities for sourcing secondary polystyrene from many different industries
		Recycle	Higher grade recycling (Upcycling)	Increasing the technical-functional- and economic value
	PUR	Rethink	Using more ecological compounds	Spray-on PUR uses blowing compounds containing HFCs. Alternatives to this may be possible
		Rethink / Reuse	Using sheets instead of spray	Sheets are easier to remove and do not require blowing compounds (which contain HFCs)
		Reuse	Reuse from former applications	Possibilities for sourcing secondary PUR from multiple different industries
		Recycle	Higher grade recycling	Increasing the technical-functional- and economic value
	PIR	Reuse	Extending the lifespan	The sheets could be removed and reused somewhere else without any damage to the material
		Recycle	Higher grade recycling	Increasing the technical-functional- and economic value
	Glass wool	Reuse / Recycle	Prevent mixing and contamination	While glass wool is already highly recyclable, it is easier to recycle when highly pure
	Wood fibre	Reuse	Use wood from former applications	Possibilities for sourcing secondary wood from many different industries within the country
	Cellulose	Reuse	Reuse from former applications	Possibilities for creating cellulose out of materials from many different industries
		Refurbish	Adding cellulose to wornout sections	More prone to degradation in certain spots, new cellulose can be applied only where needed
Cladding & roofing	Bitumen	Repair	Adding bitumen or sealant for repair	Adding or fixing damaged bitumen only where needed
		Recycle	Making new bitumen from residuals	Separating bitumen during building demolition allows it to be recycled to a fairly high grade
	Brick	Reuse	More adaptive connections	Solving the issue of bricks being difficult to remove from a wall without breaking them
		Reuse / Recycle	Using / making bricks from rubble	Making use of the large amounts of demolition waste
	Ceramics / stone	Reuse	Reuse from former applications	Possibilities for sourcing secondary ceramics or stones from many different industries
		Reuse	More adaptive connections	Solving the issue of some ceramics being difficult to remove from a wall without breaking them
		Repair	Gluing broken tiles (like a vase)	Possibility for reusing broken ceramics in an aesthetic way, akin to gluing together broken vases
		Recycle	Making new bricks from rubble	Making use of the large amounts of demolition waste
	Polymer	Reuse / Repurpose	Reuse from former applications	Possibilities for sourcing secondary polymer from multiple different industries
		Recycle	Use of lower grade recycled polymer	Secondary polymer not usable in its original way may be used in a redesigned application
		Recycle	Higher grade recycling (Upcycling)	Increasing the technical-functional- and economic value
	Reed	Repair / Refurbish	Repairing damaged sections	While reed is prone to wear and damage, it can be easily repaired or refurbished where needed
	Steel	Reuse / Repurpose	Reuse from former applications	Possibilities for sourcing secondary steel from many different industries
	Wood	Reuse	Reuse from former applications	Possibilities for sourcing secondary wood from many different industries
		Repair / Refurbish	Remove individual planks/boards	Possibilities for a high degree of adaptivity with wooden members, through smart connections
Curtains & shading	Acrylic / Polyester	Reuse / Repurpose	Reuse from former applications	Possibilities for sourcing secondary textile from many different industries
		Repair / Refurbish	Fixing tears or raffling / adding new	Damages to the textile may be fixed with relatively little effort, possibly by adding new textile
		Recycle	Higher grade recycling (Upcycling)	Increasing the technical-functional- and economic value

5.2 Improvements through use of alternative materials

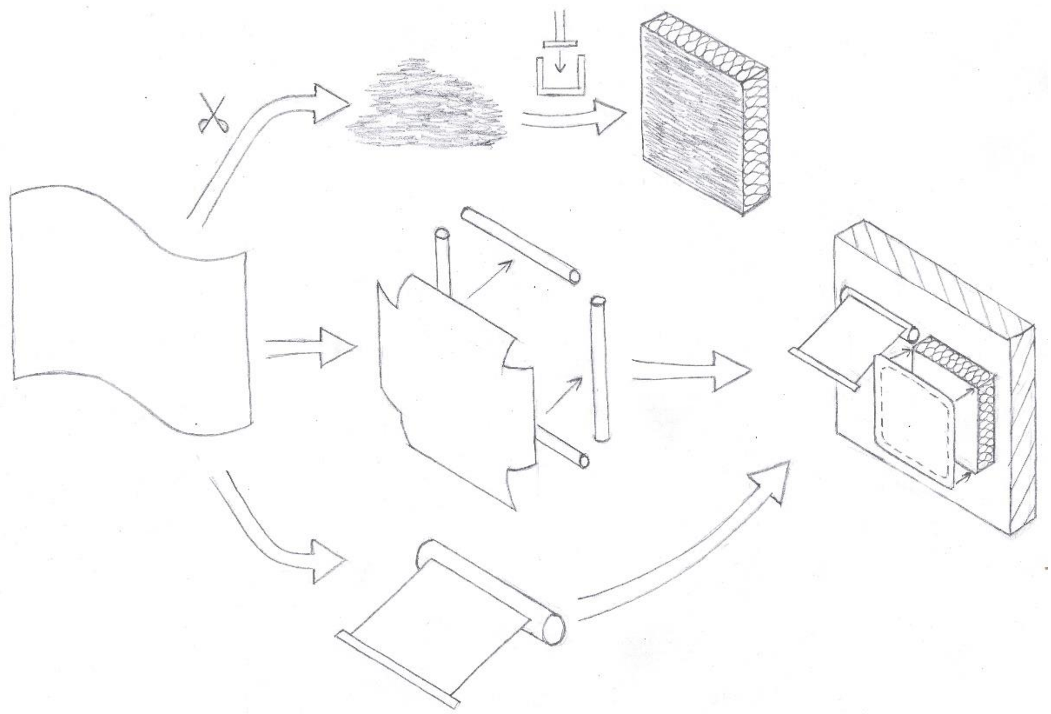
ALTERNATIVE MATERIAL				
Element (group)	**Materials**	**R-strategy**	**Alternative material**	**Benefits from improvement**
Insulation	General	Recycle	Textile (e.g. denim)	Possibilities for reuse inside -and outside the Built Environment
		Repurpose	Matresses	Possibility for using discarded matresses (which are hard to recycle) without much processing
		Recycle	Hemp	Made from a renewable material, which can be sourced from different industries
		Recycle	Flax	Made from a renewable material, which can be sourced from different industries
		Recycle	Typha	Made from a renewable material, which can be sourced from different industries
		Repurpose / Recycle	Straw	Made from a renewable material, which can be sourced from different industries
		Recycle	Coconut fibre	Made from a renewable material
		Recycle	Cork	Possibilities for upcycling of secondary cork, which is rarely reused for its original purpose
		Repurpose	Reed	Possibility for repurposing old reed, formerly used for roofing, into a non-aesthetic application
		Recycle	Paper / cardboard (panels / bales)	Possibilities for upcycling of secondary paper / cardboard, which may be of a lower grade
		Recycle	Polymer (e.g. PE, PET)	Possibilities for upcycling of secondary polymer, which may be of a lower grade
	EPS	Recycle	Bio-EPS	Possibilities for producing EPS in a more circular way
Cladding & roofing	General	Repurpose / Recycle	Cellulose (compressed)	Can be used for both cladding and roofing, with insulating properties too
		Repurpose / Recycle	Aluminium	Possibilities for upcycling of secondary aluminium, with both structural- and insulating properties
		Recycle	Paper / cardboard (pressed / granul.)	Possibilities for upcycling of secondary paper / cardboard, which may be of a lower grade
		Repurpose / Recycle	Rubber (shingles)	Possibilities for upcycling of secondary rubber into a durable product, without much processing
		Reuse / Refurbish / Repurpose	Wood from other former applications	Made from a renewable material, which can be sourced from many different industries and worked into different applications through a variety of R-strategies
		Repurpose / Recycle	Bark (panels)	Made from a renewable material, which can be sourced and applied without much processing
		Reuse / Refurbish / Repurpose / Recycle	Textile	Can be sourced from many different industries and worked into different applications through a variety of R-strategies
		Refurbish / Repurpose / Recycle	Glass	Can be sourced from many different industries and worked into different applications through a variety of R-strategies
		Recycle	Cork (bricks / panels / tiles)	Can function as both cladding and insulation
	Brick	Recycle	Polymer (PE, PET, PVC, 3D-print)	Possibilities for upcycling of secondary polymer, which may be of a lower grade
		Recycle	Glass(wool)	Possibilities for upcycling of secondary glass(wool), which may be of a lower grade
		Recycle	Paper / cardboard (pressed)	Possibilities for upcycling of secondary paper / cardboard, which may be of a lower grade
	Ceramics / stone	Recycle	Polymer (panels / slates / shingles)	Possibilities for upcycling of secondary polymer, which may be of a lower grade
		Recycle	Basalt (Rockpanel)	Made from a highly recyclable material, which also has good insulating properties
Curtains & shading	Acrylic / Polyester	Reuse	Wooden shutters	Old wooden shutter panels can be reused directly onto a new facade, maybe with new paint
		Repurpose / Recycle	Hemp	Made from a renewable material, which can be sourced from different industries

Appendix 6 – Sketch ideas

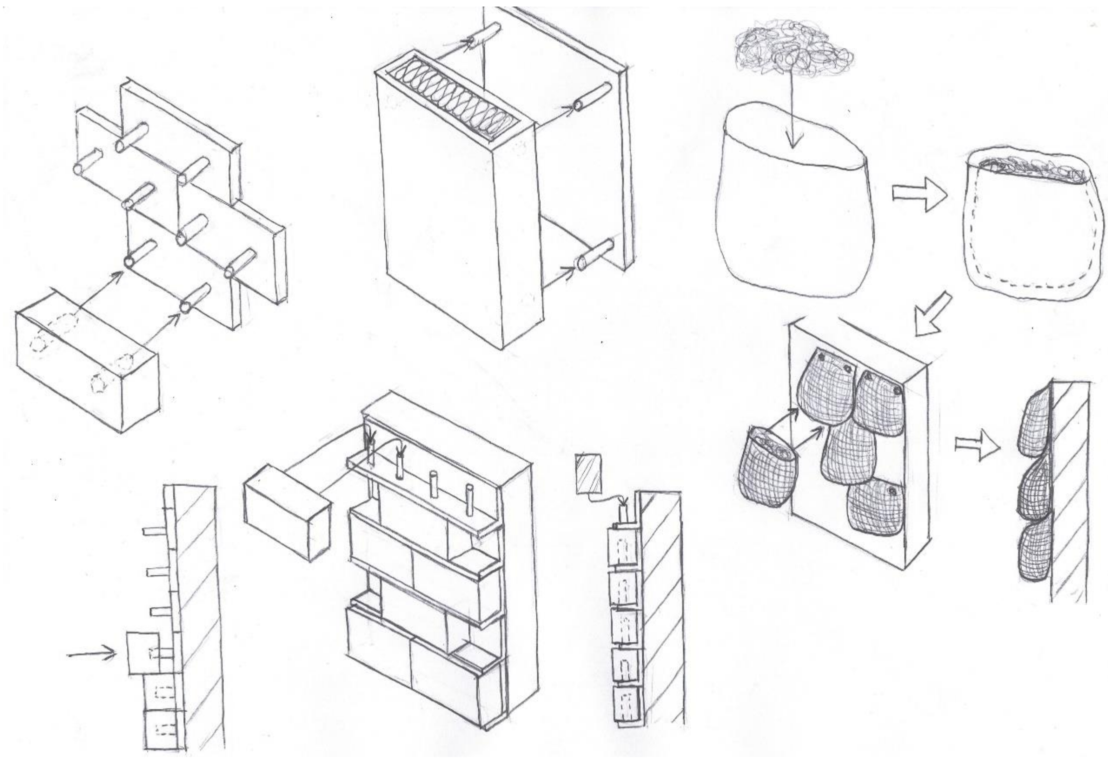
6.1 Vacuum foil insulation panel



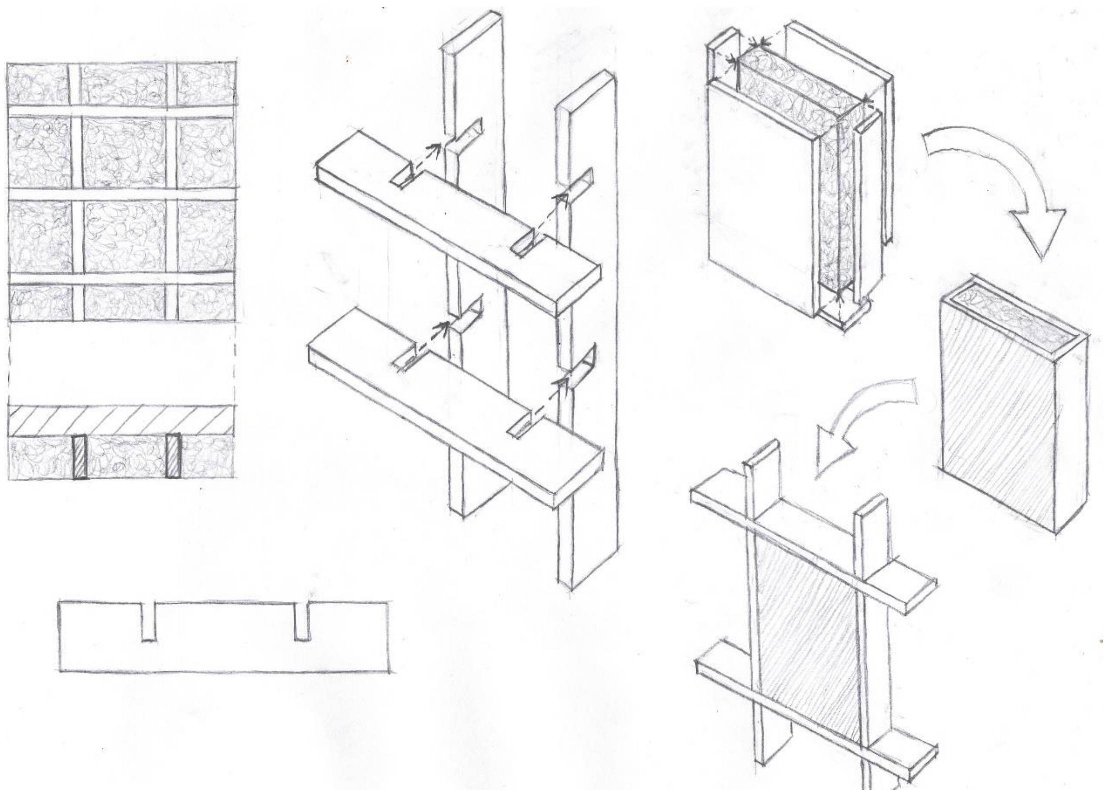
6.2 Textile-based facade



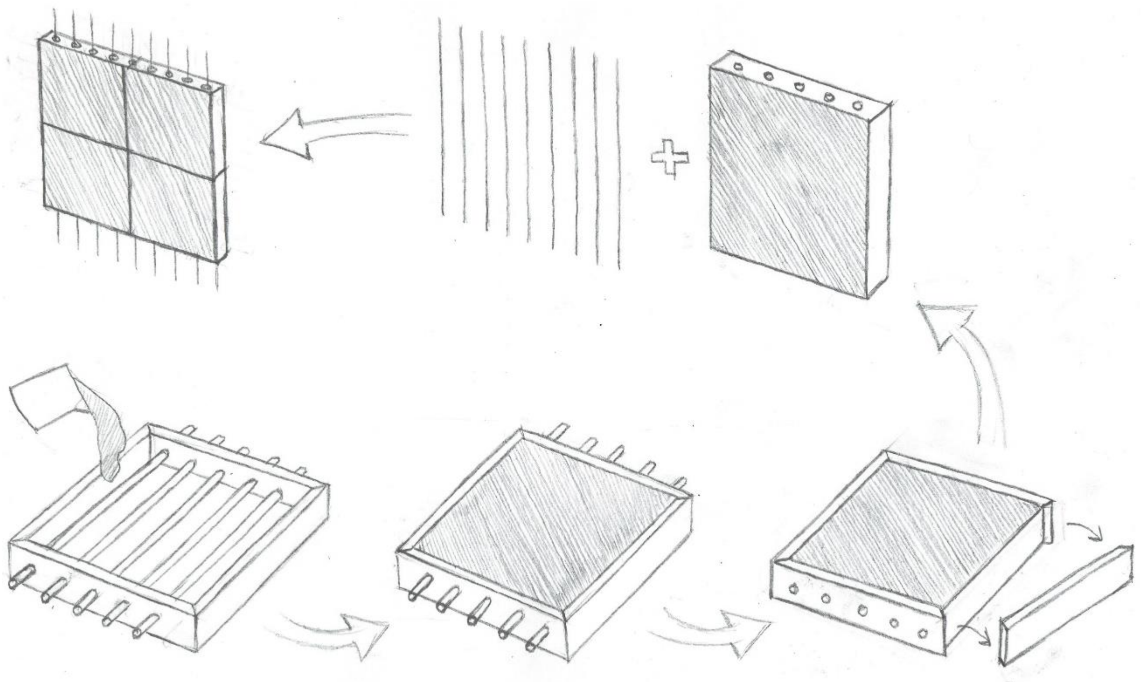
6.3 Removable bricks- or compartments



6.4 Framework-compartment cladding



6.5 Pure casted panel with removable fibre reinforcement



Appendix 7 – Selection of materials for testing

SELECTED	
Secondary material	**Explanation**
Polymer (reused / recycled)	Secondary polymer is both incredibly versatile (could be used for both insulation and cladding) and is one of the most significant problematic materials when it comes to market value.
Rubber (reused / repurposed)	While rubber is a polymer, it does behave differently than most common polymers. Since it is made through vulcanisation, its structure is irreversible without destruction of the molecular bonds. Common 'recycling' techniques for rubber therefore involve grinding it up into granulates, which are either used for new applications (e.g. playground floors, which is really downcycling) or mixed in with new rubber (in limited amounts, as to maintain sufficient quality). Efforts are being made to produce rubber that is designed to be easier to break down; for the near future however, finding ways to reuse rubber as intact and for as long as possible may be a worthy solution.
Brick / Ceramic / Stone (reused / recycled)	Demolition waste holds a huge share in total yearly waste. A large part of this waste is either downcycled or dumped. This is because masonry in particular is not built for disassembly and is therefore demolished down to rubble. Reference projects have however shown potential in reusing ceramic 'waste', as the materials themselves have a long potential lifespan. It would be worth looking for (and designing) ways in which secondary ceramics can not only be reused for new housing cladding but also be used in a way that is easy to disassemble later on.
Wood (reused / repurposed)	While wood is a naturally renewable resource, its end-of-use paths mostly include (effectively) downcycling, such as production of particle boards, wood fibre or paper. Since wood is used in so many applications, there will be cases in which the application (e.g. a piece of furniture) is at its end-of-life while the wooden components still have a long remaining lifespan depending on its durability class. Certain wood types may last over 25 years outdoors untreated (Stichting Probos, 2009) These cases form an opportunity to fully reuse wooden members that are still well-suited for cladding purposes, where also varying degrees of quality and appearance may actually be an aesthetic advantage (e.g. give a rustic look).

NOT SELECTED	
Secondary material	**Explanation**
Paper / cardboard (shredded / pressed)	In many regards, paper and cardboard are already fairly circular, with the majority of it being made from recycled material. It may also not be the most effective material for use in outside applications (sensitive to water and impacts) or insulation (poor thermal values, unless when turned into cellulose)
Bark (Reused)	Besides the fact that bark comes from a renewable (and sustainable) source, bark isn't really a resource that is plentiful in the Netherlands, given that most wood we used comes from other countries, so we would have to import most of the bark for this idea. Building-wise, bark also isn't a common aesthetic here.
Cellulose	By itself, cellulose is already a very circular material, used for many recycled applications. In fact, the same reasons for not using paper or cardboard apply here too, as cellulose forms the basis of those materials. While cellulose is better suited for insulation, there are concerns about its lifespan, fire-safety, and actually its circularity; this is because it's hard to use for facades and slanted roofs without some kind of binder. Not only do binders reduce the purity of the material, the most commonly used type (borate) is a non-renewable mined substance.
Wood fibre	The reasons here are again similar to those for paper, cardboard and cellulose; wood fibre is already fairly sustainable by itself. Another potential issue with large scale use of wood fibre is where it would come from. Currently, it is mostly produced from leftover wood produced in foreign sawmills, then imported here. Sudden mass use of this material may require mass transport from abroad to fulfil demand, which is not ideal.
Mattresses	There are several issues with this product. A mattress can really only be reused for insulation if it's dry and clean; if it's not, things can start to grow inside of it, the mattress degasses and becomes highly flammable, and will smell and rot. If a mattress is dry and clean, it may be better reused as a mattress again. Their large size is also not the most convenient, and exact materials and thickness can vary between mattresses.
Textile (cladding)	There are some interesting projects which use textile for cladding. These canvases often use aramids, which is strong and may be recycled from different former applications. As the canvases are likely polymer coated however, recycling later on may be difficult. There is likely also not a lot of infrastructure for collecting and processing secondary high-strength textile, meaning it is less ideal for large scale use.

Textile (insulation)	Textile, particularly from clothing, forms a large source of potential secondary material, especially if the clothing cannot be reused anymore. Insulation from used textile is already established however, with a variety of large companies already supplying insulation made largely from cotton fibres. It is therefore not the most interesting to dive deeper into for this project.
PUR	PUR is inherently not a very circular material. It is made through an irreversible chemical process. While there are several potential ways to recycle it, this most commonly means adding ground up PUR to a new batch. In a lot of applications, PUR is sprayed, often in a custom shape. This not only means direct reuse is difficult (no convenient rectangular plates), but the PUR will also stick to whatever it is applied on, making it hard to cleanly remove. The most common method of removing PUR from other waste is through 'windshifting', a process during which the blowing gasses are released into the atmosphere. Besides, half of all PUR waste is seen as not suitable for collection and subsequent recycling (in 2004), because of small volumes and/or wide distribution. This half is commonly incinerated for energy recovery. The other half is also not always processed in the most sustainable, since reuse or recycling is in practice not (yet) economically viable. PUR sheets that are already used for insulation are perfectly reusable, though as stated it is harder for PUR from other applications.
Cork	The biggest reason as to why cork is currently linear is that it is not separated, at least not wine corks which go with residual waste (incineration); additionally, wine corks are not commonly made from secondary material. Initiatives to collect cork are growing, with collection points throughout stores in the country continuing to grow. There are three main concerns with using secondary cork for cladding- or insulation panels. Firstly, it requires a lot of energy to make an expanded cork plate, offsetting its benefit compared to primary cork. Secondly, cork is quite expensive compared to more conventional insulators, reducing its marketability. Thirdly, it is unsure whether there really is enough secondary cork to make a substantial amount of building materials, especially as nationwide collection is not yet commonplace; if cork panels were to become more popular, this may actually cause producers to have to import additional primary cork from where it's made.
EPS / XPS	For EPS, the problem actually seems to mostly lie in a lack of separated collection. Currently it mostly ends up with residual waste, meaning a lot of it is incinerated or dumped. Reusing from other applications is possible, although many of them will not be conveniently sized or shaped. Recycling is not the easiest thing either though, as it must be dry, clean and pure to do so. Improvements in EPS circularity therefore lie more in better collection and improved recycling techniques.
XPS	For XPS, there simply aren't many applications outside of building insulation. Its composition is already pure, and its application is simple and

	removable as sheets. Improvements in the circularity of XPS boil down to those for EPS, as well as generally using it for as long as possible.
Steel	Given the focus of this project, steel is not seen as enough of a problematic material to dive deep into when it comes to increasing circularity; this can be most easily argued through a comparison with aluminium. Unlike aluminium, steel is both magnetic, making it easier to separate from rubble, and practically all alloys can be recycled to a comparable or even higher grade for a possible change in application. Also compared to aluminium, steel has a shorter theoretical lifespan as well as being more prone to corrosion, potentially making it perform worse over time - while old steel can be easily reused for a different function, due to being easy to separate, its remaining performance can be inconsistent depending on its former use. Additionally, while the benefit of recycling compared to raw production is lower for steel than aluminium (i.e. it has a strong case for reuse over recycling) the energy reduction is still nearly 50%. Given the ever increasing demand in steel (certainly also in the case of the Dutch housing task) it is still very beneficial to make as much of that demanded steel from recycled steel, as most applications (particularly structural) will have too strict quality specs for direct reuse of older steel elements anyway. One should also not forget that production of steel requires far less energy than aluminium to begin with, so recycling makes steel even more beneficial compared to aluminium.
Aluminium	The main sustainability issue with aluminium is known to be the energy required for production, which can be up to ten times higher than steel. However, unlike steel, recycling of aluminium can reduce energy costs by up to 95% compared to its raw production. The financial costs of recycling are also lower than primary production. When it comes to consumer aluminium, the Netherlands already does very well in separated collection of things like cans, thanks to its waste infrastructure. While reuse of aluminium components from former applications could be a bit more sustainable than simply recycling - after all, aluminium does have a very long potential lifespan with little degradation - it should also be considered that global demand for aluminium is still increasing. Recyclers already struggle to keep up with demand, meaning raw aluminium is still (going to be) produced in large numbers. For example, industries like automotive are using aluminium increasingly, producing lighter cars to conform to stricter fuel economies. Given the high urge of certain sectors to use aluminium, for the foreseeable future it might be best to offer as much secondary (and up) aluminium to these sectors, rather than for applications like building cladding or roofing - for which there are plenty of alternatives.
Acrylic	The circularity issues of acrylic mostly lie in its composition, often using chemical finishes to the fabric to achieve its durable properties. This durable mix of materials also makes it hard to recycle later on. Opportunities for other R-strategies, such as reuse or repurpose, seem limited, as acrylic is

	predominantly used just for sun shading applications. As sun shading, it will often be used until it is either broken or at least close to the end of its lifespan, at which point there aren't many circular options left besides recycling. Improving the circularity of acrylic would thus be best done through improvements in material composition or development in recycling processes.
Polyester	While polyester is one of the most highly produced polymers in the world, it is mostly used in clothing and bottles, both in the form of PET. Some applications, such as of course bottles, are already well separated and recycled many times. Clothing is a bit more problematic when it comes to circularity, as it isn't separated as greatly, is often mixed in with other fabrics like cotton and may get more contaminated during its long term use; all three of these issues mean it often ends up getting incinerated or dumped. Polyester clothing is also known to be a great cause of microplastics, which are released during washing and are small enough to pass through water filtration and into water streams. Since clean used polyester can be recycled back into fibres for remanufacturing however, it could be argued that recycled polyester put to good use in sun shading; after all, the lifespan of a sun shade it typically longer than that of a piece of clothing and it wouldn't have to be cleaned with water that would be put back into water streams. The issue with this application is that it has fairly high quality specifications compared to clothing, as it has to deal with outside conditions. Pure polyester by itself is not durable enough for proper long term use as sun shading, meaning it would have to be recycled fairly quickly again. To combat this lack of durability, manufacturers typically impregnate or coat the fabric with something like PVC; this however means it is then more difficult to recycle at its end of life, a similar problem to acrylic. As with acrylic, the suggestion here is to improve on material compositions (e.g. high purity or more separable coatings) or developments in recycling processes.

Appendix 8 – Calculation sheet based on CB'23 method

8.1 LCA-related indicators

Circularity measurement tool

Indicators for material supplies

Source	Category	Nr.	Indicator	Result	Share (%)	Unit
LCA based	Amount of used material	0	Total material	150,00	100,0%	kg
		1.1	Primary material	94,00	62,7%	kg
		1.2	Secondary material	56,00	37,3%	kg
		1.3	Physically scarce material	0,16	0,1%	kg
		1.4	Socio-economically scarce resources	0,00	0,0%	kg
		1.5	Socio-economically non-scarce resources	0,00	0,0%	kg
	Amount of available material for the next cycle	2.1	Material for reuse	35,00	23,3%	kg
		2.2	Material for recycling	40,00	26,7%	kg
	Amount of lost material	3.1	Material for energy recovery	55,00	36,7%	kg
		3.2	Material for dumping	20,00	13,3%	kg

Indicators for environmental impact

Source	Category	Nr.	Indicator	Result	Unit	Shadow price (€/kg)	Shadow price result
LCA	Impact on environment	4.1	Depletion of abiotic resources	0,00	kg Sb-eq	€ 0,16	€ 0,00
		4.2	Depletion of fossil energy carriers	2,55E+03	kg Sb-eq (or MJ)	€ 0,16	€ 408,00
		4.3	Climate change	1,00E+02	kg CO2-eq	€ 0,05	€ 5,00
		4.4	Ozone layer depletion	0,01	kg CFC11-eq	€ 30,00	€ 0,15
		4.5	Photochemical oxidant formation	0,07	kg C2H4-eq	€ 2,00	€ 0,14
		4.6	Acidification	0,16	kg SO2-eq	€ 4,00	€ 0,64
		4.7	Eutrophication	0,02	kg PO4-eq	€ 9,00	€ 0,16
		4.8	Human-toxicological effects	1,00	kg 1.4 DB-eq	€ 0,09	€ 0,09
		4.9	Ecotoxicological effects (freshwater)	18,00	kg 1.4 DB-eq	€ 0,03	€ 0,54
		4.10	Ecotoxicological effects (marine)	6,00	kg 1.4 DB-eq	€ 0,0001	€ 0,00
		4.11	Ecotoxicological effects (terrestrial)	9,00	kg 1.4 DB-eq	€ 0,06	€ 0,54
						TOTAL	€ 414,09

8.2 Value indicators

Indicators for value

Source	Category	Nr.	Indicator	Initial value	Next cycle	Lost value	Unit
CB'23	Amount of economic value	5.1	Total Cost of Ownership (TCO)	1000	750	250	€
Self-made	Amount of technical-functional value	6.1	Lifespan	50	40	10	years
		6.2	Standard dimensions	All	All	-	-
			Standard connections	Pins	Pins	-	-
		6.3	Adaptivity	-	-	-	-
		6.4	Purity	100	90	10	%
		6.5	Toxic materials	0	0	0	%
		6.6	Density	22,7	22,7	0	kg/m3
		6.7	Stiffness	7000	6000	1000	kPa
		6.8	Heat conductivity	0,035	0,037	0,002	W/mK
		6.9	Flammability	Flammable	Flammable	-	-
		6.10	Tolerances	2	3	1	mm
		6.11	Thermal expansion	6E-05	6E-05	0	strain/°C
		6.12	Resistance to UV	High	High	-	-
		6.13	Resistance to water	Very high	High	-	-
		6.14	Resistance to oxidation	High	Average	-	-
	Amount of social value	7.1	Circumstances around production and transportation	None	-	-	-
		7.2	Adaptivity	-	-	-	-
		7.3	Aesthetic qualities	Red, matte, smooth	Red, matte, smooth	-	-

Appendix 9 – Case study circular potential measurements

9.1 HDPE cladding panels

PRODUCT DESIGN

Category	Indicator	Unit	Result	Notes on result	Shortcomings of method
Baseline circularity criteria	Minimal amount of materials		☑	Sizing based on reference building products made from HDPE	Structural design based on optimisation is outside the project scope
	Installable and demountable as a separate unit		☑	Only dry connections are used	-
	Pure materials, unless reused		☑	Made from 100% recycled HDPE	Pure material may perform worse than a mix of materials
	No toxic substances		☑	No additives to the material are needed	-
Product specification	Material		HDPE	Can be sourced from a variety of applications (e.g. fluid containers)	-
	Production process(es)		Injection moulding, extrusion	Injection moulding is common for HDPE. Given the uniform profile, extrusion is also possible.	-
	Dimensions (L x W x H)	mm	300 x 30 x 185	The distance between the bottom edges of two units is 150 mm	Dimensions based on similar products, not structural design
	Mass per unit	kg	1.05	Assuming 0.95 kg/m3 density	-
	Connections		Screws, interlocking profiles	The units interlock over each other in a way that covers the screws	-

PRODUCT FEASIBILITY

Category	Indicator	Unit	Result	Result	Result	Notes on result	Shortcomings of method
Compared materials	Material		HDPE	Keralit	VinyPlus	Keralit is a widely used brand cladding panel; it is based on polyolefin, reinforced with glass fibre and coated with Renolit. VinyPlus is primarily made of PVC, with a UV-resistant foil.	Manufacturers of commercial products won't fully disclose the exact composition of their product, which is often a mix of polymers, perhaps fibre reinforced, with additional topcoats or foils.
	Source of material specifications		CES EduPack	Keralit ®	VinyPlus ®		
Potential units made anually	Amount of units		100 million	N/A	N/A	Based on 12,3% of all annual plastic waste (ca. 200 kton) being HDPE, of which 50% is incinerated and thus deemed available here [1]. While this is an excessive estimate, it does show the potential for cladding a substantial amount of houses (between around 20 to 40 m2).	The results are indications based on rough estimates and assumptions of availability.
	Area	m2	4.5 million				
	Amount of houses		100,000-200,000				
Economic value	Raw material market value per m2	€/m2	14	N/A	N/A	Based on current market pricing for recycled HDPE (€ 0.60/kg). While the value of the product is too difficult to estimate, the price of primary HDPE lies close to that of PVC, as primarily used by VinyPlus.	Determining the value of a non-existing product is beyond the scope of this project and relies on many unknown factors regardless. Thus, raw prices of the primary product materials are compared.
Technical-functional value	Lifespan (expected)	years	5 - 10*	30	30	Based on UV rating and references of playground equipment for HDPE. UV radiation is the biggest reason for deterioration of exposed HDPE. By comparison, underground HDPE pipes may last 50 years, and waterproof foils for facades may last 100 years. Adding even a marginal amount of UV stabilisers and adding specific colorants (e.g. white or carbon black) can increase lifespan closer to 20 years.	Most plastic deteriorate to UV, which is why both reference products made use of protective films/coatings. Given the very short lifespan of bare HDPE, adding a film may be justified.
	Density (over area)	kg/m2	23.3	7.7	7.9	Mass per m2 is more relevant in this comparison than cubic mass	-
	Stiffness	MPa	1080	1850	2000	HDPE is a relatively soft plastic compared to the two other products.	-
	Thermal resistance	mK/W	-	-	-	The cladding is assumed to provide very little thermal resistance	-
	Flammability	-	Highly flammable	Highly flammable	Highly flammable	Different ratings for flammability may be used by different manufacturers.	-
	Tolerances (per unit)	mm	< 1	< 20	N/A	Tolerances of Keralit are high due to long sections, which are cut to size regardless. The same applies for extruded HDPE.	-
	Thermal expansion	m/(m.K)	0.000152	0.000026	0.00006	All three materials have a relatively low thermal expansion coefficient.	-
	Resistance to UV	-	Fair	Excellent	Excellent	On of the main ways of degradation of most polymers is through UV exposure, with HDPE being no exception. Keralit achieves its resistance through an applied UV foil.	Most plastic deteriorate to UV, which is why both reference products made use of protective films/coatings. Given the very short lifespan of bare HDPE, adding a film may be justified.
	Resistance to water	-	Excellent	Excellent	Excellent	Neither polymer takes up moisture or degrades quickly by water	-
	Resistance to oxidation	-	Unacceptable	Excellent	Excellent	HDPE is naturally sensitive. The others are resistant by added layers.	As with UV, an added film may help to protect from oxidation

PRODUCT FEASIBILITY

Category	Indicator	Result	Result	Result	Notes on result	Shortcomings of method
Social value	Circumstances around production and transportation	Unlikely	Unlikely	Unlikely	The primary polymers are made from oil, thus circumstances depend on where the oil is sourced. Since all three of these products are made from recycled polymer, no negative social circumstances are assumed there.	It is impossible to gauge all social impacts of materials that are gathered and produced globally.
	Aesthetic qualities	Large variety in colour, soft to the touch, smooth texture	Large variety in colour, fairly stiff, wood-like texture	Large variety in colour, fairly stiff, wood-like texture	Based on reference imagery and products.	-

R - PATHS

R-strategies		Applications
R0	Refuse	Increase the use of non-primary HDPE in primary applications
R1	Rethink	
R2	Reduce	Optimise the product's structure for minimal material use
		Improve the lifespan of the product through UV stabilisers or smart color choices (white, carbon black)
R3	Reuse	
R4	Repair	
R5	Refurbish	
R6	Remanufacture	
R7	Repurpose	
R8	Recycle	High grade recycling back into itself
		Resources for other HDPE products - Fluid containers - Crates - Foils - Pipes - Playground equipment
R9	Recover	Incineration with energy recovery

9.2 Rubber (tire) shingles

PRODUCT DESIGN

Category	Indicator		Result	Notes on result	Shortcomings of method
Baseline circularity criteria	Minimal amount of materials		☑	The shingles are made from car tires that are worn down beyond limits	The product may be bulkier than needed for its application, although nothing needs te be added either.
	Installable and demountable as a separate unit		☑	Only dry connections are used	-
	Pure materials, unless reused		☑	The product is made from a reused product, made from mixed materials	-
	No toxic substances		☑	Tires are generally considered safe in terms of toxicity for handling, although toxic smoke is released when they burn.	It is debatable if the toxic substances contained in tires are a large-scale threat in building use, as reuse means no incineration.
Product specification	Material		Car tire (rubber, polymer, steel, nylon, filler)	While rubber shingles exist, few seem to make use of direct tire reuse	-
	Production process(es)		Cutting, flattening	A whole tire is cut in a way where is can be easily flattened out.	-
	Dimensions (L x W x H)	mm	1600 x 320 x 12	Based on average of common tires (195/205 mm width, 15/16 inch dia.)	Tire sizes can vary quite heaviliy, as can the amount of wear. Large mismatches of sizes and weights together should be avoided.
	Mass per unit	kg	2.5 - 10	The mass depends heavily on how worn down the profile depth is.	
	Connections		Nails	The tire shingles are meant to function the same way as normal shingles	-

PRODUCT FEASIBILITY

Category	Indicator		Result	Result	Result	Notes on result	Shortcomings of method
Compared materials	Material		Car tire	Bitumen shingle	Ceramic tile	Bitumen shingles are the closest conventional comparison for the tire shingles. Ceramic roof tiles are also looked at, being the most common type of roofing in the Netherlands.	It is difficult to translate some of the performance specifications of tires to roofing, as expected factors like lifespan and resistance to degradation differ in applicability.
	Source of material specifications		MICHELIN	PRECIT	Koramic Madura		
Potential units made anually	Amount of units		10 - 40 million	N/A	N/A	Based on 110,000 tires being discarded annually, of which a minimal 20% is reused and thus 80% is deemed available [1]. While this is an excessive estimate, it does show the potential for roofing of a substantial amount of houses (between around 50 to 75 m2).	The results are indications based on rough estimates and assumptions of availability.
	Area	m2	4 - 16 million				
	Amount of houses		50,000-300,000				
Economic value	Raw material market value per m2	€/m2	-	N/A	N/A	In theory, used car tires can have negative values, as garages and dealers have to pay collectors to pick them up. Since there is no apparant market for reused tires, no value is known.	Determining the value of a non-existing product is beyond the scope of this project and relies on many unknown factors regardless. Thus, raw prices of the primary product materials are compared.
Technical-functional value	Lifespan (expected)	years	10+	20 - 25	50	The lifespan for tire shingles is based on recommendations by Michelin, to replace tires on a car after 10 yeass regardless of having been used. This is likely due to safety concerns for use on a car, which are not an issue when simply laying on a roof, therefore lifespan is expected higher.	Estimating the actual lifespan is impossible to do, as this also depends on the state of the collected discarded tires, causing large variations. A quality check would seem necessary for each tire used.
	Density (over area)	kg/m2	6 - 24	9.4	42.6	Mass per m2 is more relevant in this comparison than cubic mass	Tire sizes can vary quite heaviliy, as can the amount of wear. Large mismatches of sizes and weights together should be avoided.
	Stiffness	MPa	N/A	N/A	N/A	Stiffness is not a concern, as shingles are flat and fully supported	-
	Thermal resistance	mK/W	-	-	-	The cladding is assumed to provide very little thermal resistance	-
	Flammability	-	Highly flammable	Self-extinguishing	Non-flammable	While tires only ignite at temperatures exceeding 400°C, they do burn very quickly when ignited and may produce harmful substances. By comparison, bitumen is made to spread as llittle as possible, and ceramic doesn't combust at all.	Fire safety is one of the biggest concerns in using this product, as tire fires are hard to put out and produce toxic smoke.
	Tolerances (per unit)	mm	-	N/A	N/A	Tolerances are not very relevant, as the shingles overlap and can be cut to size. Regardless, tires are assumed to have tight tolerances.	-
	Thermal expansion	m/(m.K)	N/A	N/A	N/A	Thermal expansion is likely small for tires, given their regular application, nor would it be a concern for overlapping shingles.	-
	Resistance to UV	-	Fair	Excellent	Excellent	UV radiation is one of the most siginificant factors of tire degradation.	Degradation is a much greater concern for tires on a car, thus it is hard to determine the severity for building applications.
	Resistance to water	-	Excellent	Excellent	Excellent	All three products perform well against water.	-
	Resistance to oxidation	-	Excellent	Excellent	Excellent	While oxidation can lead to degradation of tires, the associated safety risks are not so relevant in its use as roofing material.	-

PRODUCT FEASIBILITY

Category	Indicator	Result	Result	Result	Notes on result	Shortcomings of method
Social value	Circumstances around production and transportation	Potential exposure to fumes	Potential exposure to fumes	Unlikely	In the production of both rubber and bitumen, workers may be exposed to harmful fumes. While regulations are set for concentrations, these should be ensured. During installment, both materials are safe to handle.	It is impossible to gauge all social impacts of materials that are gathered and produced globally.
	Aesthetic qualities	Black, smooth, slight profile	Variety in colour, rough texture	Variety in colour (mostly red or black), fairly smooth texture	Based on reference imagery and products.	-

R - PATHS

R-strategies		Applications
R0	Refuse	Use new techniques and compositions for making rubber that is designed to be recycled without breaking molecular bonds.
R1	Rethink	
R2	Reduce	Only use tires which are worn beyond potential reuse on a car
R3	Reuse	
R4	Repair	Glue / fill small cracks in the rubber
R5	Refurbish	
R6	Remanufacture	
R7	Repurpose	
R8	Recycle	Conventional applications for recycled rubber: - Surfaces for playgrounds or sport - Shoe soles - Floor mats
		Mix in part of the old rubber granulate with primary rubber
R9	Recover	Incineration with energy recovery

9.3 Rubble compartments

PRODUCT DESIGN

Category	Indicator		Result	Notes on result	Shortcomings of method
Baseline circularity criteria	Minimal amount of materials		☑	Thin steel wireframe cages are used to contain the rubble	-
	Installable and demountable as a separate unit		☑	The compartments are designed to open and close for easy (un)loading of the contents and are laterally fixed by hooks. The compartments are stacked on top of each other, meaning the facade does not carry vertical loads. Connecting the compartments with wire ties is recommended.	-
	Pure materials, unless reused		☑	Different types of rubble can either be mixed or kept seperate per compartment, to create different color patterns.	It should be ensured that the rubble is separated well and is not dirty or contaminated.
	No toxic substances		☑	As long as separation of materials is done carefully during demolition	
Product specification	Material		Steel, building demolition rubble	Steel can be recycled for many cycles.	-
	Production process(es)		Steel: wire drawing, bending, welding Rubble: breaking down to size	The wires form a mesh of 47x47 mm squares. The rubble therefore should be large enough to not fit through a square and fall out.	-
	Dimensions (L x W x H)	mm	600 x 100 x 600	Width and height based on common spacing of facade support elements, thickness the same as common brick thickness.	Unlike the other two case study examples (or even common materials like brick), this product cannot be cut to size on site as easily, thus careful measurement of the facade is needed beforehand to gather dimensions for edge pieces.
	Mass per unit	kg	Steel: 2.24 Rubble: 62.28 (concrete), 46.71 (brick)	Weights for concrete and brick are based on 75% volume coverage of a compartment. The total weight could easily be carried by two persons.	-
	Connections		Gravity, hooks, wire ties	The compartments rest on top of each other, being held in place by hooks screwed into the facade structure and wire ties.	The hooks may sometimes be difficult to insert, if the contents of the compartment get in the way.

PRODUCT FEASIBILITY

Category	Indicator		Result	Result	Result	Notes on result	Shortcomings of method
Compared materials	Material		Steel, rubble	Brick and mortar	Ceramic panel	Given that the compartments may be filled with brick rubble and how common brick is, this is an obvious first comparison. Since the compartments also act as panels, ceramic panels are compared too.	-
	Source of material specifications		CES EduPack	Knb Keramiek	Mosa ®		
Potential units made anually	Amount of units		N/A	N/A	N/A	Estimating the possible annual units produced is hard to do, mostly due to the availability of steel. There are many types and compositions and the vast majority is recycled, possibly making secondary steel scarce. Building waste in theory has ample availability, given that 50% of all Dutch waste is building-related, however it is uncertain how much of that is reserved for infrastructure use.	Unlike the other two case studies (HDPE and rubber), steel and rubble are two streams without a clear share of 'waste' streams, e.g. being incinerated. Steel is one of the most recycled products in the world and most rubble is utilised for infrastructure purposes; there may be a risk of 'taking away' these streams from other applications if this product were to be produced.
	Area	m2					
	Amount of houses						
Economic value	Raw material market value per m2	€/m2	5.6 (steel) N/A (rubble)	N/A	N/A	Rubble does not have a market value, in fact may be considered to have negative value since one has to pay to have it picked up. This means it would likely be very cheap to gather the material. Steel is relatively expensive in comparison, though very little is used per compartment.	Determining the value of a non-existing product is beyond the scope of this project and relies on many unknown factors regardless. Comparing raw resource prices is only useful for products made of similar materials and similar processes.
Technical-functional value	Lifespan (expected)	years	20 - 30	100	50	For product 1, the steel will likely deteriorate the fastest, as long as clean- and uncontaminated rubble is used. The rubble could later be transferred into a replacement compartment.	-
	Density (over area)	kg/m2	179 (concrete) 136 (brick)	180	28	Given that the compartments are the same thickness as masonry and won't ever be fully filled, densities are comparable.	Densities depend on the kinds of rubble put into the compartment (though large variations are not expected).
	Stiffness	MPa	-	7000	N/A	Stiffness is not so relevant in this comparison, the steel wire of product 1 is much thinner than the brick and mortar of product 2. The thickness of the wires in product 1 are based on similar elements used for creating self-supporting rock walls for gardens and roadsides.	-
	Thermal resistance	mK/W	-	0.125	-	Brick and mortar typically provides a small amount of insulation value, especially with a cavity behind it.	-

PRODUCT FEASIBILITY

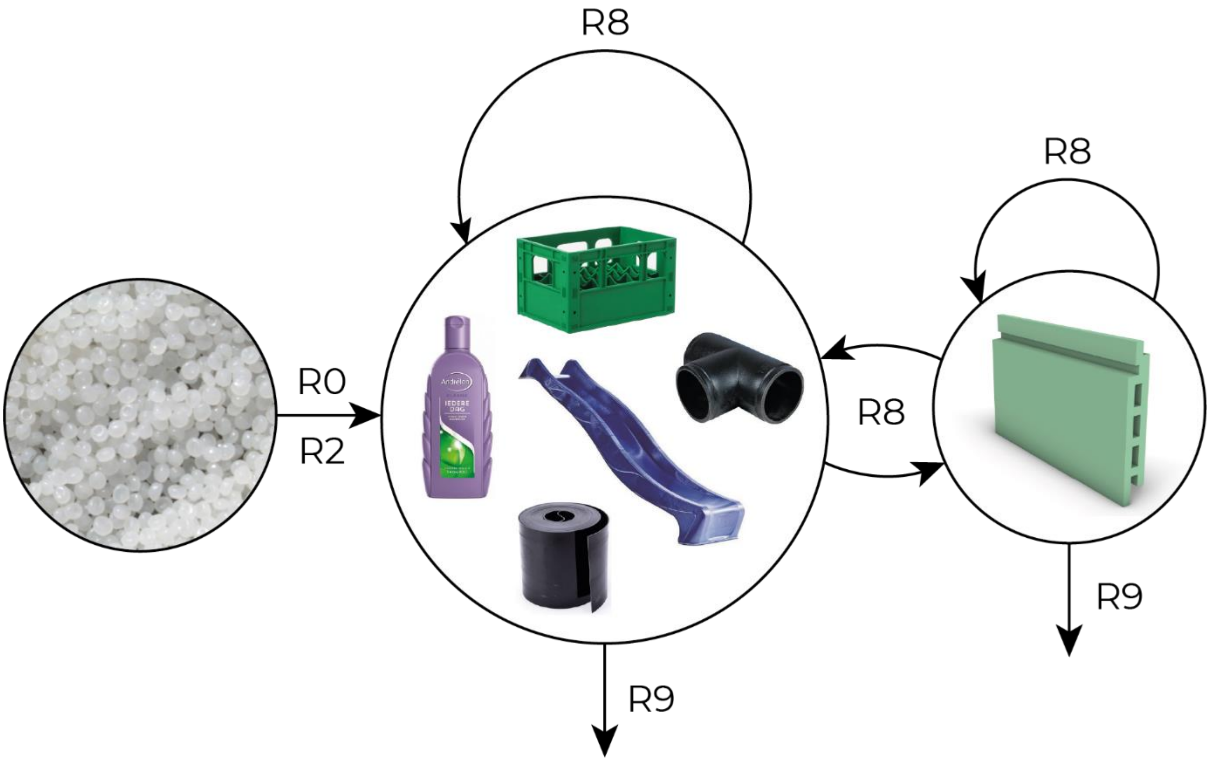
Category	Indicator		Result	Result	Result	Notes on result	Shortcomings of method
	Flammability	-	Non-flammable	Non-flammable	Non-flammable	-	-
	Tolerances (per unit)	mm	N/A	3 - 6	0.3	Tolerances of rubble in the compartments doesn't matter as long is they are sized about right to fit in and not fall out. For steel, tolerances are likely a few mm, as the wires have to be welded together into a cage.	Since the compartments rest on top of eachother, it should be avoided that high differences occur between adjacent stacks.
	Thermal expansion	m/(m.K)	0.000012 (steel)	0.000006	0.000008	All materials have similarly low coefficients.	-
	Resistance to UV	-	Excellent	Excellent	Excellent	Steel, concrete and ceramics are all highly durable materials.	-
	Resistance to water	-	Excellent	Excellent	Excellent		-
	Resistance to oxidation	-	Excellent	Excellent	N/A		-
Social value	Circumstances around production and transportation		Unlikely	Unlikely	Unlikely	The materials in all three products are highly common- and regulated materials. Clay for ceramics is sourced with the preservation of the surrounding area in mind. TATA steel, one of the largest global manufacturers, also operating in the Netherlands, has a labor protection system in place at all iron ore sourcing locations around the world.	-
	Aesthetic qualities		Earth- or gray tones, hard, rough texture	Earth tones, hard, rough texture	Earth- or gray tones, hard, fairly smooth	Based on reference imagery and products.	-

R - PATHS

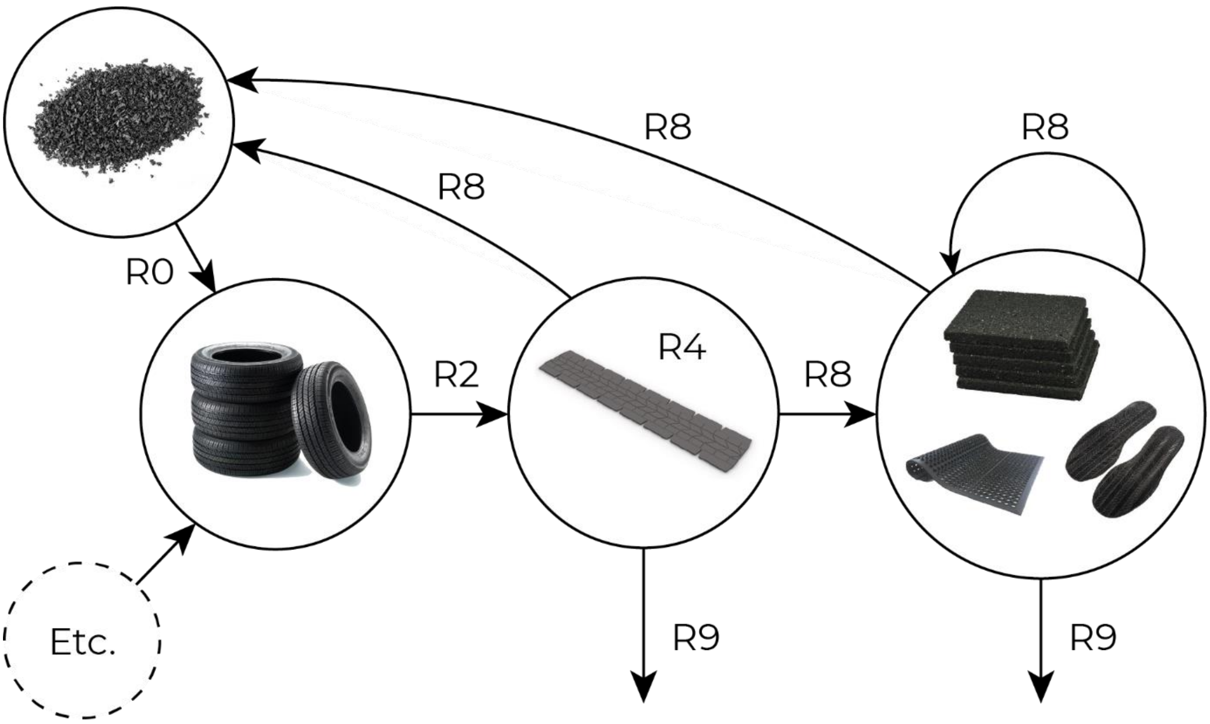
R-strategies		Applications
R0	Refuse	Demolish buildings more carefully, as to preserve as much whole material as possible.
		Use alternatives to mortar for achieving a brick look, while being easier to disassemble.
R1	Rethink	
R2	Reduce	
R3	Reuse	Reuse the entire product on a different building
		Transfer the rubble into a new compartment when that wears out.
R4	Repair	Weld broken wires of compartments
R5	Refurbish	Remove rust of old compartments
R6	Remanufacture	
R7	Repurpose	Use either the entire product or only the steel cage as self-standing walls for gardens, roadsides, etc.
		Use the rubble as filler for planter boxes or garden ground areas.
R8	Recycle	Recycle the steel back to its original quality, for any suitable application.
		Use the rubble as a resource for infrastructure (asphalt, concrete).
R9	Recover	

Appendix 10 – Case study R-paths

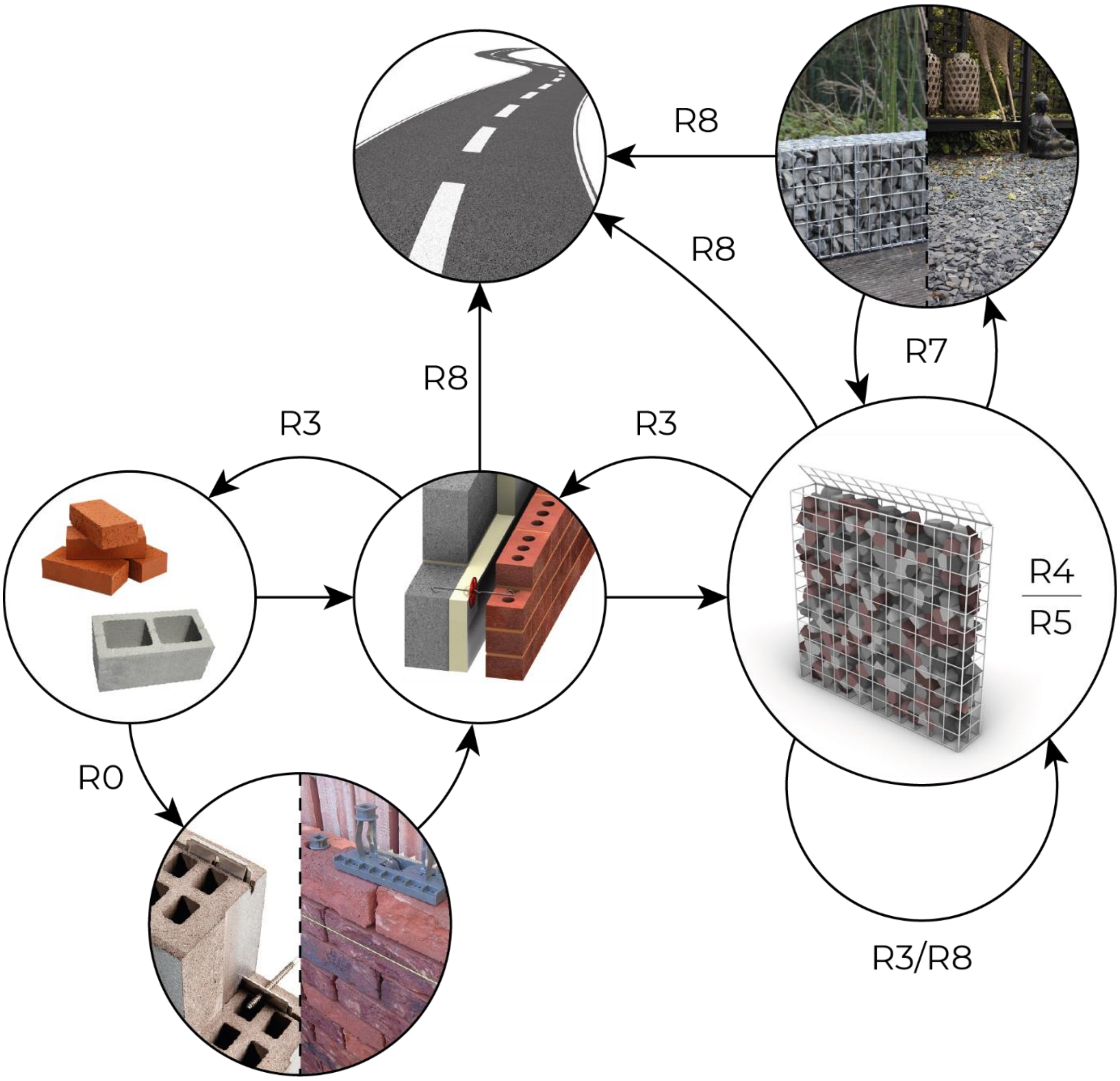
10.1 HDPE cladding panels



10.2 Rubber (tire) shingles



10.3 Rubble compartments



Appendix 11 – All methodological steps and decisions in the report

Methodology step	**Decision / result**	**Principles**
Setting goals and criteria for answering the main research questions	• List of design criteria • List of primary and secondary project goals	• Government ambitions • Priorities towards the need for mass housing
Establishing circularity definitions	• Use of R-strategies • Preserving / creating value	Main findings from research on a variety of perspectives
Establishing measuring method for circularity	CB'23 method with selfmade indicators for tech.-func. value and social value.	The method offers a solid list of indicators, lacking just methods for certain values.
Conventional housing envelope elements	Table with all conventional elements considered relevant	Distinguishing elements to a reasonable level of detail
Ranking conventional elements by significance	Three tiers of significance towards the project goals	Placement based on three self-made criteria
Gauging circularity of most significant elements and their materials	Gauging circularity through the expected lifespan and highest common end-of-use cases	R-strategies in combination with lifespan were deemed a reasonable estimation
Selecting elements and materials with the highest potential for improvement	Selecting or discarding each element and materials based on potential for improvement	Personal reasoning on where potential lies, based on information about the material
Thinking of R-strategies for selected elements and materials, and how those would be executed (ideas)	Selecting all R-ladder steps which may improve circularity of the element, specify the improvement, give examples	Method following the established definition for circularity, supported by own- and existing ideas
Selecting most relevant ideas towards the project goals and criteria	Prioritising improvements that are based on reuse of residual materials	Hand-selection of the R-strategies and materials most relevant to the goals
Making a final selection of ideas to perform circularity calculations on	Selecting a handful of residual resources to be able to test calculations more carefully	Only a handful was chosen, since the calculations are quite extensive in time
Selecting which former application the residual materials considered for calculation are taken from	Finding the most problematic source of the residual material, which would serve as the 'cradle' in lifecycle analysis	Research most common applications of the material, and which are the main source of residual material
Performing a comparative circularity calculation of each final idea with a similar conventional elements- and material	Conceptualise the lifecycles of the compared conventional and alternative element, measure their circularity based on chosen sets of indicators	Attempt to gather data from certified databases, to get an accurate overview of the material lifecycle and measure its impacts
Considering how future changes towards a circular economy may affect the design proposals	Overview of projected changes, barriers and solutions towards 2030 based on government ambitions, also for each material	Predict how the circularity and use of selected materials may be affected by changes in economy, policies, culture, etc.