HOW TO REACH THE CIRCULARITY GOAL IN A GROWING RESIDENTIAL CONSTRUCTION SECTOR?

A case study of the Municipality of Leiden and BAM

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ABSTRACT

The Dutch government aims to become fully circular in 2050 and to reduce the virgin material demand by 50% in 2030 (Rijksoverheid, 2016). For a country that has relied on a linear economy for centuries, this will prove to be a major challenge (Circle Economy, 2020; Rijksoverheid, 2016). Simultaneously, due to urbanization, the Dutch government intends to build one million dwellings between 2016 and 2030 (Ministerie van Binnenlandse Zaken, 2020). These two goals conflict because the first one aims to reduce material demand, whereas the second indirectly increases it. So far no study has paid attention to the impact of different circular construction solutions on the abiotic material demand. This is the gap that this thesis aims to fill, using the city of Leiden as a use case.

To help solve this problem, three steps were taken: 1) create a baseline of the total material demand for the residential sector, starting from the assumption that we continue to build in a linear way; 2) examine the views on circular solutions among experts; and 3) quantify the impact of certain circular solutions on the baseline in order to assess whether the goals defined by the government can be reached. The main aim of this thesis is to create a model that enables us to quantify the impact of five solutions in six different scenarios. In the first scenario the research on the potential of urban mining materials from Verhagen et al. (2020) is expanded and followed up by a second scenario in which the loadbearing structure was replaced by a (partly) wooden alternative. Thirdly, other elements of the building (e.g. facade and interior walls) were replaced by a biobased variant. In the fourth scenario the floor area of the apartments is decreased and in the fifth scenario the basements commonly built under high-rise apartment buildings are removed, whereas in the sixth, and last, scenario the first five are combined.

From the analysis results that the two goals mentioned above are only achievable through a combination of multiple solutions. The total virgin abiotic material demand for an average year between 2020 and 2030 would be around 155,000-tons in the business-as-usual scenario. The biggest impact came from switching the concrete loadbearing structure to a wooden (CLT) alternative, which leads to a reduction of 46% of the virgin abiotic material demand. The second largest impact resulted from converting the low- and high-rise apartments into micro-apartments in combination with downsizing the single-family dwelling size by a quarter, which leads to a reduction of 27% of the virgin abiotic material demand. Similar to this solution is excluding basements for parking under high-rise apartment buildings, which gives a 24% reduction. This is followed by the Urban Mining scenario, in which the released circular demolition waste is recycled/reused. This scenario had an impact of 19% on the total virgin abiotic material demand but is less difficult to implement compared to downsizing living space or parking spots. The scenario with the lowest impact was replacing abiotic material in the fit-out of a building, which only yields 7% of the virgin abiotic material demand. All solutions combined the total reduction was 91%, which clearly transcends the absolute goal of 69%. The results of the quantitative part of this thesis were in line with the results from the interviews, where changing the structure was mentioned as “the biggest fish” and changing the fit-out “rumbling in the margins”.

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1. INTRODUCTION AND PREVIOUS STUDIES

The Dutch government aims to be fully circular in 2050, and as an intermediate goal, to reduce the virgin material demand by 50% in 2030 (Rijksoverheid, 2016). For a country that has relied on a linear economy since the industrial revolution, this will be a major challenge (Circle Economy, 2020; Rijksoverheid, 2016). Simultaneously, due to urbanization, the Dutch government intends to build one million dwellings between 2016 and 2030, an aim that was recently revised to 845,000 dwellings between 2020 and 2030 (Ministerie van Binnenlandse Zaken, 2020). These two goals conflict as the first one aims to reduce material demand, whereas the second indirectly increases it.

The construction sector is responsible for 50% of the virgin material demand and 40% of waste in The Netherlands (Rijksoverheid, 2016). Although the construction sector is responsible for the largest material flow, it also has the biggest potential to reduce it (TNO, 2018). What is needed are different ways of construction: "high quality, pure material use and anticipated material regeneration routes." (Geldermans, 2016, p 301).

URBANIZATION GOALS

The urbanization task is a product of the housing shortage which has steadily risen in the last decades, resulting in an increase of rental prices (Lennartz, 2018). Therefore, the Dutch Government has come up with the plan to build an extra 845 thousand dwellings and decrease the housing shortage from 2,6% to 1,9% of the total stock in 2030 (Neprom, 2018; Ministerie van Binnenlandse Zaken, 2020). This demand for new housing in the Netherlands can be attributed to the population increase, the increase of average dwelling size and the decrease of persons per dwelling (Müller, 2006; CBS, 2018). The latter is caused by the fact that people stays single longer, get children at a later age and because the population ages and people live longer in big houses (Ted Barkhuis, personal communication, June 6, 2020).

Even though the government and interest groups have set the goal to build a million homes in 2030, the construction sector has reported that after the last economic crisis of 2008 the sector does not have the capacity to construct such a large number of dwellings (Lennartz, 2018).

CIRCULARITY GOALS

The circular economy (CE) is a different way of looking at the economic model, in which the reuse and recycling of materials and products are essential in reducing waste and maintaining the highest value within the economy (Ghisellini et al., 2018). Although there are many different definitions, suggesting that there is no consensus yet, there is agreement on this general idea (Kirchherr et al., 2017; Cossu and Williams, 2015; Geissdoerfer et al., 2017; Korhonen et al., 2018; Ellen MacArthur Foundation, 2013). The definition by the Ellen MacArthur Foundation (EMF) is the most well-known accepted definition (Geissdoerfer et al., 2017), and describes CE as "an industrial economy that is restorative or regenerative by intention and design" (EMF, 2013: 14). EMF illustrates this with the well-known butterfly graph, which splits the economy in a technical and a biological loop. The different smaller loops within the technical loop show the cascading of value streams, in which maintenance is most preferable and recycling the least. An successive framework is the R-strategy framework identifying three to nine circular strategies from 'Refuse' and 'Rethink', to 'Recycle' and 'Recover' (Ghisellini et al., 2016; Kirchherr et al., 2017; van Buren et al., 2016; Potting et al., 2017).

The reason for the Netherlands to set the ambitious goal to become fully circular in 2050 is twofold. First, to reduce the environmental impact, and two to reduce the dependency on other countries (Rijksoverheid, 2016). At the moment the Netherlands is highly dependent on other countries for its material supply and imports 68% of its materials (RLI, 2015). For Europe, only a one fifth of the aggregate demand for construction can be supplied from within Europe (Fellner et al. 2017). The goal is defined by the government as a 50% reduction of the abiotic materials (minerals, metals) in 2030.

THE STATE OF CONSTRUCTION

The construction sector currently, as well as literature, focusses only on the lower R-strategies (recycle and recover) (Ghisellini et al., 2016). In the Netherlands 80-98% of the construction and demolition waste (C&DW) is recycled, which is considered as an example for the rest of the world (Schut et al., 2016, TNO, 2018; CLO, 2015; Potting et al., 2017; Adams et al., 2017). While this sounds promising, however, most of this recycled material is downcycled as road foundation and filler material (Coelho & de Brito, 2017; Di Maria et al., 2018; Schut et al., 2016; TNO, 2018) and ensures that the construction sector stays the biggest (50%) consumer of virgin materials (Kamali et al., 2019; TNO, 2018).

The Circularity Gap Report (2019), which focusses on how circular the economy is, does not take this into account. In this report the total amount of secondary material in the economy is divided by the total material demand, in which no distinction is made in the grade of recycling (Circle Economy, 2020).The Netherlands still scored 24,5% on the national circularity index (NCI), while the average of the world is still on 9%. In this research the circularity index is calculated as the rate of secondary material in the entire economy (Circle Economy, 2019; Platform CB23, 2020), in which case the Netherlands does well in the downcycling of C&DW.

SUSTAINABILITY VS CIRCULAR ECONOMY

Circular Economy is not a goal in itself, but rather an approach towards a holistic sustainable economy. Of the total Green House Gas (GHG) emissions worldwide the main environmental impact of buildings is due to energy demand in the usephase (Ibn-Mohammed et al., 2013; Lawrence, 2015). However, in the literature there is no consensus about how much can be attributed to energy use as rates range between 40 to 90% (Heeren et al., 2015; Van Ooteghem & Xu; 2012; Ibn-Mohammed et al., 2013; Thormark, 2005; TNO, 2018; EIB, 2020; Rossi et al., 2011). Still about one fifth of the total impact pertain to embedded emissions of materials (Heeren et al., 2015). Therefore, the circular economy can help reach the Paris agreement goals to reduce the energy consumption by 30% in 2030 (Block et al., 2019).

Circular economy (CE) is a hot topic but the impact of the implementation is still not broadly researched. This thesis will mainly focus on solutions from the technical pillar of Industrial Ecology and add to the impact in the environmental pillar (Clift & Druckman, 2016). Due to time limitations, it does not take into account the social requirements and possible barriers for these solutions.

Circular solutions in literature

Even though the construction sector is the largest consumer of materials, it is viewed as a sector that is easiest to transform due to its regional and national character (TNO, 2018). To accomplish this a systematic change is needed. The EIB (2019) has identified four opportunities to change the construction sector: 1) Improve the use of secondary materials in construction; 2) reduce the virgin material demand through different design; 3) expand the lifespan of a building; and 4) use less damaging/renewable materials as alternatives.

URBAN MINING

The first solution, a direct translation of the EIB strategies is Urban Mining (UM), which can be seen as a new recycling principle of C&DW (Brunner, 2011) and is defined by Brunner (2011, p. 339) as: "a systematic reuse of anthropogenic materials from urban areas.". Instead of only low grate recycling of conventional demolition UM focuses on reuse, remanufacture and high-grade recycling within the sector. The potential of Urban Mining to reduce material demand could be significant, especially given the fact that the incoming and outgoing streams of construction material are expected to come closer together (EIB, 2020).

This study is a follow-up of the researches done by Benjamin Sprecher (2020) and Teun Verhagen et al. (2020) which focus on the impact of UM as a circular solution for the city of Leiden. These studies have quantified the material intensity of circular demolition waste and quantified the supply of demolition waste expected for Leiden until 2030.

In the Netherlands UM practices are, among others, carried out by *New Horizon*, who dismantle buildings rather than demolish them to reclaim the highest possible value of the secondary materials (Sauer, 2019). In this process of demolition, materials are extracted from the buildings, separated in individual streams and the transported to producing partners who turn them into new products, often in combination with a supplement of virgin material. Moreover, material stream elements (eg. pluming) are separately extracted and reused as they are (Verhagen et al., 2020).

The literature that can be found on UM is extensive, but overall is rather descriptive (Koutamanis et al., 2018; Brunner, 2011; Zhang et al., 2019; Cossu & Williams, 2015). Some studies calculate the material stock in a particular city in order to estimate the potential UM in the future (Gontia et al., 2019; Koutamanis et al., 2018) Others evaluate the current situation of UM in a city (Ragazzi et al., 2017). What is not addressed in the literature, however, are the possibilities of reusing these materials in new buildings. Sauer (2019) has researched the environmental impact reduction UM can provide compared to conventional demolition. However, no study has compared this to other circular solutions.

In the study by Sauer (2019) and Verhagen et al. (2020), the same material intensity and composition was assumed for newly built houses as for the demolished ones. In reality, the construction method has changed over time (Tanikawa et al., 2015). As Sauer (2019) mentioned in her thesis, multiple studies have been written on material intensity of residential buildings. Marinova et al., (2020) and Heeren and Hellweg (2018) studied an average material intensity of the world from 1970 until 2050, whereas Müller et al., (2006) studied the possible concrete flows in the Netherlands from 1900 until 2100. Various other studies looked into material intensities for other European countries (Bergsdal et al., 2007; Heeren & Hellweg, 2018; Gontia et al., 2018), but except for Müller no studies about the Netherlands could be found. And as Gontia et al. (2018) states, the data is very site specific and varies per country. This research adds a comparison to the urban mined supply and the material demand of current construction methods to the already existing literature and critically assesses the claim by Verhagen et al. (2020) who assume a collection rate of 95% for all waste streams.

Although this is a step up from current demolition practices in most regions of the world, including the Netherlands, UM will not cover the growing material demand (Verhagen et al., 2020; Deetman et al., 2020). In the study of Verhagen et al. (2020) a detailed account of the potential of UM materials turned out to supply 40% of the material from 2020 until 2030. This means that still 60% still needs to be supplied by virgin material and that only with UM the circularity goals will not be reached. What can other solutions contribute to reach the circularity targets in 2030? This thesis will look into to potential of other promising circular solutions as well.

(OTHER) CIRCULAR BUILDING SOLUTIONS

Some of the most promising circular building solutions, besides UM, are biobased materials, designing more flexible buildings and living smaller. Although limited studies focus on creating an overview of circular construction solutions (Adams et al., 2017; EIB, 2019), there is more research on individual solutions. Table 1 shows some circular construction solutions categories by the strategies suggested by EIB (2019).

Table 1 – Circular solutions found in literature

Category (by EIB, 2019)	Circular solution	Main sources
Secondary material	Reused, recycled material	Brunner (2011), Verhagen et al., (2020), Koutamanis (2018)
Renewable, less polluting material	Biobased	Lawrence (2015), Peñaloza et al., (2016), Carus & Dammer (2018)
Change in design	Flexible. Modular, design for deconstruction, Cradle-to-Cradle	Habraken (2008), Brand (1994), Geldermans (2016), Quale et al., (2012), Durmisevic & Yeang (2009), Kamali et al., (2019); Tingley (2012)
Lifespan extension	Renovation vs newly built	EIB (2020)
Other (not mentioned by EIB, 2019)	Downsizing living space	Sandberg (2018); Kim et al. (2020); De Vries (2018); Alexander (2016)

Biobased materials

One solution to reduce the abiotic material demand is to replace it with regenerative materials often called 'biobased materials' (Carus & Dammer, 2018). Wood, the most common biotic material, has been used as building material for thousands of years and in the Netherlands has gradually been replaced by brick and other mineral materials after the middle of the 14th century , due to scarcity of wood and fire hazards (Jonker et al., 1984). Now it is making a comeback as circular building material and many innovations evolve around Cross Laminated Timber (CLT), because of the potential of larger span width (Brandner et al., 2016). Most of the mass of buildings can be attributed to structure (WE Adviseurs, 2020; EIB, 2020), replacement of this part of the building has a major impact. Low-rise construction can be fully replaced by wood structure (P. van der Vliet, Personal communication, June 19, 2020) and for high-rise apartments the first example of hybrid wood- or wood-concrete has been realized in Amsterdam (ARUP, 2018). Besides the structure, brick accounts for a considerable mass. Looking at different exterior finishes could help bring down material intensity as well.

Biobased materials are part of the biobased economy (BBE) which is closely linked to the circular economy, but which solely focusses on changing the economy from leaning on fossil fuels to biobased alternatives (Staffas et al., 2013). However, literature on BBE is mostly focused on energy and food supply.

Apart from BBE there are more terms found in literature with the same meaning: Biobased material, renewable materials, regenerative materials, biogenic material.

Whenever a Life Cycle Assessment (LCA) is used to assess the climate impact of buildings, those with a large share of biobased materials result with the lowest impact (Lawrence, 2015; Peñaloza et al., 2016). This is due to a lower energy demand during production and fewer transportation emissions, as the materials are often locally grown and lighter than their abiotic alternatives (Lawrence, 2015). Although this is not always the case the LCA perspective should be applied in the decision of materials (Bribrían et al., 2010). According to Thormark (2005), emboddied emission of 40% could be decreased with 17% by a different material choice.

Flexible construction techniques / change design strategies

The average design of building does not allow materials to be easily extracted during demolishing (Schut et al., 2016), which is due to a lack of flexibility in the design. Flexibility (and adaptability) have however, been discussed within architecture for many years (Habraken, 2008; Brand, 1994). Habraken presented the concept of dividing a building into a base building (structure) and a fit-out in 1961 (Habraken, 2008). Brand (1994) added to this concept by splitting the building into six layers (site, structure, skin, services, spaceplane and stuff) all with its own lifespan to ensure the lifespan extension of components and the building itself.

There are many different terms and frameworks going around in literature about changing the design to improve flexibility and the environmental impact. Examples: Cradle-to-Cradle (McDonough & Braungart, 2003), regenerative design (Lyle, 1994), modular design (Quale et al., 2012; Kamali et al., 2019), design for disassembly (Durmisevic & Yeang, 2009); and build to rebuild. While the ambition level and direction of each solution differ, the overall aim is the same. Noteworthy is the introduction by the Cradle-to-Cradle idea of buildings as material banks (McDonough & Braungart, 2003)

Downsizing dwellings

A solution which is not often mentioned in literature in relation to circular solutions in the literature is the concept of decreasing living space, although the environmental impact of this option could be substantial (Sandberg, 2018). Heeren & Hellweg (2018) concludes that decreasing the dwelling size would significantly bring down the material demand. This concept is more prominent in the context of a degrowth economy and shared housing. Degrowth economy revolves around downscaling production and consumption, in which smaller co-housing is seen as a method (Alexander, 2016; Schneider et al., 2011). Shared housing is a concept in which a tenant is offered a small private room in combination with shared common space (Kim et al., 2020). This concept is becoming increasingly more popular as people stay longer alone.

Another concept related to smaller living are Micro-Apartments. With a living area of max. 50 m^2 these apartments are popular in mega cities such as Tokyo. These are examples of downsizing, driven by economic, environmental and social reasons. (Geffner, 2018; De Vries, 2018).

Only one study could be found on downscaling the dwelling size in the Netherlands, which concluded that a substantial part of the population would be interested in such an option and that 30% of the new dwellings in the Netherlands could be built as Micro-apartments (De Vries, 2018). However, reality shows that overall dwellings have rather become bigger while the household size has deceased (Müller, 2006).

Renovation vs newly built

A solution for the category "lifespan extension" is renovation instead of demolishing and building new. However, the literature on this subject is very scares. Renovation requires significantly less materials, according to EIB (2020), compared to newly built, because the structural elements are not often altered. Even though renovation only accounts for 8% of the material demand, it resulted in 29% of the material impact in 2014 (EIB, 2020). This relatively high impact is explained by the high embedded emissions of installations which are always renewed during renovation.

Other solutions

There are other circular solutions besides the once mentioned above that will not be extensively covered in this thesis. A concept that is often mentioned is the 'product as a service' business model in which the producers stay owner of the product and lease it per use or per performance. This motivates producers to make long lasting flexible products (Selvam et al., 2019) and has been implemented for elevators and light fixtures (De Groot, 2017).

OVERCOMING BARRIERS

Besides solutions, an integrated political approach is essential in reaching sustainability goals, such as a circular economy (Ghisellini et al., 2018). A report by RLI (2015) stated the following political and economic barriers in the transition to a circular economy, of which some of the most relevant to the construction sector are listed here. Firstly, the Dutch labor taxes are higher than on resources, which makes repairs and renovation more expensive compared to buying virgin material (Circle Economy & IMSA, 2013). Secondly, a lack of alternative circular business models. According to Backes (2015), the payback time of circular buildings is 10 to 40 years, which makes the economic incentives for investors too small. Lastly, the ecological cost are not included in the price (shadow costs), so that polluters do not pay the 'true cost' and is not incentivized to change its actions (Circle Economy & IMSA, 2013).

Calculating the true cost within the construction sector is done in a life-cycle-approach, called the 'Environmental performance buildings' (Dutch: Mpg) indicator, that translates the Life Cycle Assessment (LCA) to a shadow cost. Since 2013 the 'Environmental performance buildings' tool is a required part of the building process for new houses and office buildings bigger than 100m2. However, the target is still set on 1€/m2, which, according to Backes (2015) is a rather low ambition.

Beyond political and economic barriers, social and cultural barriers also render the transition toward a circular construction sector difficult. Think of a lack of urgency to change and the public opinion on ownership. Furthermore, legally waste is not a resource. A law put in place to protect public health but rendering the recycling of materials (RLI, 2015).

Another barrier in the transition toward a circular construction sector is that the payback time of circular buildings is 10 to 40 years, which makes the economic incentives for investors too small, states Backes (2017)

An important part of the implementation of circular concepts within a building project is determined in the tender process, which is a part of the procurement process. Incorporating sustainability criteria in this stage could help the move toward a circular construction sector (Witjes & Lozano, 2016).

Conclusion solutions and introduction

Of the more direct solutions (e.g. urban mining), the impact can be (partially) quantified whereas others have a more indirect impact (e.g. change in tax). This research will try to make an overview of the solutions and quantify the impact of some of the solutions for the material demand of Leiden until 2030.

three literature gaps have been identified. First, in the study by Verhagen et al., (2020) the analysis is missing current material demand data to compare the urban mining data with; Secondly, in the Urban Mining study a collection rate of 95% is assumed, which could differ per material; and thirdly, an overview of the impact of various circular solutions on the abiotic material demand is lacking in the literature to which this study will contribute.

Research question

The three aims mentioned in the paragraphs above result in the following main research questions:

"How can the circularity and urbanization goals be reached for the city of Leiden by 2030 and what circular solution has the biggest impact?"

To answer these questions this research is divided into two sections.

1. *What is the primary material demand for conventional residential dwellings in Leiden until 2030?*
2. *Which circular construction principles are needed to reach the target of 50% circularity in the construction sector by 2030?*

CASE STUDY LEIDEN

This study takes the city of Leiden as a case study. Leiden is a medium sized university city in the Netherlands. Of the million dwellings, 11,700 dwellings are appointed to this city as housing shortages are, with one of the highest in the country (Sauer, 2019; ABF Research, 2020). This means a 20% increase of households in Leiden by 2030 (Sauer, 2019).

2. METHODS

This research has combined the urbanization and circularity goals set out for Leiden in the year 2030 and is a combination of quantitative and qualitative approaches. In the research flow diagram below, the main steps are summarized and will be further explained in this chapter. These three steps are: 1. to quantify the material demand for residential building in Leiden until 2030; 2. to interview circularity experts to get a better understanding of the different circular construction solutions; 3. to explore what the impact of different circular construction solutions can be and to determine whether the goal can be reached.

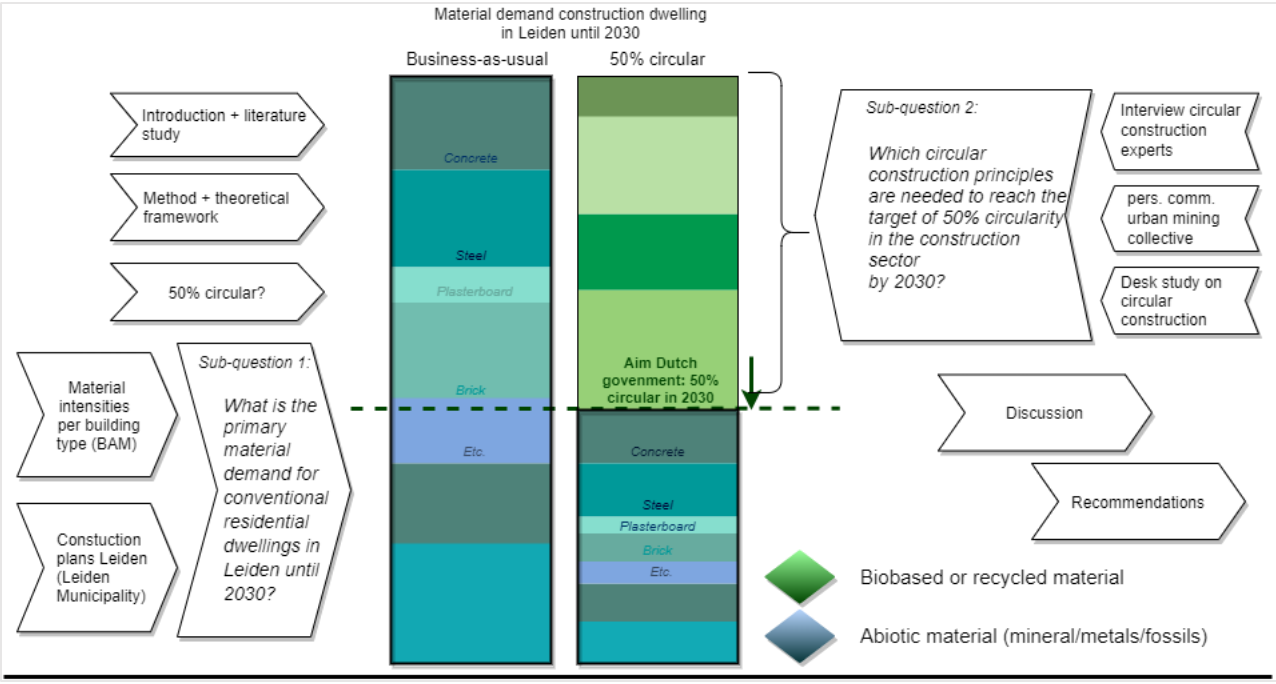

Figure 1 – Research flow diagram

This methods chapter is split into three main parts. First, concepts that are frequently mentioned in the method are clarified first within the theoretical framework. Second the system boundary is presented to determine the scope of this research and third and last the method used and modeling choice per research step are presented.

dividing attention and stuff

2.1 Theoretical framework

In this section different frameworks and definitions used in this study are clarified.

2.1.1 DEFINITIONS

Table 2 contains terms and definitions often used in this study.

Table 2 – Terms and definitions used in this research

Term	Definition	Source
Circular Economy	"an industrial economy that is restorative or regenerative by intention and design"	EMF (2013; p14)
Urban Mining	"reclaiming compounds and elements from any kind of anthropogenic stocks, including buildings, infrastructure, industries, products (in and out of use)"	Cossu & Williams (2015, p1)
Biobased materials	"Material that is grown, naturally replenished, or cleansed, at a rate which exceeds depletion of the usable supply of that resource."	*ASTM E2114-2004, via* Chambers & Muecke (2010; p. 91)
Abiotic material	Abiotic resources are the product of past biological processes (coal, oil and gas) or physical/chemical processes (deposits of metal ores).	Swart et al. (2015; p. 248)
Biotic material	"Biotic materials are materials derived from presently living organisms."	Swart et al. (2015; p. 248)
Material intensity	"Used to describe the material composition of different components of the built environment."	Gontia et al. (2018; p. 229)

2.1.1 CLARIFY CIRCULARITY GOALS (50% CIRCULAR?)

The main question of this research is how the goal of 50% circularity can be reached in the residential construction sector. However, there are two ways to interpret this goal: as an absolute target, in which the reduction is an absolute number; and a relative one, in which the material intensity is reduced by 50%. The differences are discussed in this subchapter.

Firstly, the absolute goal of reducing 50% of the total abiotic resources by 2030, regardless of the number of dwellings that are being built in the Netherlands. Secondly, this study will investigate how a relative goal can be reached, which can be translated into a cap on the use of abiotic material per square meter floorspace.

When viewing at the circularity goals as an absolute reduction, it strongly depends when (which baseline year) the 50% is built, a fact that isn't mentioned in the 'Circular in 2050' report by the Dutch state (Rijksoverheid, 2016). The RIVM and NEN later stated 2016 as the base year (RIVM, 2017; NEN, 2017). This implies that the circularity goal is an absolute target and the number of buildings being constructed will not change the goal. In this case, the goals are harder to reach when there is a high demand and easier in times of economic crisis, in which the construction production largely implodes. Moreover, due to fluctuations in construction in 2016 in different municipalities the extent of absolute reduction will differ in every municipality, which is not fair and sends mixed messages to the market.

The goal can also be framed a in relative terms in which the impact of volume of materials per building needs to be reduced by 50%, in which case the number of buildings does not influence the goal. This raises the question to which solution is preferable? In the practical field an absolute goal is irrelevant, because business do not influence the construction plans and therefore a relative goal could possibly have more impact on the reduction of the material intensity per floor area (kg/m2). Though in case of a high demand the total goal might not be reached.

This research analyses the absolute demand, because this is the standard of the Dutch government. However, in the sensitivity analysis the relative goal will be assessed and difference in impact will be calculated and evaluated in the discussion

2.1.3 THE CONCEPT OF AREA

For this study, Gross Floor Area (GFA) was chosen as the standard floorspace type, which in Dutch translates to BVO (Bruto vloeroppervlak). There are multiple types of floorspace which include and exclude different parts of buildings. The most well-known are GFA (Gross floorspace) and UFA (Usable floorspace). GFA includes almost all floorspace whereas UFA only pertains to floorspace within a dwelling. Due to densification of cities in the Netherlands, such as Leiden, the urbanization goals result in many high-rise buildings. These buildings need additional floor space is needed to ensure the safety and accessibility of these dwellings and create enough parking spaces. Therefore, the UFA/GFA ratio is relatively higher when compared to rowhouses. Nevertheless, the additional space implies additional material and should be taken into account in this study.

2.1.4 BUILDING TYPE, DWELLING TYPE AND HOUSING TYPES

In studies on building and construction, various terms are being used when it concerns housing. The three most important used in this thesis, are the following:

<u>Building types</u> are used in this thesis to indicate different types of structures. The residential building types used for this study were high-rise apartments (>9 floors), mid-rise apartments (6-9 floors), low-rise apartments (3-5 floors), row houses, semi-detached and detached houses (Hachem et al., 2014). As no data was studied on midrise apartments, everything above five stories are called high-rise in this study. These types are similar to those applied by Verhagen et al. (2020) and Sprecher et al. (2020) and are the most common dwellings in the residential building sector (Sauer, 2019).

<u>Dwelling types</u> are used in this study to differentiate types of housing as defined by the Municipality of Leiden. The first distinction that is made is between single-family (SF) dwellings and multiple-family (MF) dwellings. SF dwellings, as the name indicates, are buildings in which one family can live. This covers the building types: rowhouses, semidetached houses and detached houses. MF dwellings are buildings in which multiple dwellings are brought together, which can be apartments but historically also row house which have been split into two (or more) apartments. However, according to data controller from the Municipality of Leiden D. Lucassen (personal communication, 2020), in the new building plans no such dwellings are incorporated.

Housing types are used by the municipality of Leiden to differentiate their dwelling stock in terms of ownership: owner-occupied homes, private rental homes, social housing; and student housing.

2.1.5 URBAN MINING TERMINOLOGY

Term used related to urban mining are the 'Waste Material Collection Rate' (MCR) and 'Recycled Content' (RC). The terms are visually explained in figure below. The MCR measures the separation efficiency and calculates the usable share of material in the total feed (the volume that comes into the separation facility).

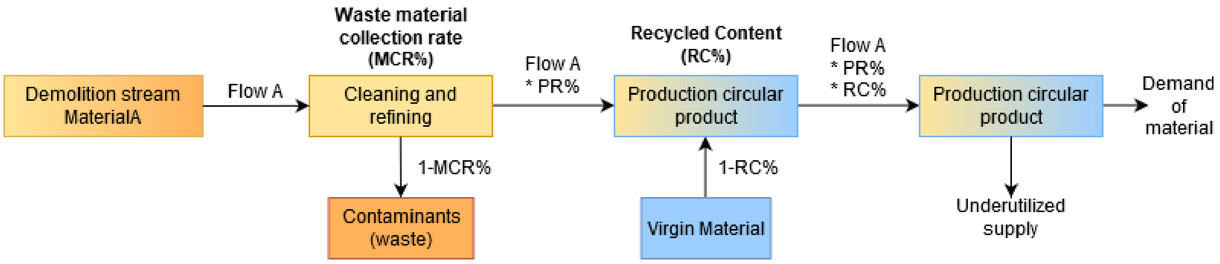

Figure 2 – Terminology urban mining visually explained

The recovery rate of valuable materials suited for recycling in the demolished material stream that enters the production facility is called the Waste material Collection Rate (1) (Yang, 2020).

$$Waste\ material\ collection\ rate\ (\%) = \frac{Usefull\ supply\ for\ production\ circular\ materials\ (kg)}{Total\ supply\ of\ demolition\ waste\ (kg)} \quad (1)$$

The share of recycled material in the circular product is called the Recycled content (2) (Greadel et al., 2011).

$$Recycled\ Content\ (\%) = \frac{Recycled\ material\ in\ new\ product\ [kg]}{Total\ material\ needed\ in\ product\ [kg]} \quad (2)$$

2.2 System boundaries

The goal of this study is to quantify how the urbanization task and the circularity goals of the Netherlands can be reconciled and reached by 2030, using the medium sized city of Leiden (120,000 inhabitants) as a case study.

This study uses a mix of methods to answer the main question. The first sub-question sets up the baseline and takes a quantitative route. The second sub-question, analyzing experts view on circular solutions, is studied by interviewing experts in the field of circular construction. In the third sub-question, where the impact of certain circular solutions is quantified, again takes a quantitative approach.

Even though the two aims impact the Netherlands as a whole, this research focuses only on the city of Leiden to explore the impact at the middle-sized urban level. The aims focus on the urbanization plans that started in 2017 and look forward to 2030. The circularity goal also has 2030 as an intermediate deadline in a longer policy goal that leads up to 2050. Furthermore, only the big construction streams are considered. Installations and other element like sanitation are left out due to complexity of these components and irregularities in the provided models. Additionally, materials tools and machines needed during construction are not included.

This study has been performed in cooperation/collaboration with the Municipality of Leiden, who is challenged in taking on their part of the urbanization task and expected to become increasingly more circular in the coming years.

As stated in the introduction this thesis builds on a research conducted by Marijn Sauer who is currently working for the municipality of Leiden and has helped to guide this research. The gathered data include the most recent and detailed plans to build the adequate number of dwellings in Leiden. This is further explained in step 1.

Data on material intensities of current building practices has been collected in cooperation with BAM. The Royal BAM Group is one of the biggest contractors in the Netherlands and faces the challenge of transforming to less virgin material intensive building practices. In the white paper of AM (the project development side of the company) they state the intention to play a central role in the circular construction transition but, Dinant ten Brinke (personal communication, December 9, 2019), CEO Bam Wonen states that it is not yet clear to them what this might mean. They were, therefore, willing to participate in this research. They supplied 3D BIM models of recently built, or to be built, dwellings of different types, which is further explained in step 1.

The existing database on material intensities from demolished buildings was updated by using data provided by the circular demolition company New Horizon (NH). New Horizon is a circular construction company which is affiliated with the research group “The Resilient Cities HUB” and has agreed to participate in this research.

The sources used for this study range from literature and databases to 3D BIM models and oral sources. Databases from Leiden, BAM and Sustainer Homes were used to gather data as well as 3D models containing material data of buildings. The oral sources can be divided between ‘semi-structured interviews’ (sub-question 2a) and ‘personal communication’, in which specific information was gathered from the practical field.

2.3 Step 1: Determining the primary material demand

In this first step of the present research, the goal was to answer the following question: "*What is the primary material demand for conventional residential dwellings in Leiden until 2030?"*. To answer this question, a baseline has been modelled. This baseline uses two data sources: the construction plans of the municipality of Leiden and datasets of construction projects from contracting company BAM. *(structure)*

2.3.2 MATERIAL INTENSITY PER BUILDING TYPE

Within BAM, models from currently built projects were gathered and provided as 3D Revit BIM (Building Information Models), to project the material intensity of the current construction sector. The models used are from buildings constructed in the year 2019-2020 and are therefore the most up to date material data available for the Netherlands. These practical models contain a range of information including detailed drawings, how the building will be constructed, and which materials will be used. BIM models are also used to determine (at an early stage) the life cycle impact of a building (Rezaei et al., 2019). For this thesis, the models have been altered slightly and material data exported as text files. These files contain raw data that was imported into excel and categorized per building element, and then converted into usable tables. Examples of these categories are floors, walls, insulation, foundation piles, interior wall finish, and non-construction elements. In each category a table per building type shows the relevant data. The table at the top of the Excel sheet summarizes the sheet as a total volume or mass per building type (see appendix B).

BIM models were gathered from the following building types:

- High-rise apartment – 10 stories tall; 124 apartment units
- Mid-rise apartment – no data
- Low-rise apartments – 5 stories tall; 48 apartment units
- Low-rise dwellings, rowhouses – three stories; 21 dwellings
- Low-rise dwellings, semidetached - three stories; 2 dwellings
- Low-rise dwellings, detached - three stories; 1 dwelling

In the model the distinction is made between the following materials: concrete, steel, other metals, abiotic insulation, glass, wood, gypsum, brick (incl. mortar), limestone, ceramics, chalk, composite and bitumen. A building is made up out of many different materials, so categorization is necessary for analytic purposes.

Table 3 – material categories

Abiotic/biotic	Material categories as defined by Gontia et al. (2018)	Materials
Abiotic	Mineral-binding materials	concrete
	Mineral-binding materials	limestone
	Mineral-binding materials	gypsum
	Mineral-binding materials	chalk
	Iron and steel	steel
	Ceramics and brick	brick
	Ceramics and brick	ceramic
	Stone and aggregates	gravel
	Miscellaneous	wood abiotic part (paints, additives)
	Miscellaneous	aluminum
	Miscellaneous	insulation (EPS, glass wool)
	Miscellaneous	glass

	Miscellaneous	composite (abiotic part)
	Miscellaneous	bitumen
Biotic	Wood-based materials	wood (biotic part)
	Wood-based materials	composite (biotic part)
	Wood-based materials	insulation (wood fiber, flax)

Besides categories, for each material the abiotic content is estimated, in order to measure the total abiotic material demand.

To make the data representative of a more varied construction sector some data from the models was altered. First, the models used are all based on a full concrete structure which currently represents the majority of the newly build dwellings. However, in low-rise dwellings about 30% of the dwellings the loadbearing walls are made up of sand lime brick (E. Sokkel, personal communication, June 18 2020). Secondly, the foundation piles are aligned to an average length of 18,5m for in Leiden (N. Breuer, personal communication, July 13, 2020). Thirdly, the high-rise apartment exterior finish data is altered to represent the current practice in the construction sector, which still uses predominantly brick (P. van der Vliet, personal communication, June 19, 2020). Lastly, the window and doorframe data were altered so that 25% consists of aluminum and 75% of wood (P. van der Vliet, personal communication, June 19, 2020).

Because the BIM models only provide information on the volume of elements, the weight is calculated by using average densities of materials. Different internet sources have been consulted to gather the data, see table 1 in Appendix A. Additionally, in the models no distinction is made between concrete and steel rebar, therefore averages per building type were provided by constructor J. Roeleveld (personal communication, June 15, 2020). For all materials the net demand is taken, so no cutting waste is taken into account. Additionally, J. Roeleveld provided the average concrete density of 2500 kg/m3 (compacted, no rebar).

As the total of material needed for a building does not make sense in itself, dividing it per area enables us to compare the types and make various calculations and comparisons. This research uses GFA as a default floorspace to calculate usable indicators (Explained in TF sub chapter 2.1.3). The floorspace per housing unit and of complete buildings (in UFA and GFA) were calculated using drawings and/or subtracted from the model itself. The difference between UFA and GFA in the models was used to calculate the material per unit in 2.3.4. Due to complexity the final material demand is regarded, assuming that the raw material consumption and losses, like cutting waste, are the same for all materials in a building.

The high-rise apartment model is a model with commercial space on the first floor that constitutes in total 5% of the total UFA. Therefore 5% of the material demand has been allocated to the commercial space instead of the apartments in the building. In the tab 'total' of Appendix B, all the material data is summarized in one table. Afterwards, the total material data is divided by the total floor area to present the material intensity in kg/m2 GFA.

2.3.3 DWELLING DEMAND LEIDEN

Construction plans for dwellings in Leiden, that together form the urbanization plan, were gathered from the Municipality of Leiden. Two main databases, the 'Nieuwbouw monitor' and the 'Realisatielijst', keep track of the construction plans and the already realized dwellings in Leiden. The missing data or details were provided by a city planner of the Municipality of Leiden (T. Barkhuis, personal communication, June 19, 2020).

Construction data is needed for the years 2016 and 2020 until 2030. Although the urbanization goal covers the period 2017-2030, making changes in the past is not possible. Furthermore, the study by Verhagen et al., (2020), that will be used to assess the potential of Urban Mining, also takes the scope of 2020-2030.

This research only takes into account the new buildings. For Leiden, the urbanization task means increasing the housing stock by 11,700 dwellings. To build these dwellings, low-rise structures need to be demolished to make space for high-rise. The total number of dwellings to be built from 2020 until 2030 is 17,000, which is more than the actual plan.

In the database, a distinction is made between multiple-family buildings and single-family dwellings, which is further subdivision of the building types used in this study. Of the multiple-family dwellings, meaning multiple housing units (addresses) per building plot, 75% are high-rise apartments and the other 25% is intended as low-rise apartments. Single-family dwellings are generally row houses with an occasional (in total 24) semi-detached dwelling. There are no current plans for detached dwellings in Leiden

In the data provided by the Municipality of Leiden a distinction is made between multiple-family (MF) dwellings and single-family (SF) dwellings, as explained in 2.1.5. According to T. Barkhuis (personal communication, June 6, 2020), all multiple-family dwellings are high-rise apartments and low-rise apartments, of which 70-80% of the multiple-family dwellings that are planned to be built will be high-rise. Of the single-family dwellings in total 24 are semidetached, and the remaining will be row houses.

The demand is calculated by using the area (GFA) (see chapter 2.1.3) instead of per unit because the varying UFA of the dwelling impacts the material demand as well. The area per dwelling is not given in the 'Nieuwbouw-monitor' and therefore had to be manually added. Due to time restrictions, an average area in UFA) per building type was procured in dialogue with city planner T. Barkhuis of the Municipality of Leiden (Personal Communication, June 19, 2020), as shown in Table 3.

To determine the GFA of the given average UFA, the UFA/GFA ratios from the BIM models were selected as the best available data. However, the units in the model used for high-rise apartments are on average bigger (110m2 compared to 70m2). Therefore, the ratio might be different, because in apartment buildings more floorspace is required for staircases, corridors and entrance halls. It can be argued that the same space is needed outside the apartment no matter the size. However, corridors are shorter and in luxury apartment buildings more space is used for these elements than in more standard flats. Therefore, the same ratios (of 48% UFA/GFA) was used for the high-rise building. For all the UFA/GFA ratios see Appendix A, 3.1.1.

Table 4 - Floor area per dwelling type as defined by Municipality of Leiden (T. Barkhuis, personal communication, June 19, 2020).

		baseline scenario		scenario 4 smaller living		
Multiple-family dwellings		UFA	GFA	UFA	GFA	
high-rise apartment	private rent	70	146	40	83	m2
	private for sale	77,5	161	40	83	m2
	social housing	60	125	40	83	m2
	student	27,5	57	20	42	m2
low-rise apartment	private rent	70	106	40	61	m2
	private for sale	77,5	117	40	61	m2

	social housing	60	91	40	61	m2
Single-family dwellings						
row dwellings	private rent	105	118	80	90	m2
	private for sale	105	118	80	90	m2
	social housing	80	90	80	90	m2
semi-detached dwellings	private rent	105	109	80	83	m2

Extra details need to be taken into account to calculate the number of dwellings that are provided to be built, such as project failure rates and newly built rates. The projects in the Database are provided with a status that indicates the phase of the project. In the exploration and the initiation phase the chance that the project fails is still high, which is why the municipality has more plans than dwellings it intends to build. For the (first) exploration phase, the failure rate is 50% and for the (second) initiation phase, the failure rate is 30% (Barkhuis, pers comm., 2020). This is taken into account in the baseline.

2.3.4 TOTAL MATERIAL DEMAND LEIDEN

Results from the material intensity and dwelling demand dataset are combined to constitute a baseline calculating the amount of material needed for the urbanization task for an average year between 2020 and 2030. In this section the material intensity data and size of the flow come together in a total demand. The general formula used for this section is shown in formula 4.

$$Material\ Demand\ \left(\frac{ton}{year}\right) = floor\ area\ per\ building\ type\ i\ \left(m2\,\frac{BVO}{year}\right) * material\ intensity\ buildingtype\ i\left(\frac{ton}{m2\ BVO}\right)\ (4)$$

An average year between 2020 and 2030 is taken instead of the actual demand in 2030, due to fluctuations in construction plans per year and the probability that construction projects are often postponed. This average was taken because the aim is to reduce the material demand by 2030 and the years before having less of an impact on the conclusion of this research. Furthermore, an average seamed more just due to the fluctuations and expected delays in construction.

2.3.5 QUANTIFY CIRCULARITY GOALS

There are multiple ways to interpret the circularity goal of 50% reduction of abiotic material by 2030. As further explained in the theoretical framework the goals can be interpreted in two approaches: an absolute and a relative goal (as explained in 2.1.1). Both will be calculated in this study.

For the absolute goal, it does not matter how much is erected as long as the total abiotic material is reduced by 50% in 2030 in comparison with 2016. This is assessed by comparing the material demand of 2016 to the demand in the BAU scenario to see how much this needs to be decreased. It is assumed that that from 2016 until 2030 the demand will be stepwise reduced to 50% of the material demand in 2016.

For the relative goal it will not matter how much is constructed, but the baseline is the material intensity per floor area, calculated in 2.3.2. In this case the idea is to find solutions that will impact the virgin material intensity.

2.4 Step 2: Detecting circular solutions (qualitative)

As no overview of circular construction solutions was available in literature, the second step of this research is to conduct semi-structured interviews to create an overview of perspectives on circular solutions from practice and to validate the solutions quantified in the next steps. Moreover, the interviews were used to get a better understanding of the municipalities role within the transition to a circular construction sector and discussed in the recommendation section.

The persons interviewed are all circularity experts from different fields, including: two consultants working in the field of sustainable construction (incl. CE), one architect, one person working at a municipality and one person working for a construction company. In table 5 the names and positions of the interviewees are listed.

Table 5 – Circular building experts interviewed

Name interviewee	Position + organization
M. Sauer	Policy consultant for the Municipality of Leiden
T. Blankendaal	Project Manager Circular Economy at BAM
F. Schiferi	Partner and Designer at Superuse Studios
D. Vancso	Consultant sustainable construction
M. Schokker	Consultant for a sustainable built environment

2.4.1 INTERVIEWS

The semi-structured interviews were used to understand how circularity is viewed in practice, what solutions are applied and to get a better grip on how a municipality can help circular construction advance in practice. The main goal was to validate the solutions chosen to quantify in the next part of this study. The semi-structured interviews were based on three questions.

Question 1. "Which definition of circular construction do you use?"

This question on the definition of CE helps us to create a common ground/baseline needed to interpret their answers. Furthermore, this knowledge is necessary because, as explained in the introduction, the definition has been altered and practitioners might share a different view on the matter, which might change the outcomes of the next question. Net to slight changes in the definition some have interpreted the CE as "another recycling or sustainability initiative" (Adams et al., 2017 p 16).

Question 2. "Which solutions are needed to reach the circularity targets in the residential building sector?"

The second question focused on what circular construction solutions the interviewee considered necessary for reaching the circularity goals.

Question 3. "How could a municipality help improve circularity in the residential construction sector?"

As this last question, centered around improvements for a Municipality to improve circular construction, does not directly answer the main question of this research it was taken out of the results and merely discussed in the recommendation section (chapter 5.1). The same structure as in the second question used.

After the interviewee finished with naming a range of solutions, solutions that other interviewees brought up were presented to get the interviewee's opinion on those as well. Thus, all interviewees gave their opinions on most of the solutions. To establish this the consent form that was send also included the solutions they had not given their answer to yet. The consent forms are included in Appendix E. The interviews are conducted in Dutch as the Dutch construction sector is mainly Dutch speaking.

2.4.2 OVERVIEW AND ANALYSING RESULTS

An overview was created by labeling the answers into five categories ranging from agree to disagree (see table 5) and combined a total overview of the most frequently mentioned solutions according to practice were given.

Table 6: Legend to interview answers

++	Agree: interviewee volunteers with the solution him- or herself.
+	Agree: Interviewee agrees with solution after it was presented
+/-	In doubt: Interviewee agrees that the solution could have sufficient impact, but doubted its implementation
-	In Doubt: Interviewee has doubts about the possible impact.
--	Disagree: Interviewee disagrees that this solution could have sufficient impact
	No answer: Interviewee was not asked or had not enough experience in this subject.

2.5 Step 3: Impact of circular solutions (quantitative)

The third step of this research was to quantify five solutions by modeling their impact on the abiotic material demand. This is split up in two parts. The first solution that is quantified is Urban Mining, of which an extensive research, specifically for the city of Leiden, was conducted in this year. This presented possibilities for a more detailed analysis when combined with more realistic material demand data.

In the presentation of the results the materials categories are reduced to: 1) virgin material abiotic; 2) virgin material biotic; 3) secondary material from urban mining and 4) secondary materials from other waste streams. These categories are split up into the largest material streams and a 'other' material stream containing less significant flows. However, in the calculations the same categories as chapter 2.3.2 are used.

2.5.1 SCENARIO 1: URBAN MINING

The first scenario deepens out previous research on Urban Mining (UM) by talking to producing partners of the Urban Mining Collective and calculating the impact with more in-depth material demand data (step 1).

Previous studies on urban mining

Main sources of data are the study by Sprecher et al., (2020) which contains material intensity data of circular demolished buildings in the Netherlands (see figure 3), whereas Verhagen's research combines these intensities with the demolition plans of Leiden until 2030.

The main data source for this part are studies by Verhagen et al., (2020) and Sprecher et al., (2020) on the potential of urban mining. Their research was done in partnership with New Horizon. Sprecher et al., (2020) made an analysis of material intensity of circular demolished buildings per building type (figure X). Verhagen et al., (2020) combined these intensities with the demolition plans of Leiden until 2030. These plans pertain to buildings that have to make room for the new dwellings. The buildings consist of different, also non-residential, structures with different material use.

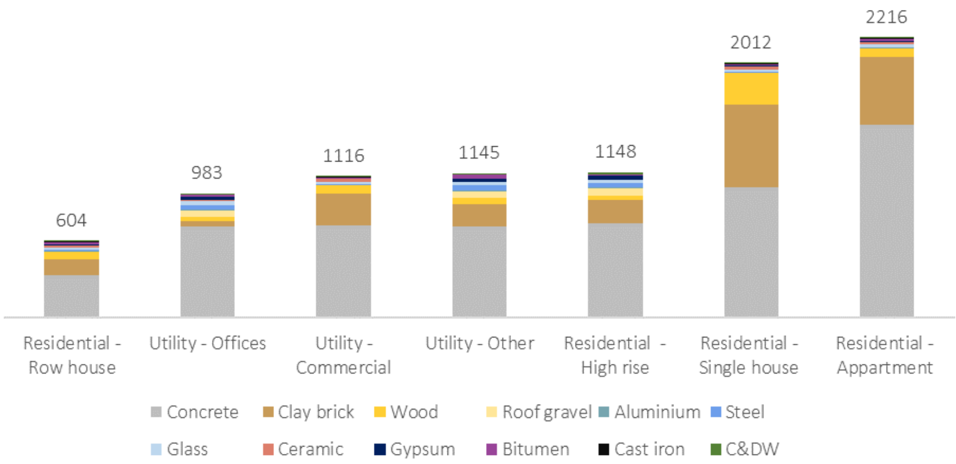

Figure 3 - Material intensities from circular demolition (Sprecher et al., 2020)

Understanding the supply chain of circular producers

As an addition to the two studies mentioned above, this study examines the supply chain of the partners involved in the circular demolition process to determine the 'Waste Material Collection Rate', the 'Recycled Content Rate'.

Data on the 'Waste Material Collection Rate' and 'Recycled Content Rate' (see TF 2.1.5) was gathered through personal communication with E. Koremans and P. Naaijkens of New Horizon and five of New Horizons producing partners. These partners produce circular concrete, brick, bitumen, gypsum board and chipboard. Recycling routes for other materials such as steel, aluminum and glass are more mature and for these materials rates from Verhagen et al (2020) were used. Other materials, such as limestone, insulation and ceramic there is currently no circular production option within the Urban Mining Collective and is assumed to be produced exclusively from virgin material.

Some materials have mature recycling streams due to the high value of the material (e.g. aluminum and steel). As these practices are seen as business as usual these are not further examined and average recycling rates are used (P. Naaijkens, personal communication, June 7, 2020; Dubois et al., 2013).

Modeling the potential of urban mining (scenario 1)

The results of this analysis are then combined with the demand for materials calculated in step 1. It was assumed that the supply must to be used in the same year, because storage of these materials is not economically viable.

The study by Verhagen et al. (2020) does not contain plans for the years 2026 until 2028, thus demolished material supply data is extrapolated from the other years. This difference in data is due to alterations in the construction plans.

An average potential recycling rate is used to calculate missing demolition data for the years 2026, 2027 and 2028. The study by Verhagen et al. (2020) relies on an earlier version of Leiden's construction plans in which no data construction plans were made for the years 2026, 2027 and 2028. To resolve this and create a more objective analysis the potential recycling rate (PRR), explained in 2.1.5, is calculated for every material.

The scenarios make a distinction between abiotic virgin material, biotic virgin material, secondary materials from UM and secondary materials from other sectors' waste streams. The latter because the circular variants of brick and chipboard that are produced use - besides UM material - additional waste streams from different sectors. The remaining virgin material demand is calculated as a share of the total demand.

2.5.2 SCENARIO 2-4: IMPACT OF CIRCULAR BUILDING SOLUTIONS

The urbanization and circularity goals were combined to see how both targets can be reached. This part of the research consists of quantifying the impact of three circular solutions. Three solutions are chosen after reviewing the relevant literature and conducting interviews with circularity experts (chapter 2.4). The solutions that have a direct impact on the material demand were modelled and the impact on the abiotic material demand quantified. The modeling results were afterward combined with step 1 and 2 of this research to conclude if the goals can be reached.

Modeling scenarios

The scenarios calculated in this study are: CLT for the structure of high-rise, modular wood structure for low-rise, smaller living units, and substituting also skin and interior of buildings with biobased alternatives.

The solutions mentioned in the interviews and in the literature include little to no quantified data on these solutions, so for the scenarios data was gathered from companies who are testing this in practice.

For the third scenario, the impact of biobased materials was measured for the fit-out, as described by Gerldermans (2018) who derived it from Habraken (1961), meaning the façade and partitioning elements.

Data

Data on the scenarios derive from the practical field as not enough information could be found in literature. Data on scenario 2 come in two forms. Low-rise buildings are assumed to be realized according to the techniques of Sustainer Homes, a prefab constructor in the Netherlands building detached dwellings (www.sustainerhomes.nl). Next to detached houses, they developed a row house concept. 'Environmental performance buildings' calculation sheets are used to estimate the material intensity (in kg/m2 GFA). For high-rise apartments literature on hybrid CLT material demand is limited. Moreover, the practice is not very familiar with high rise CLT structures and its associated material demand. Therefore, an exemplary building, HAUT in Amsterdam, has been selected because it offers sufficient information on the material demand.

For the third scenario, volumes of insulation and areas of the exterior finish are converted into biobased versions. The alternative biobased versions and the related volumes and weight derive from the NIBE website (www.nibe.info.nl).

For the fourth scenario, smaller housing, one source states that the maximum size of a micro apartment is 50m2 (De Vries, 2018).

Scenario 2 – Wooden structure
For the second scenario the concrete structure, which is on average 80% of the weight of new buildings (EIB, 2020), is replaced with a (partly) wooden one. Two different construction systems are assumed for this part. For low-rise buildings and apartment buildings a fully wooden structure and for high-rise apartments a hybrid CLT-concrete structure is presumed.

Low-rise structures bear smaller loads and can be fully constructed from wood (P. van der Vliet, personal communication, June 19, 2020). In collaboration with Sustainer Homes (SH), a company that develops and constructs wooden modules as dwellings, data was gathered on the material demand per dwelling and the total floor area in UFA and GFA. Two types were analyzed: a row house and a detached house. The material intensity for the rowhouse is used for low-rise apartments and rowhouses and the detached for the semi-detached dwellings.

As the Sustainer Home example is based on a different building method the material intensity of not only the structure but all elements changes. The SH example does not include brick as exterior finish, which is changed to a brick one for this scenario to keep it in line with the scenario. Instead for the same façade area a 100mm thick brick wall is assumed. Also, the insulation material in the Sustainer Homes concept is abiotic material, glass wool.

For high-rise apartments the above-mentioned exemplary building, HAUT in Amsterdam, is used as enough data could be found on the project online. HAUT is a CLT-concrete hybrid in which the structure up to the second floor and the elevator shaft are constructed in concrete and besides that CLT is used (ARUP, 2018). The floors are made of 300mm thick CLT, which is similar to the concrete version. Therefore, the walls and columns are assumed to have the same volume in concrete as in CLT. Except for steel columns, which have 10-15x the Bending strength as CLT wood (24-28 N/mm2 for CLT (Brandner et al., 2016) vs 300 N/mm2 for steel (Van Dam and Van Den Oever, 2019). For the conversion the volume of steel is multiplied by 15.

Scenario 3 – biobased fit-out
In this scenario the isolation, façade finish and interior walls are replaced with biobased variants. For insulation a rigid wood fiber insulation is assumed to replace EPS (the standard hard isolation in the model) and flax instead of glass wool (standard soft insulation in the model). A concern with biobased alternative insulation material is often their lower insulation quality, which is compensated with additional volume. A correction value is incorporated in the model to even out this fact (wood fiber: 1.11; flax: 1.09). For façade material a wood finish product is assumed which replaces the mainly brick facades in the model. And lastly the interior walls, often constructed from gypsum blocks (For full list of materials see Appendix XX), are replaced by a timber frame structure in combination with flax and chipboards.

Scenario 4 – smaller living
In the fourth scenario the impact of reducing the floorspace is measured, for this a extreme scenario was taken to see the maximum impact. All multifamily dwellings (high- and low-rise apartments) are converted to 40m2 UFA and the single-family dwellings (row and semi-detached) are reduced with 25%. Student housing is reduced from 28 to 20 m2 UFA. Table 4 show the new floor areas used. This scenario does not take into account a difference in the UFA/GFA ratio as this is too complicated to guess.

2.5.3 SCENARIO 5 – NO BASEMENTS

This fifth scenario calculates the impact of taking out the material needed for the basement, because Gontia et al. (2018) state "building elements related to basements (basement walls, basement ceilings, etc.) make a significant contribution to the MICs". This Material Intensity Coefficient (MIC) consists of concrete and steel rebar. In this scenario the impact of cutting out the basements is quantified, which are for the largest share used for car parking.

For this scenario only the wall and floor material is considered. Potentially a part of the foundation and foundation piles are reduced due to an elimination of basements, however this is a very complex calculation and was not taken into account in this scenario.

2.5.5 SCENARIO 6 – COMBINING SOLUTIONS

In the first five scenarios the impact of single solutions on the abiotic material demand are quantified, none of which reduce the virgin abiotic material demand enough to reach the absolute goal. Therefore, combinations of solutions are necessary. In the seventh scenario different combinations of solutions are modelled and discussed.

The solutions in the scenarios one to six are statically modelled and have implications on different parts of the material demand. Therefore, the reductions of one scenario cannot simply be added up to obtain the combined impact.

2.6 Sensitivity analysis

The sensitivity analysis of this study is focused on input uncertainty as well as on model uncertainty. Both types need to be assessed to estimate the robustness of the model (Müller, 2006; Ortlepp et al., 2016). For input uncertainty the density of concrete was chosen and for model uncertainty the failure rates are assessed as well as changing the material intensity from volume to mass per square meter.

2.6.1 RELATIVE GOAL

The first sensitivity analysis takes a different approach to the interpretation of the circularity goal and quantifies the impact of the solutions in case of a relative goal. Whereas all the scenarios are modelled according to the absolute goal, in which the goal is set and is not altered when demand changes, a relative goal looks at the relative material demand per floor area. Even though the Dutch government formulated the circularity goal as an absolute one, this is hard to implement in practice. A relative goal is more compatible to business practices.

For this sensitivity analysis, the relative goal is quantified as specified in 2.3.5 and applied to the material intensities of the scenarios. Because this relative goal refers to the material intensity, the smaller living scenario (S4) will not result in an impact and is therefore left out. The impact is evaluated for high-rise apartments, row houses and detached dwellings because these are the three building types with the most diverse material intensities.

2.6.2 VOLUME INSTEAD OF MASS

The second sensitivity analysis is performed to assess the difference in outcome when the material intensity is changed from mass per area to volume per area. When discussing the impact on mass materials, material with a low density are often overlooked. This sensitivity analysis quantifies the scenarios using volume by dividing the mass through the density.

2.6.3 CONCRETE DENSITY

The third sensitivity analysis looks into the concrete density, because it is the main share of the material composition found in this research and in literature the opinion on the concrete density is divided. This thesis applied the concrete density of 2500 kg/m^3, because this was provided as average for BAM by constructor J. Roeleveld (J. Roeleveld, personal communication, June 15, 2020). However, previous studies and companies have used different densities ranging from 2100 kg/m^3 (Gontia et al., 2018), to 2380 kg/m^3 (Bribián et al., 2011) to 2400 kg/m^3 (Sustainer homes, 2020). To evaluate the difference in outcome due this parameter for the first sensitivity analysis the concrete density is changed from 2500 kg/m^3 to 2100 kg/m^3.

3. RESULTS

The result chapter is divided into four sections. The key result of this research is first presented, answering the question of how the circularity and urbanization goals can both be reached by 2030. Then this key result is chronologically explained by splitting up the result section into four sections. Firstly, the material demand for new dwellings in Leiden is quantified for the years 2016 up until 2030. Secondly, the vision of experts on circular solutions was gathered; Thirdly, the impact of five circular construction solutions on the abiotic material demand was quantified. Finally, the results from the sensitivity analysis is presented.

Figure 4 displays the key result of this thesis in which the difference in (abiotic) material demand of the business-as-usual scenario is compared to the six scenarios, for an average year between 2020 and 2030. The figure shows that only in the last scenario, when all solutions are combined, the goal of an absolute maximum of 78,100-tons abiotic material can in principle be reached. Because in the same period (2016-2030) the dwelling stock is meant to increase due to the urbanization task, a reduction of 72% is needed. This is achievable when the five solutions are combined, which would reduce the abiotic material demand to 91%.

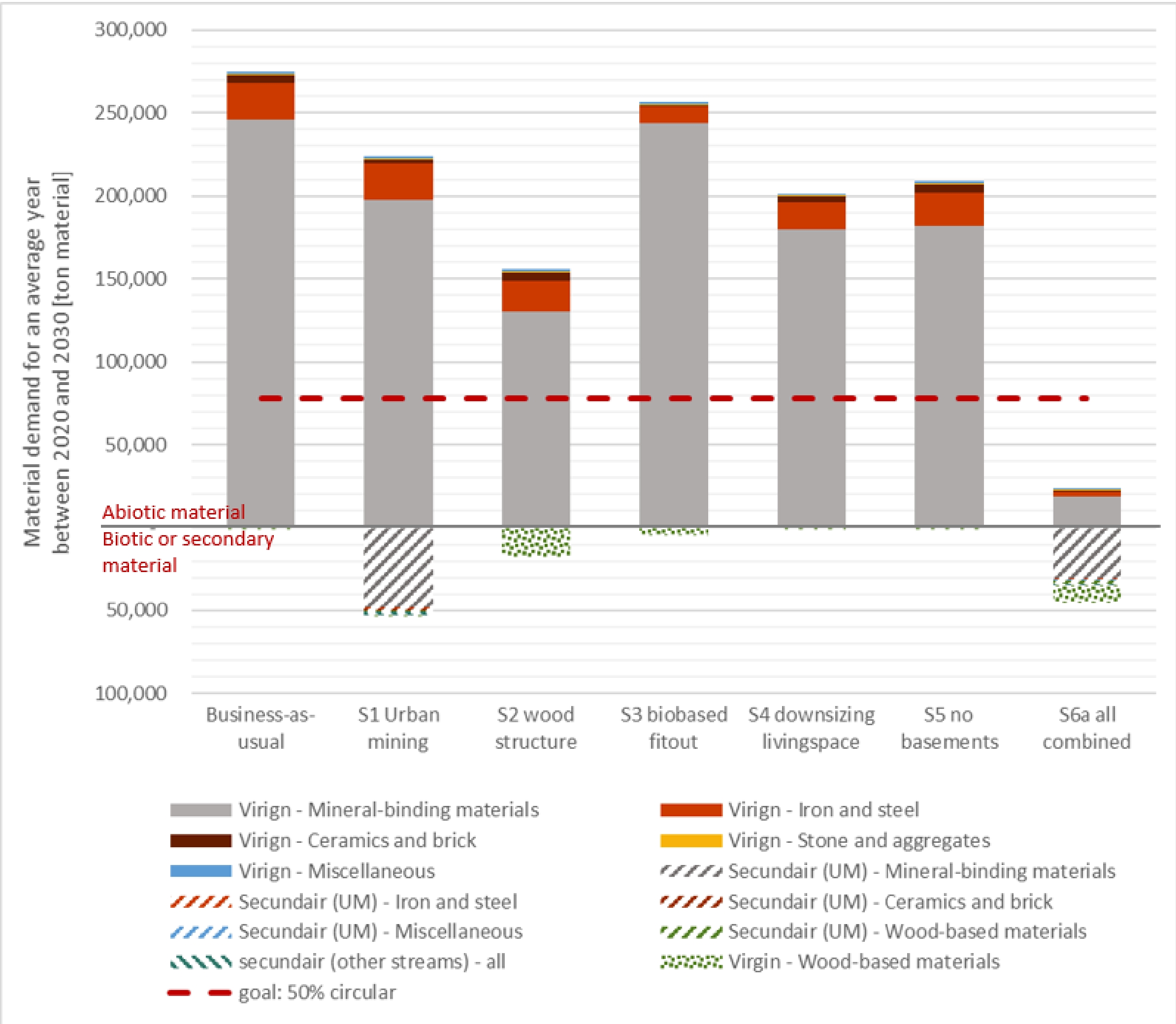

Figure 4 – Key result: impact of the scenarios on the material demand with virgin abiotic material demand above the zero-line and biotic and secondary material below the zero-line.

3.1 Baseline - determining the primary material demand

The first step of this research is determining a business-as-usual (BAU) scenario, also called the baseline. This step is a combination of two results divided into the five building types. First the material intensity (in kg/GFA) of the current construction sector is quantified; secondly the total demand of floor area (in GFA) in Leiden is determined between 2020 and 2030. Thirdly the first two steps are combined to quantify the baseline and lastly the circularity goals for this thesis are determined.

3.1.1 MATERIAL INTENSITY PER BUILDING TYPE

The first step of creating the baseline is to determine the materials required of the current construction method. Figure 5 shows the material demand per square meter by building type compared to the material demand per unit. High-rise requires the highest material intensity per m^2 GFA and row houses for the lowest.

The left side of Figure 5 shows the material intensity in kg/m2 GFA in which high- and low-rise apartments as well as detached dwellings have the highest material demand per area. On the right side the figure shows the material demand per average unit. For this the average numbers of the municipality were used (see 3.1.2). In this case the gap between material intensity of high-rise apartments and the other building types is larger because more space is needed. This is further explained in the next section (3.1.2). More specific information about the material intensity can be found in table 7.

The largest flow of materials is concrete followed by steel and brick. This is a combination of the high densities of these three materials, large volumes required, mainly used for the structure and the exterior finish.

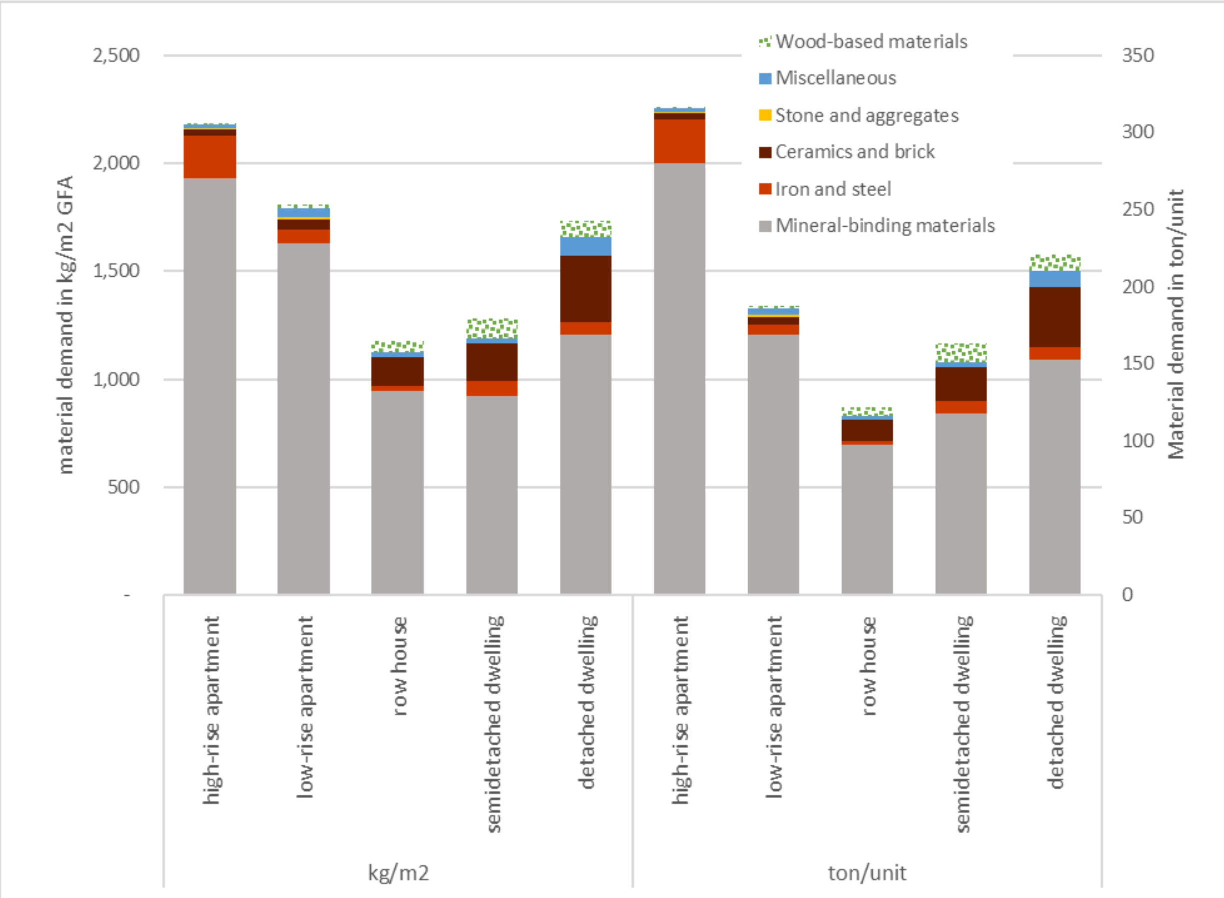

Figure 5 – Material intensities of each building type per Gross Floor Area (left) and per unit (right)

table 7 - material intensity derived from BIM models [kg/m2 GFA]						
material category	material	high-rise apartment	low-rise apartment	row house	semi-detached dwelling	detached dwelling
Abiotic						
Mineral-binding materials	concrete	1,913.7	1,507.5	835.2	843.3	1,101.4
Mineral-binding materials	limestone	-	63.2	78.9	52.8	70.0
Mineral-binding materials	gypsum	8.0	13.4	9.4	8.4	9.4
Mineral-binding materials	kalk etc	0.2	0.3	0.1	0.1	0.1
Iron and steel	steel	80.7	55.8	18.0	65.3	60.9
Ceramics and brick	brick	24.5	41.7	102.1	143.5	242.4
Ceramics and brick	Ceramic	4.2	7.1	35.8	31.5	65.3
Stone and aggregates	Gravel	6.6	10.6	-	-	0.8
Miscellaneous	wood (abiotic part)	0.6	1.5	1.7	3.1	2.8
Miscellaneous	other metals	0.4	0.7	0.9	0.8	1.3
Miscellaneous	insulation (abiotic)	-	-	-	-	-
Miscellaneous	glass	5.1	8.9	10.9	9.2	15.0
Miscellaneous	composite (abiotic part)	0.3	22.3	0.4	0.4	57.8
Miscellaneous	bitumen	0.2	0.4	-	-	0.1
	total abiotic	2,044.5	1,733.4	1,093.4	1,158.3	1,627.3
Biotic						
Wood-based materials	wood (biotic part)	12.0	29.5	57.1	97.9	85.6
Wood-based materials	composite (biotic part)	-	1.4	-	-	-
Wood-based materials	insulation (biotic)	13.2	20.5	16.5	25.2	21.9
	total biotic	25.1	51.4	73.7	123.1	107.4
	total material intensity	2,069.6	1,784.8	1,167.0	1,281.4	1,734.7

The majority of the material is needed for the load bearing structure of the building (67-97%). The rate of materials required for the structure ranges from 810 kg/m^2 GFA for semi-detached houses, to 2000kg/m^2 GFA for high-rise dwelling. This difference is due to the difference in vertical and horizontal loads. In general, the taller the building, the higher the material intensity of the structure, due to the required thicker structural elements (J. Roeleveld, personal communication, June 15, 2020). The high-rise example includes a one-level basement for a parking garage, which accounts for 28% of the total material intensity, due to the need for a one-meter thick concrete slab. In the used model for mid-rise apartments this accounted for 1.2 parking spaces per apartment.

Apart from the structure, the façade requires the largest flow of materials for single-family buildings (10% for row dwellings and 20% for detached dwelling). However, for the apartment buildings this was much lower (2%). This difference can be explained by the fact that apartments are built more compact compared to single-family dwellings and the relatively high total material demand of the apartments.

Subsequently, the (non-loadbearing) interior walls and floor finish require the most materials (around 4-9% of the total material demand). Within floor finish the largest flow is the concrete wearing screed layer. Roof finish and other elements (e.g. stairs, gutter etc.) both result overall in less than 1% with the exception of roofs of low-rise single-family dwellings that result in 4-5% mainly due to the wooden structure require for the gable roof.

Although single-family dwellings are identical in height, detached and semidetached houses need more material for the structure to ensure stability, whereas for terraced houses the stability is more distributed over the total row according to constructor J. Roeleveld (Personal Communication, June 15, 2020). The material demand for the structure of rowhouses may be lower than the apartments buildings, but the material demand for the façade (bricks) and roof (wood structure with ceramic rooftile) are higher. Rowhouses are again more efficient in relation to the material demand for the facades compared to the (semi-)detached dwellings.

In total on average 96% of the material intensity is abiotic. Only 4% consist of wood, mainly in partitioning walls, and roof structures of single-family dwellings. The low number can only be partly explained by the low density of wood (450kg/m3 compared to concrete (2500kg/m3 excluding steel rebar). The greatest share of the total material demand is concrete, between 63% (for rowhouses) and 88% (for high-rise apartments).

In appendix A 3.1.1 the division for concrete is shown, of which the biggest share is used for floor structures (43% for rowhouses and 72% in high-rise buildings, including the basement floors). Followed by the walls (avg. 17%) and wearing screed floor layer (10%)

3.1.2 DWELLING DEMAND IN LEIDEN

The second step of this sub-question concerns the construction plans for new dwellings of the Municipality of Leiden. This is a combination of the plans for units, the average floor area per dwelling type and the average GFA-UFA ratios (see appendix A, table 2).

The dwelling plans of the municipality combined with the average floor area per dwelling type result in a total new dwelling demand between 2020 and 2030 of 132,000 m2 GFA on average per year, of which 66% will be high-rise apartments, 16% high-rise student housing, 16% low-rise apartments, 2% rowhouses and 0,2% semi-detached houses. The inclusion of fall-out rates in the model results to 23% less dwellings.

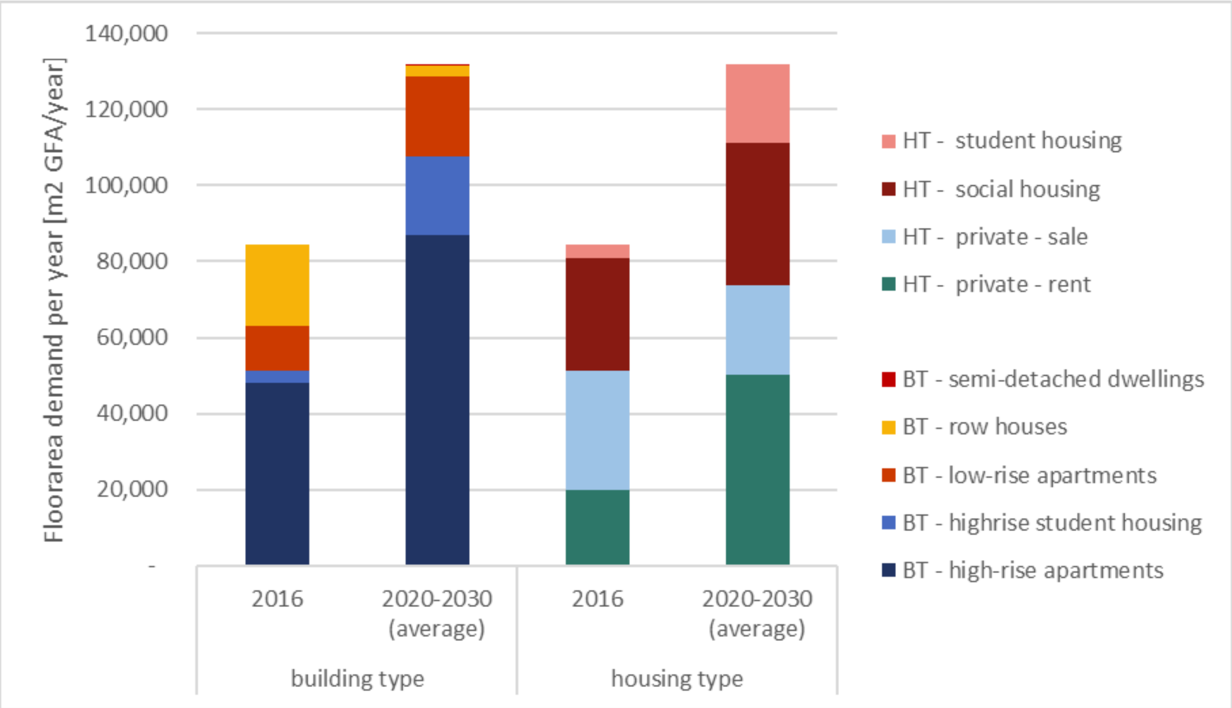

Figure 6: The total floor area demand in GFA for the years 2016 and an average year between 2020 and 2030. Split up in building type (BT) and housing type (HT).

The total new dwelling demand in 2016 resulted in 710 housing units, which on average will rise to 1217 new dwelling units per year between 2020 and 2030. This is accompanied by an increase in the proportion of high- and low-rise compared to row houses, as can be seen in figure 7. Figure 7 also displays that the proportion of privately rented dwellings and student housing increases by more than 10% and are then privately sold, which decreases the share of social housing.

These differences in dwelling types between these years impacts the material demand, because the social and student housing differ greatly in floorspace (see table 4 in 2.3.3). Figure 4 shows the total material demand per building and housing type, which for student housing and social housing is one third to one half of the material demand compared to some rent or bought dwellings, regardless of the building type. This is completely due to the reduction of floor space. This means that the demographics of the housing demand impacts the material demand as well.

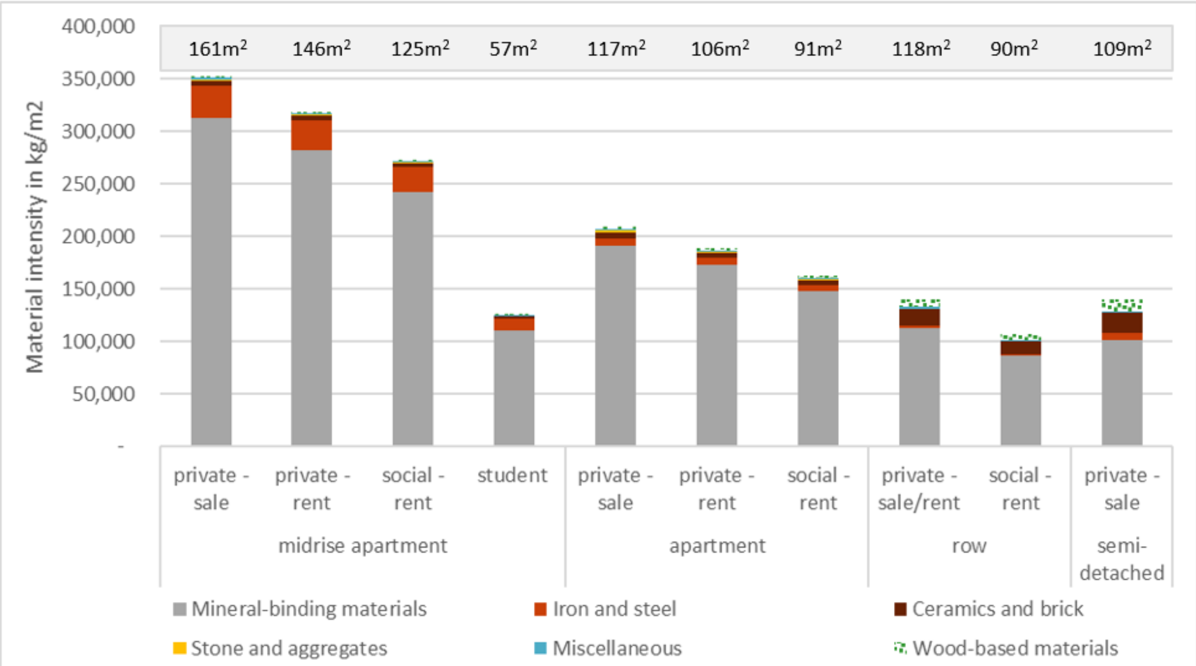

Figure 7 – Material demand per housing type within building type, included the average floor area in GFA per housing type.

3.1.3 TOTAL MATERIAL DEMAND IN LEIDEN

Combining step 3.1.1 and 3.1.2 Figure 5 presents the total material demand per year. The high proportion of high-rise in the dwelling plans of Leiden makes for an increasing demand of loadbearing structure materials, such as concrete and steel.

Due to the fluctuations in construction plans (see appendix A, figure 1), an average year between 2020 and 2030 is used for the analysis of this study. This average is coincidentally only 8% lower than the current plans for 2030 but as these plans. In appendix A 3.1.3 the dynamics of the different years is shown. A peak in construction is expected in 2023, which is twice as high as the average demand and almost no construction is planned for 2028 (2028 is 70% lower than the average).

When dwellings are constructed in the linear, conventional, way 276,277 -tons virgin material is needed for an average year of 2030 (meaning an average year between 2020 and 2030). It almost exclusively concerns abiotic material. Most of these materials are concrete (87%) followed by steel (8%). On average only 0.4% is biotic material.

3.1.4 QUANTIFYING CIRCULARITY GOALS

As described in chapter 2.3.5, the circularity goals require a 50% reduction of virgin material, compared to 2016. Chapter 2.3.5. explains that it is not yet clear how this reduction is interpreted, as it can be seen as an 'absolute' or a 'relative' goal.

Absolute goal

This study explores two ways of interpreting the circularity goal. The first is in an 'absolute' way, as is also described in the 'Circular in 2050' report by the Dutch government (Rijksoverheid, 2016). The absolute goal will not change when the demand in dwellings changes. The base year for this goal is 2016.

Figure 6 displays the modelling results of the baseline compared to 2016 and the resulting absolute goal. The total absolute goal, 50% compared to 2016, is to reduce the material demand by 78,120 tons/year. This means a reduction of 71% of abiotic materials in the baseline scenario. In the year 2016 fewer dwellings were built resulting in a lower material demand, compared to the construction between 2020 and 2030. This lower abiotic material demand makes the target harder to reach.

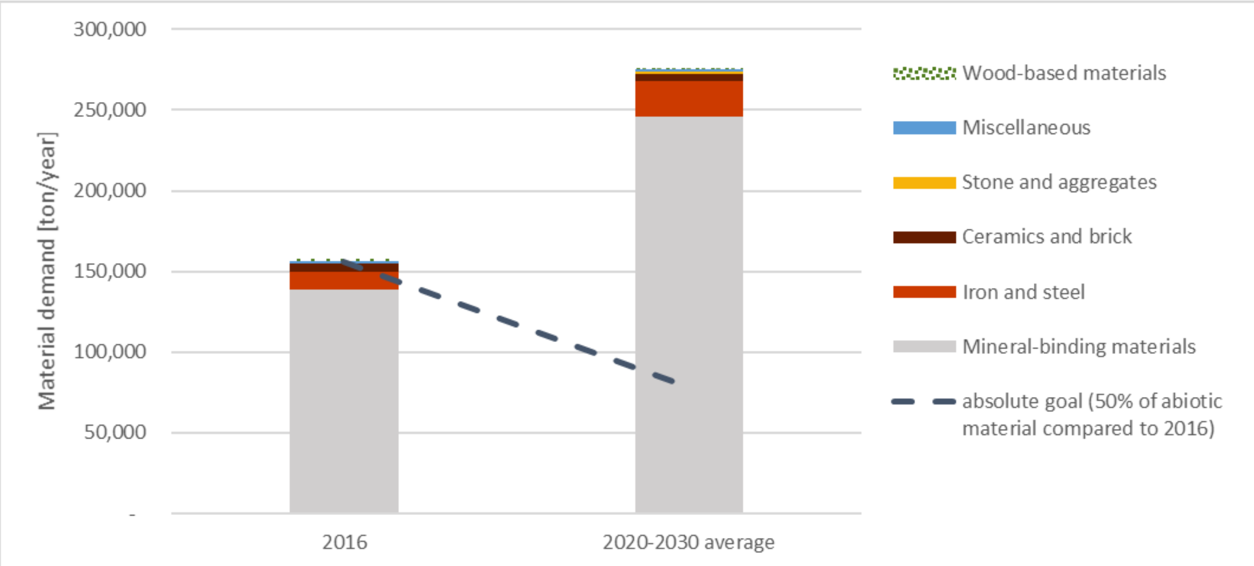

Figure 8 – the material intensity of the absolute goal.

Relative goal

Another way to interpret the circularity goals is to see it as a 'relative' goal, for which the material demand per floor area is relatively decreased to 50%. In this case the total construction demand does not influence the target (see chapter 2.3.5).

The relative goal is based on the results of 3.1.1. and is 50% of the total abiotic material demand of the baseline's material intensity. The result of the relative goal is shown in figure 7. This means that the relative goal is almost twice as high for high-rise buildings (1090 kg/m2 GFA) compared to rowhouses (560 kg/m2 GFA).

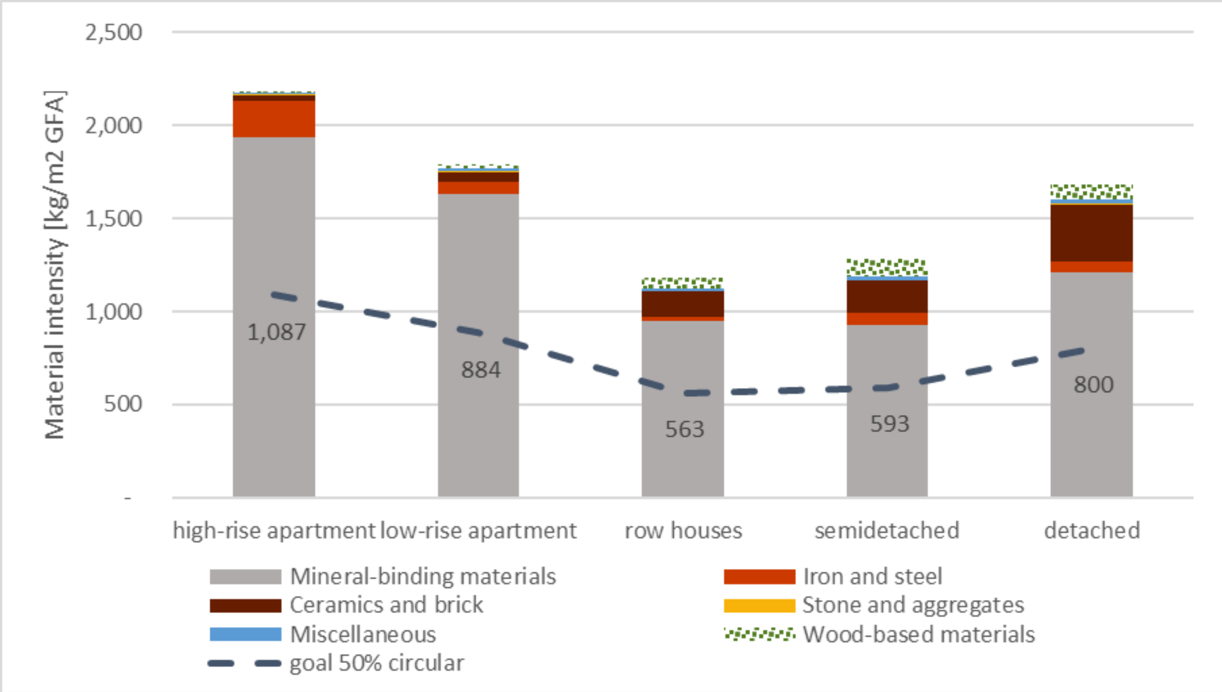

Figure 9 – the relative quantified per building type [kg/m2 GFA]

Of the two goals presented here the absolute goal will be harder to reach as the demand for dwellings increases, when however, due to a financial crisis less dwellings are built in this timeframe, the absolute goal will be less hard to reach.

3.2 Detecting circular solutions (theoretical)

3.2.1 INTERVIEW CIRCULAR SOLUTIONS OVERVIEW

To create consensus on the (most effective) circular solutions, five circularity experts were interviewed using a semi-structured interview. In these semi-structured interviews three questions were posed of which one is included in this result section (for all the answers given, see Appendix D). In the semi-structures interviews the interviewee were asked to identify the most relevant circular solutions pertaining to the key question of this thesis. Then they were presented with solutions suggested by other interviewees and asked for their reactions.

To categorize the answers from the interviews the color codes presented at the bottom of table 8 were used. The colors ranges from complete agreement to disagreement and also indicates whether the interviewee suggested the answer themselves, because this this reveals how important they consider the solution.

Circular solutions

This section presents the answer to the second question, "Which solutions are needed to reach the circularity targets in the residential building sector?". This resulted in the following most prominent solutions: the use of biobased materials (for construction); changing the inflexible way of building; using urban mining materials; create new legislation to make circular construction more profitable; and finally, use 'Environmental performance buildings' to do this. These solutions are overall in line with the solutions often mentioned in literature.

An overview of the answers were given in Table 8, in which the answers per person are categorized and an average opinion is given using color codes.

Table 8 - Outcomes interview question 2: circular solutions incl. legend

	Marijn Sauer	Tom Blankendaal	Floris Schiferi	Dora Vancso	Menno Schokker	average opinion
Biobased Materials	++	++	++	++	++ -	++ ++/+
Change the design/construction method (Modular, Flexible, adaptable)	++	++	++	++	+	++/+
Urban Mining	++	+/-	++	++	+	++/+
Embodied emissions	+	+	++	++	+	++/+
Change in rules and regulation	+	+	++	++	+	++/+
Extension of buildings lifespan	+	+	++	+	+	+
Lowering 'Environmental performance buildings'	+	+	+	+	++	+
Subsidy or fine	++	+		+	++	+
Smaller housing	++	+/-	+	+	+	+
Upscaling supply chain recycled construction materials	+	++		++	+/-	+/(+/-)
Transparency on supply and demand of materials	-	+/-	++	+	+/-	+/-
Using the Building Circularity index	-	++		-	+	+/-
Material passport	+/-	+		-	-	-
Reverse design process (design with secondary materials)	+	-	+	-	--	-
Product as a service	+/-	-		--	-	-

legend

(dark green)	Agree: interviewee volunteers with the solution him- or herself.
(light green)	Agree: Interviewee agrees with solution after it was presented
(light yellow)	In doubt: Interviewee agrees that the solution could have sufficient impact, but doubted its implementation
(light pink)	In Doubt: Interviewee has doubts about the possible impact.
(orange)	Disagree: Interviewee disagrees that this solution could have sufficient impact
(grey)	No answer: Interviewee was not asked or had not enough experience in this subject.

The most frequently mentioned solution is the use of biobased (and other low impact) materials, a subject that every interviewee mentioned as 'very important'. Schokker argued that the reduction of concrete, by replacing it with Cross Laminated Timber (CLT), should be the number one priority, and added that the impact of changing the façade and insulation is small and should not be a priority. Blankendaal explains that for low-rise (including apartments up to 4 stories high) a completely wooden structure is possible, but that for high-rise in practice often hybrid structures are used such as CLT-concrete or CLT-steel to ensure stability. Schiferi stresses that biobased is only a good solution as long as the energy needed for extraction and production is renewable and adds that the supply chain needs to be scaled up to create efficiency and affordable products.

A point that Sauer, Blankendaal and Schiferi make is that the goal, when using virgin materials, should be using materials with a low carbon footprint rather than just stating 'biobased materials'. Sauer states that overall, biobased materials result in a lower carbon footprint compared with abiotic materials. Therefore, taking the environmental impact of the whole lifecycle of a project into account is important when selecting materialization. Schiferi states that even though "he believes fully in biobased materials; the embodied energy is an important side note". The embodied emissions are a measure of the CO2 emissions produced by generating the energy needed for extracting, producing and transporting materials. Schiferi states that it is nonsense to state that biobased materials are in themselves environmentally friendly. Rather, they are biodegradable and come from natural sources. He believes that biobased can only be a sustainable solution if energy needed for production is also renewable.

Schokker adds that the production of concrete needs to become more sustainable. Because even though CLT is a good alternative to concrete, not all concrete will be replaced. He also mentions that when looking at the building from a life-cycle-perspective the next most impactful elements are installations (e.g. ventilation and heating installations) and glass.

Changing construction methods by a building technique that is more adaptable is also considered 'very important' by all interviewees. The most important aspects that were mentioned are: 1) designing for a long lifespan; 2) designing in flexibility, allowing functions to change without demolishing and 3) using standardized prefabricated elements.

Schiferi suggest taking this further and wants to pledge, together with a group of architects, to use only a certain set of materials in their designs. This would make reuse and designing with secondary materials less complicated. Their main message is that current construction methods are not circular. However, the methods, and terms and solutions proposed by experts differ. Different solutions that were mentioned are: transformable, standardization, modular, dismountable, adaptable and flexible.

Almost all the persons interviewed propose Urban Mining as a good solution. However, Blankendaal states that this can only work if supply chains are scaled up, like *New Horizon* has done. Sauer thinks that this is only a good solution when the secondary material is designed in a way it can be dismantled at the end of the life cycle. She also states that the quality of the recycled material needs to be good enough for the lifespan of the building. Schiferi disagrees by stating that "also low-quality material should be used, as they are already produced."

On the solution of smaller housing the opinions were divided. Three experts think it could work, two believe that the solution could have impact on the abiotic material demand, but doubt whether this will be accepted by consumers. According to Schokker downsizing housing is already happening in practice, driven by high prices and lack of space in inner cities. Blankendaal states that resident's acceptance of this needs special care.

All persons interviewed agreed that rules and regulations play an important role in the transition to a circular construction sector. Schiferi states that "a 'total cost' approach needs to become standard in which the shadow costs of materials are included. As long as this doesn't happen, circularity won't be able to compete". Blankendaal and Vancso think that without negative economic incentives circularity will not come about. "The current economic system is not in order yet to give circularity a chance." According to Schokker this is why the transition moves as slow as it does.

Different versions of using rules and regulations are mentioned, but all agree on the necessity of lowering the ‘Environmental performance buildings’ (Dutch: Mpg) to incentivize circularity. ‘Environmental performance buildings’ is a tool to calculate the environmental impact of a product (further explained in the introduction). Everyone agrees it’s a good solution to promote circular construction. However, multiple side notes were presented regarding this tool. Sauer and Blankendaal state that right now the ‘Environmental performance buildings’ only includes the environmental impact of the material itself and not the detachability of the elements within a building. But according to Blankendaal, the government is working on including this element within the tool at the moment. Sauer argues that a limitation for the CO2 tax (which could be enforced using ‘Environmental performance buildings’) is that from all construction materials LCA’s will need to be carried out and the environmental impact quantified. Schokker also thinks ‘Environmental performance buildings’ is a very important tool as circularity lacks behind energy transition. Schiferi is curious to what extent it is going to stimulate. ‘Energy Performance Coefficient’ (Dutch: EPC; the energy variant of MPG) has led to a large increase in PUR insulation in the construction sector”. But also admits that ‘Environmental performance buildings’ goes a step further in including environmental impact and could be “a step in the right direction”.

Another solution within the realm of rules and regulations, suggested by Schiferi, is decreasing the tax on labor and increasing the tax on raw materials. Schiferi and Sauer both think that currently it is cheaper to get raw material internationally than to refurbish materials locally in order to use urban mined materials. Sauer states “even though we (as a municipality) want to create more jobs for people with a distance to the labor market”. Although Schokker agrees with the solution, he thinks it is even more complicated, because this has international implications and could lead to a negative business climate in the Netherlands and could eventually lower our competitive position within the world economy.

All the interviewees were presented with the question: subsidy or fine? This after Schokker stated that he notices that developers are more incentivized to increase the use of circularity solutions, when faced with a fine if certain circularity goals aren’t reached. Vancso’s opinion is the same as Schokker but she also adds that subsidies are also important to stimulate circularity/sustainability. Sauer and Blankendaal opt for subsidy rather than fines as this stimulates innovation more and gives frontrunners the opportunity to realize and scale up their innovations. Sauer assumes that “fines only work when there is a new status quo and the stragglers need to catch up. In contrast to the current situation where we want to pull people out of the status quo to create a more sustainable construction sector”. She believes that possibly in 2040 fines might be introduced.

The interviewed experts were divided on the usefulness of material passports. Blankendaal thinks that the it is “a no brainer”, Schokker also is “increasingly doubting it”, and calls it an “ideological idea”. Three persons (Sauer, Vancso and Schokker) mention that it does not have impact in itself and that it depends how it is used, but that the idea of knowing what materials a building consists of could be useful. But strict agreements are needed to ensure the passports are used at the end of the life-cycle (Schokker). Blankendaal thinks it also useful for their company to have all the project data clustered and ready in case of maintenance and repairs.

The solution which received the least enthusiastic response was product-as-a-service (PAAS). PAAS is a business model in which the producer remains owner of the product, creating an incentive to produce long lasting easily detachable products. According to Vancso this business model does not fit in the business structure of the construction sector. And according to Sauer this business model only works for products with a lifetime of maximum 20 years. In the experience of Schokker the desired impact was not reached, and the same product is leased instead of sold.

Other solutions, like reversing the design process, upscaling the (circular) supply chains and transparency of the supply and demand for secondary materials were mentioned in the interviews only by one person but others did not have a strong opinion. More information on these in Appendix D.

The answers to the third question on the role of the municipality in transition toward a circular construction sector are discussed in chapter 5.2.1 (recommendations for the municipality) and the full answers can be found in appendix D.

3.3 Modeling impact of circular solutions (quantitative)

In the third and last step of my research, the impact of five circular building solutions was quantified. First the research on the potential of Urban Mining materials was expanded and followed by a scenario in which the loadbearing structure is replaced with a wooden alternative. Finally, the fit-out of the building (e.g. facade and interior walls) are replaced with a biobased alternative, whereas in the fourth scenario the size of the apartments is decreased.

3.3.1 SCENARIO 1 - URBAN MINING

In the first scenario the potential of using urban mining materials is modelled. This the results of Verhagen et al. (2020), in which the supply of urban mining material released between 2020 and 2030 are modelled, and personal communication with the producing partners of the Urban Mining Collective about their production process. Their acquired Waste Material Collection Rate and the Recycled Content are presented in Appendix A 3.3.1.

Figure 4, on page 29, shows the overall reduction of the abiotic material demand by on average 52,000-tons per year, which results in a reduction of material of 19%. In this scenario the overall material demand remains constant but is replaced by urban mined materials released in Leiden as a consequence of the urbanization task.

The largest streams of recycled materials are concrete rubble (91%), brick (3%), steel scrap (2%), wood (2%) and gypsum (1%). The other materials constitute less than 1%.

Figure 10 shows the origin of each material used in this scenario and presents their reduction potential. This is a combination of the urban mining supply, the 'Waste Material Collection' rate, the 'Recycled Content' rate and the demand of materials in the business-as-usual scenario.

In this scenario, of the overall material demand 19% of the material comes from urban mined materials, 1% from other waste streams and 81% is virgin abiotic material. Of the remaining virgin material demand 4% is used for the required re-production of the urban mined materials. When looking per material different barriers can be identified.

For concrete and steel, the main barrier is a lack of supply of Urban Mining materials. Because the supply of these materials is already used, and much more is needed. The overall rates of this scenario are very comparable to the concrete rates, because concrete constitutes over 65-90% of the material demand. In this scenario concrete can be replaced for 20% with urban mined materials, whereas the recycled content rate is 85%.

The opposite is the case for brick, for which no virgin brick is needed because in every year there was sufficient supply, however still 14% of the total weight is virgin mortar needed for masonry. Secondary brick of Douveren is produced by using urban mined brick and ceramics in addition to glass and the slip fraction from other waste streams. Next, wood can almost fully be supplied by urban mined material and is supplemented with wood from other waste streams, whereby only abiotic glue is required for production. This low demand of virgin wood is mostly due to the low material use of material in high-rise apartment buildings. Aluminum is a material with high recycling possibilities, but the Waste Material Collection rate of the supply stream is low (50%). This is due to the low amount of aluminum within the window frames, according to CEO New Horizon P. Naaijkens (personal communication, June 7, 2020). Therefore, only 19% of the usable supply is used between 2020 and 2030 and 79% underutilized.

For glass and bitumen, the supply is sufficient, but the recycled content too low. Figure 10 shows that 40% of the glass demand can be supplied with urban mined glass and the remaining 60% is supplemented. This corresponds to the recycled content given in Appendix A 3.3.1. However, still 75% of the usable supply is underutilized, suggesting that if the recycled content would go up most secondary material could be used.

For bitumen it is the same story, with exactly the same recycled content of 28%. Overall, the recycled content rate is kept low to ensure the same quality as virgin material. However, personal communication with New Horizon and Icopal clarified that in the case of bitumen (and possibly other materials as well) the recycled content is deliberately kept low to ensure a bigger output of circular materials, as demand for these materials is growing faster than the supply of urban mined materials. (c. Den Hartog personal communication on March 26, 2020; P. Naaijkens, personal communication on June 7, 2020).

For gypsum, overall the supply is sufficient, but the fluctuations per year of the supply and demand of this material were too large and besides, the recycled content rate was relatively low as the urban mined gypsum boards are not reused by Knauf as the finished layer (Knauf, 2018). Knauf currently only reuses the gypsum boards and does not recycle the finishing boards.

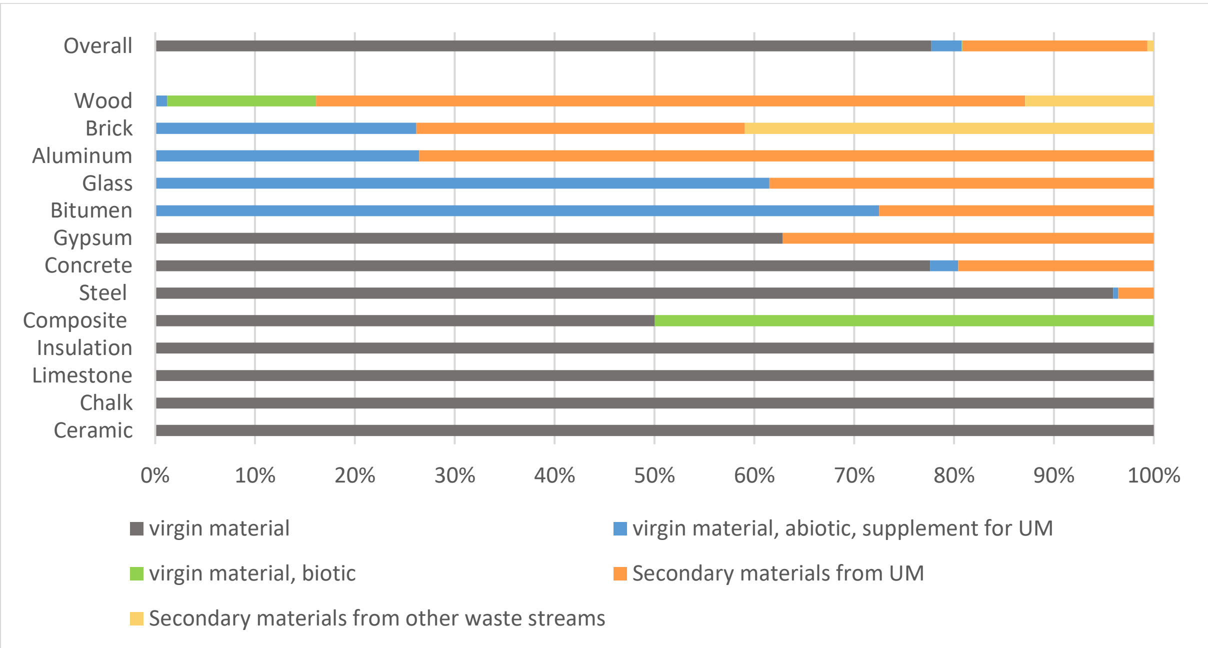

Figure 10 – Total material division for the urban mining scenario, per material type (%)

Whereas one fourth of the material demand can be replaced by urban mining materials, still 20% of the supply that can be high-grade recycled or reused is still underutilized. The largest flows of underutilized material streams are brick, ceramics and wood. This results to on average almost 17,000-tons material per year that could be used for construction. Only scrap steel and concrete rubble can be completely used again as the demand of these materials is so high and the recycled content is favorable as well.

The flow of unusable material is on average over 85,000-tons per year, which constitutes almost 57% of the total supply of urban mined materials. This consists mainly of roof gravel, residual flow of C&DW and the waste stream at the factory due to contaminants in the material flows. This can be considered as the other half of the Waste Material collection rate (1-MCR).

This scenario is based on what is currently being executed by New Horizon and is therefore technically, economically and socially viable, this can however be improved in the future. The potential of urban mining could be larger than assumed in this scenario. However, due to a mismatch in the type of materials, the occasionally low recycled content and fluctuations in supply and demand this is not yet realistic.

3.3.2 SCENARIO 2 – WOODEN STRUCTURE

The second scenario, replacing a part of the loadbearing structure with a CLT (wooden and therefore, biobased) structure, results in an abiotic material reduction of 43%, as can be seen in figure 4 on page 29.

This scenario shows a large reduction, not only in abiotic material but also in total material demand (37%), when comparing mass. However, the density of CLT is over six times lower than to concrete. The total volume of the building has actually slightly increased. This also explains that the total share of abiotic material for high-rise is still around 90% of the total demand when only looking at mass, and on average 75% for low-rise. This relatively high abiotic rate is because part of the construction is still constructed in concrete, for high-rise apartments only 40% of the concrete structure is replaced by CLT.

Figure 11 shows that the reduction of material intensities in this scenario differs per building type, the largest decrease is 80% for low-rise apartments and the smallest decrease is 35% for high-rise. The material intensity for apartments and row houses per floor area are the same, as well as that of semi-detached and detached dwellings. The change in reduction is due to the different data used. For all low-rise dwellings the detailed data of Sustainer Homes was used, whereas for high-rise a less ambitious CLT-hybrid example (HAUT in Amsterdam) was applied. High-rise is currently not often built in CLT and using this example was viewed most realistic. The HAUT example is based on using concrete up until the second floor and for the elevator shaft and CLT for the third until the nineth floor.

The difference in material intensity between high-rise and the other building types has become larger, due to the concrete-hybrid structure assumed for high-rise and the almost entirely CLT (with the exception of the foundation) structure of the low-rise buildings. This is because, for low-rise apartment buildings, a wooden structure is more common and can be, with the exception of the foundation piles, be constructed from wood. Whereas, for high-rise a CLT-structure has more complications, such as stability issues. For this reason, a hybrid structure was chosen.

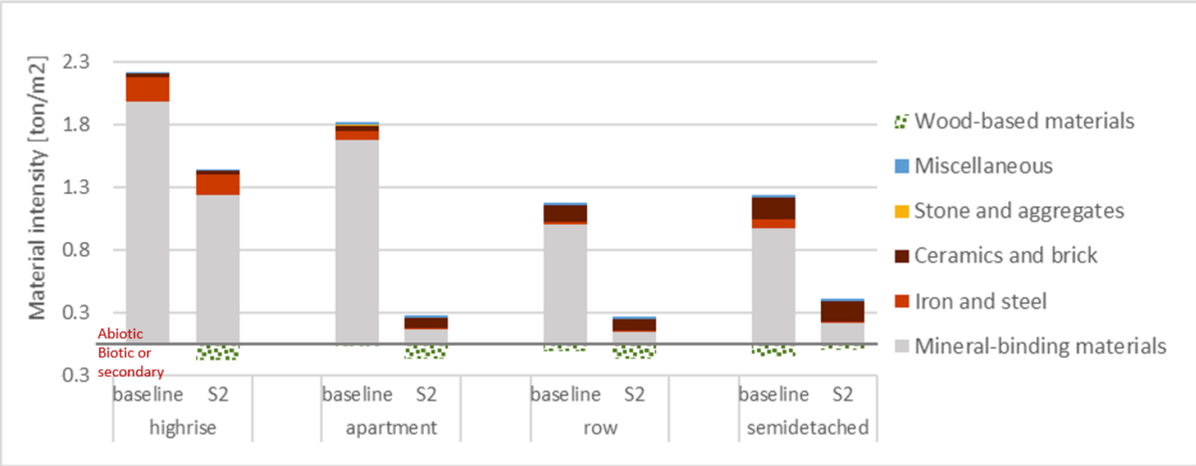

Figure 11 - Material intensity per building type - scenario 2: wooden structure [tons/m2]. Above zero-line virgin abiotic material, below biotic or secondary material.

Due to lack of data, the row house example of Sustainer Homes is used as second best, however this might not portray the reality of building a CLT apartment building. This scenario is based on data that is already being built in the Netherlands, however, more ambitious examples exist outside of the Netherlands and could be implemented in the future.

3.3.3 SCENARIO 3 – BIOBASED FIT OUT

The third scenario focused on quantifying the impact of replacing the materials of the façade (mainly brick), interior walls and insulation. The key result in figure 4 (page 29) shows an overall reduction of the virgin abiotic material demand of 7%. This is the lowest score of all five scenarios. This relatively low reduction is due to the small share of materials it is replacing compared to the total material demand. As explained in 3.3.2 the largest share can be attributed to structural materials. Materials that are reduced in this scenario are brick, limestone and abiotic insulation materials. All are replaced by biobased alternatives.

Figure 4 in Appendix A, figure 3 shows that the material intensity compared to the baseline decreases between 6% (for high-rise) and 18% (for detached). This difference is related to the share of façade material was larger in single-family dwellings and particularly in (semi-)detached dwellings.

3.3.4 SCENARIO 4 – SMALLER HOUSING

The fourth scenario, revolving around decreasing floorspace per housing unit, results in a 27% reduction of material demand compared to the baseline. For this scenario the multi-family dwellings are reduced to 40m2, which is considered a micro-apartment and the single-family dwellings are reduced with 25%.

3.3.5 SCENARIO 5 - NO BASEMENT

The fifth scenario is another social solution and looks at the impact of eliminating the parking garages under high-rise buildings which resulted in a reduction of 24% of the abiotic material demand. This solution has a relatively high impact due to the high share of high-rise apartment buildings in the construction plans of the Municipality of Leiden.

For this scenario only the materials needed for the basement walls and floors are considered. The reduction might be larger when also a part of the foundation piles and foundation is considered. This is however a very complex calculation and was not taken into account.

The material demand per scenario can be found in table 9. There the material demand is plit up in origin, virgin or secondary and abiotic or biotic. Also, the total GFA floor area demand and the total reduction per scenario are included.

Table 9 – Total material demand per category per scenario

Material demand in 2030	Baseline	S1 Urban Mining	S2 wooden structure	S3 biobased fitout	S4 downsize housing	S5 no basements	S6 cmbining all solutions	unit
Dwelling demand [m2 GFA]	131,944	131,944	131,944	131,944	96,300	131,944	96,300	[m2 GFA]
virgin material, abiotic, [ton]	275,106	223,898	155,926	256,213	201,197	208,957	23,861	[ton]
virgin material, biotic [ton]	1,171	201	17,333	4,477	841	1,171	10,688	[ton]
Secondary materials from UM [ton]	-	51,042	-	-	-	-	33,681	[ton]
Secondary materials from other waste streams [ton]	-	1,726	-	-	-	-	625	[ton]
total material demand [ton]	276,277	276,867	173,259	260,690	202,038	210,128	68,855	[ton]
reduction [%]		**18.6%**	**43%**	**7%**	**27%**	**24%**	**91%**	**%**

3.3.7 SCENARIO 6 - COMBINING SOLUTIONS

In scenarios one to five the impact of single solutions on the abiotic material demand are quantified, of which none of them reduce the virgin abiotic material demand enough to reach the absolute goal. Therefore, combinations of solutions are necessary. In this sixth scenario different combinations of solutions are modelled and discussed. Figure 12 shows scenarios of some combinations of solutions, starting with the most extreme combinations on the left side and less extreme on the right.

Scenario 6a is the most extreme sub-scenario where all the solutions of scenarios one to five are combined and resulted in a virgin abiotic material demand of 22,000-tons which is a reduction of 92%. In this scenario half of the total material demand is replaced by urban mined material. However, even in this most extreme scenario in some years there is not enough supply of urban mined concrete.

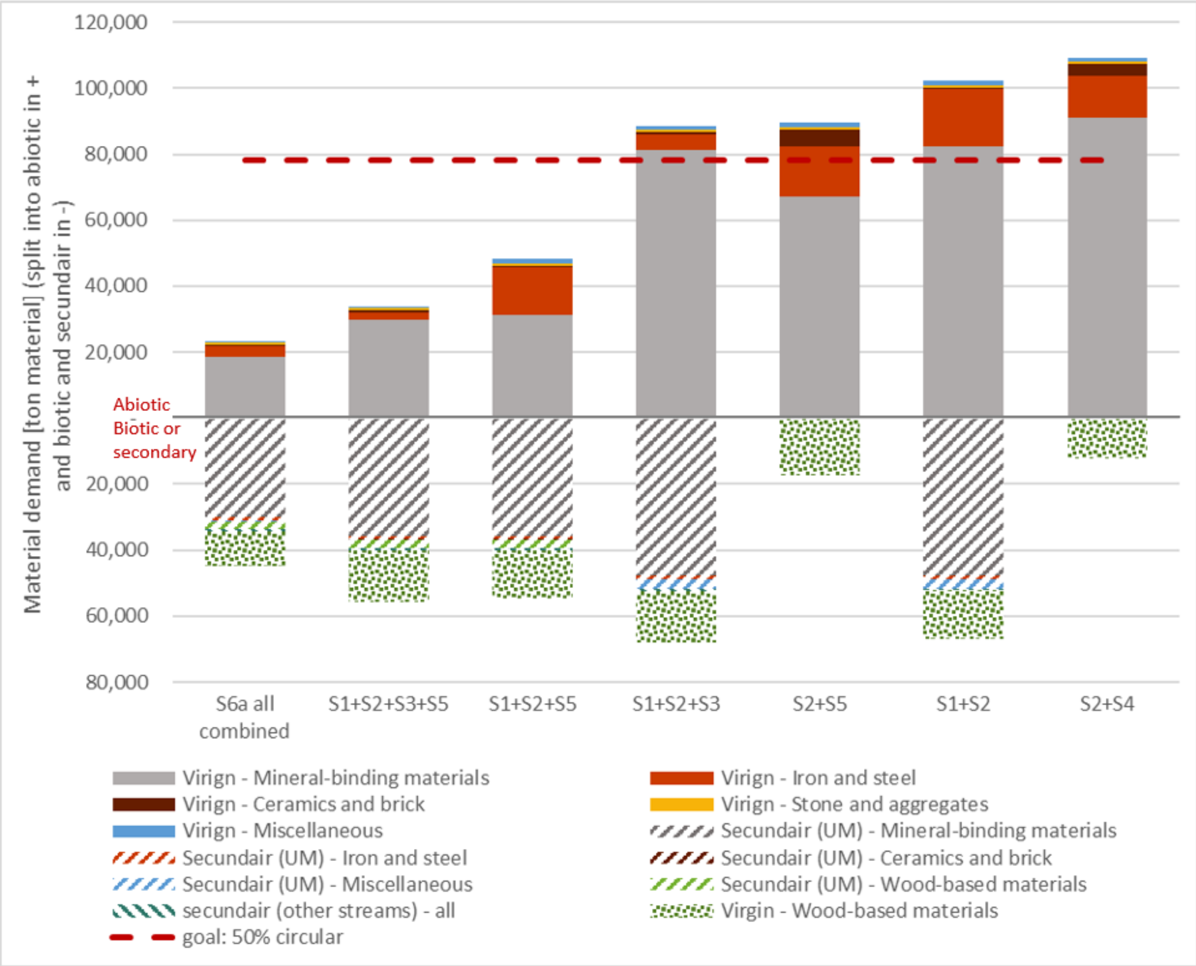

Figure 12 – The material demand of combinations of solutions (S1: Urban Mining; S2: Wooden structure; S3: Biobased fit-out; S4: Downsizing living space; S5: Excluding parking garages under high-rise buildings). Above zero-line virgin abiotic material, below biotic or secondary material.

Scenario 6b is similar to the previous scenario besides that the smaller housing solutions are taken out, because in the current social and political context this is most unlikely to happen. However, figure 12 shows that in this scenario the absolute goal can still be reached with a total material reduction of 91%.

In the Scenario 6c the wooden structure solution is combined with the reduction of parking basements which results in a reduction of 82%, which, as figure 12 shows, still reaches the absolute goal. Compared to 6b in this scenario, the least impactful solution of changing the fit-out to biobased alternative is taken out. This comparison shows the non-linearity of the model, as in section 3.3.3. the solution had an impact of 7% which is now reduced to 5%. If only half of the parking garages would be cancelled, this sub-scenario would result in a reduction of 73% and the target would still be reached.

Scenario 6d demonstrates the impact of the three material related solutions: urban mining (S1), wooden structure (S2) and biobased fit out (S3) and results in a reduction of 68% of materials. This scenario only barely does not achieve the absolute goal and shows that with only material related solutions have a big impact notwithstanding.

The last three sub scenarios, scenario's 6e to 6g, are the combinations of only two solutions that reach the highest impact. Table X shows all combinations of solutions in matrix form. Scenario 6e reaches almost the same reduction of 67% abiotic material as scenario 6d, because it is a combination of scenario two, wooden structure and scenario five in which the basements are eliminated. The wooden structure scenario impacts the material demand above ground but not that of the basement. Leaving these out can therefore have the same impact as in the original scenario. Sub-scenario 6f, which is a combination of urban mining (S1) and wooden structure (S2) reaches a reduction of 63%. Sub-scenario 6g, finally, combines the wooden structure (S2) and the downsizing of living space (S4), leading to a reduction of 60%. All other combinations are smaller than 50%.

Table 10 – reduction of combinations of scenarios on the virgin abiotic material demand

	S1	S2	S3	S4	S5
S1	19%				
S2	63%	43%			
S3	24%	50%	7%		
S4	46%	60%	32%	27%	
S5	43%	67%	31%	45%	24%

3.4 Sensitivity analysis

For the sensitivity analysis the effect of some interpretation and robustness of the model were checked. The sensitivity analysis goes into the following parameters: 1) the effect of a relative goal 2) the density of concrete; and 3) calculating in volume instead of mass. The impact of the relative goal on the scenarios, as well as the impact of volume instead of mass, is further evaluated in the discussion.

3.4.1 RELATIVE GOAL

The results of this research were all compared to an absolute goal, which does not change when the demand changes. However, when the circularity goal is translated in regulations for practice, especially at a local scale, a relative goal might make more sense, because it is more compatible with the building concepts of the market. Figure 13 shows how the material demand, in the case of a relative goal, differs for three building types. This does not take into account the increasing dwelling demand, which would make it impossible to reach the absolute goal. Therefore, the downsize housing scenario (S4) is not included. The figure shows that for high-rise apartments the relative goal cannot be reached, most of all because no single solution is able to reduce the structural material demand. Row and detached dwellings can reach the goal if the structure is altered to a wooden alternative.

The overall conclusion is that a relative goal is easier to reach with the growing dwelling demand but harder to reach when the housing market would crash due to the effects of Covid-19. A downside to the relative goal interpretation is that the size of the dwelling will not matter, although in reality it most likely will.

Figure 13 – results scenario on the relative goal [kg/m2 GFA]]

3.4.2 VOLUME INSTEAD OF MASS

When the material demand is converted from mass to volume the relative share of materials change as well as the impact of the solutions. Figure 18 shows a reduction in the baseline of 'mineral binding materials' and especially 'steel and iron', and an increase of 'miscellaneous', which used to be on average 2% of the mass but is converted to 17% of the volume. This is caused by the large volume of insulation in the building with a low density. This causes the impact of the third scenario, in which the fit out is replaced by biobased variants, to have a bigger impact than before (19% abiotic material reduction compared to 7% in the main model). In both the main model as well as the sensitivity analysis the absolute goal is reached when all five solutions are combined.

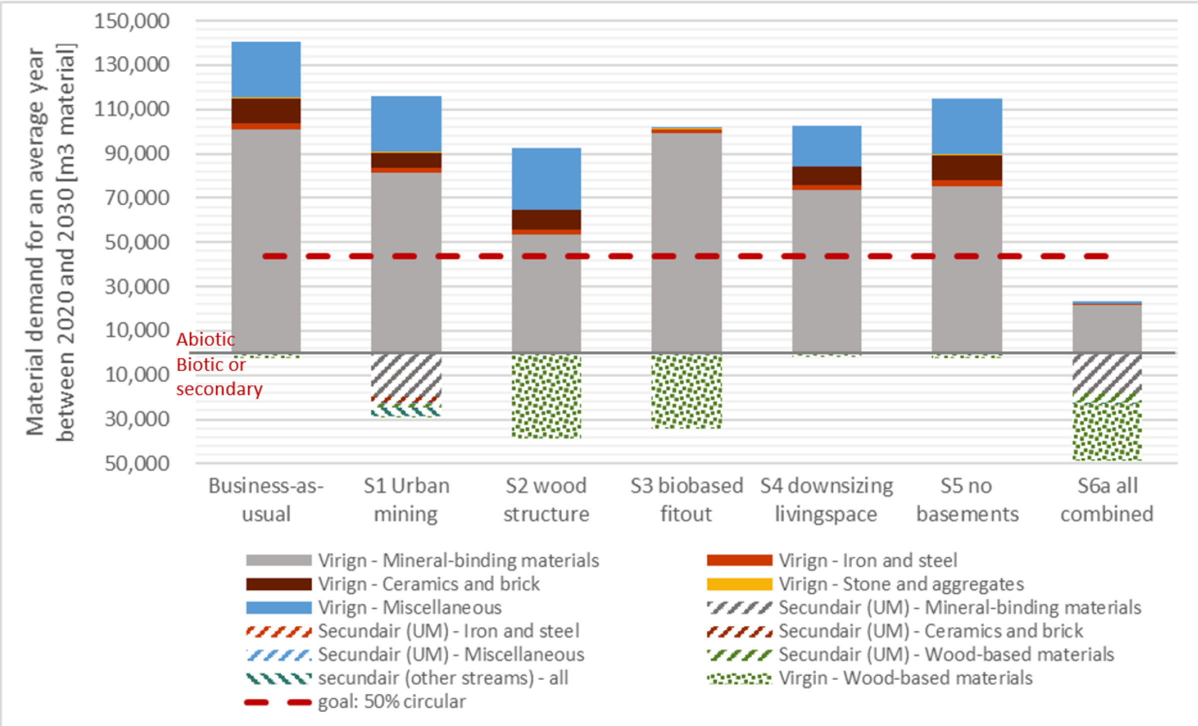

Figure 18 – key result in m3/m2 instead of tons/m2

3.4.3 DENSITY CONCRETE

When the concrete density is altered from 2500 kg/m^3 to 2100 kg/m^3 the baseline changed form a material demand of 275,000-tons to 239,000-tons in the average year of 2030. The difference in material intensity is 117 kg/m^2 for row house and 249 kg/m^2 for high-rise.

The impact of the scenarios only changed a maximum of 3.6% compared to the main method. The biggest reduction change was from the elimination of basements scenario (S5), which changes from 24% reduction to a 28% reduction of virgin abiotic material demand compared to the baseline. This can be explained because this scenario is mainly dependent on the reduction of concrete, therefore the change is largest for this scenario.

4. INTERPRETATION AND DISCUSSION

The goal of this study is to determine what solutions are necessary to reach the Dutch circularity goal (to reduce the virgin abiotic material demand with 50% by 2030 compared to 2016) as well as the urbanization goal (to build over one million dwellings to cope with the housing shortage between 2016 and 2030), and to get a better understanding of the impact different available circular building solutions. This study has taken a case study on the city of Leiden to determine the circular solutions required to reach both goals. Previous studies have focused on the environmental impact of certain options, but to my knowledge no study has focused on quantifying, comparing and combining the impact of different circular building solutions. Nor has any study looked into how the Dutch circularity goals can be reached in 2030. This study aims to do both.

This study is a combination of qualitative and quantitative methods. The first step was to determine the business-as-usual scenario, followed by interview results pertaining to circular construction solutions and ending with quantifying the impact of some of these solutions. A unique aspect of this study is the combination of academic and practical data and information, leading to a better understanding of future demands. The solutions of which the impact was calculated are: 1) using urban mined material sources in Leiden related to the urbanization task; 2) replacing the concrete and steel structure of buildings partly by wood; 3) replacing fit-out materials with biobased alternatives; 4) downsizing floorspace dwellings; 5) eliminating the (parking) basements; and 6) combining the five previous solutions in different variations.

The circularity goal can be interpreted in different ways. The key results are mainly based on an absolute goal, for which the end goal will not change also when demand changes. This makes it harder to reach in combination with the urbanization goals. According to the databases of the Municipality of Leiden the Gross Floor Area (GFA) demand in 2016 was 84,321 square meter GFA. This means that if material intensity would stay constant, the aim would be to build a maximum of 42,161 square meter GFA. However, the plans are to create an extra 131,944 square meter GFA between 2020 and 2030. For an absolute goal this would mean a decrease of the virgin abiotic material intensity of 72%.

4.1 Key results

The analysis in this thesis shows that the goal of 50% circularity is technically possible, while also reaching the urbanization goals. As figure 4 (page 29) shows, by combining the four different solutions even a reduction of 91% of the virgin abiotic material demand compared to the business-as-usual scenario.

This thesis determined that the largest impact on the virgin abiotic material demand, with a reduction of 43%, is to be found in (partly) altering the load-bearing structure of a building by a CLT (engineered wood) alternative (scenario two). This was to be expected, as 60-83% of the total material demand of the business-as-usual scenario is used in the structure (see appendix A, 3.1.1). The remaining concrete (on average 340 kg/m2) is used as the foundation and stability of high-rise buildings.

The results of the second scenario are in line with the results from the interviews, in which Schokker states "The first priority is concrete; We need to make the concrete sector more sustainable as well as try to replace it with alternative materials, such as CLT." And all others agree that using more biobased materials are one of the most important solutions.

Furthermore, in the wooden structure scenario, the total material demand has significantly decreased as well, at least in terms of the mass. The total volume of materials, however, has slightly increased, as the density of wood is 5.5 times lower than concrete and 17 times lower than steel (appendix A, 3.1.1).

The solution with the second largest reduction - 27% of the virgin abiotic material demand - is the elimination of parking lots underneath high-rise buildings. This percentage is high because 80% of the dwellings will be built with more than five floors and parking garages are responsible for 28% of material intensity of the high-rise apartments. Therefore, a change in mobility (e.g. more public transport or shared cars) will also benefit the circularity of construction.

The urban mining scenario (Scenario 1) resulted in a reduction of 19% of the virgin abiotic material demand, by substituting part of the virgin abiotic demand with secondary (recycled) materials. Of the remaining 81% virgin abiotic material, 4% is used for the refurbishment of the secondary material. However, still over 55,200 tons (which is 19%) of the usable supply will not be used in this scenario due to a mismatch of materials or low recycled content. This mismatch is caused by large demand of certain materials, such as concrete and steel, and a low demand, but high supply, of other materials, such as brick aggregates, bitumen and wood. Besides that, this scenario is based on the material released related to the urbanization task in Leiden. When incorporating other construction waste streams, or on a larger temporal scope the decrease can be higher.

However, some materials demanded for new construction are currently not recovered, such as insulation material and lime-stone brick. Urban mining could be improved by optimizing the number of clean streams during demolition, which increases the recycled content and makes buildings easier to disassemble. Currently there is no separate stream of insulation material, due to low quantities (Sauer, 2020). Also, rules and regulations regarding urban mined materials could benefit from an increase in recycled content.

Currently some materials have a low recycled content, due to quality issues. But as CEO of circular demolishing company, New Horizon, P. Naaijkens (personal communication, June 7, 2020) states: occasionally the recycled content is deliberately kept low to be able to sell as much ‘circular’ material as possible. Because due to a lack of regulation currently every product, even with the least traces of secondary material, classifies as ‘circular’. Lastly, from the interviews and personal communication it was concluded that the current way of constructing is challenging to adapt and disassemble, which causes contaminations in the secondary stream and/or a more expensive demolition process.

This urban mining scenario is based on practical data, meaning that these numbers are what is not only technically but also economically and socially currently acceptable. However, much can be improved. More different streams of material could be extracted if this would become economically viable. Moreover, technical developments can improve the recycled content. However, personal communication with New Horizon and producing partners revealed that currently there is more demand than supply which results in producers keeping the recycled content deliberately low in order to sell more ‘circular’ products. This suggests that in the future these practices should be more regulated, but also that more than the current scenario is possible.

Scenario three, in which the façade finish, insulation and interior walls were replaced by biobased alternatives, gave a total virgin abiotic material reduction of 7%. This is in line with what Schokker stated in the interview that changing anything, but the structure is “rumbling in the margins”. This is especially the case for high-rise.

The fourth scenario, decreasing livable floor area, resulted in a 24% decrease of virgin abiotic material demand, simply because less floor area is built. This scenario changed the average UFA of multiple-family dwellings from 75 to 40 square meter and downsized the single-family dwellings with 25%. This reduction is only applicable in case of an absolute goal, because the relative goal would be a limitation on material use per floor area. Therefore, a reduction of floor area would not impact the relative goal.

The reduction of living space and the elimination of parking garages requires a social and cultural change, and even though these have the potential to decrease the material demand and therefore the environmental impact, they are almost never mentioned. Smaller housing could especially be interesting for young professionals who nowadays are not eligible for social housing and for who the private rent/buy are getting increasingly more expensive. People stay single longer and shared housing could be interesting for this target group. However, for families the idea of living smaller is probably not the most attractive idea.

As with none of the scenarios the absolute goal was reached, the sixth scenario looked into which combinations of solutions would make the absolute goal achievable. A variety of different sub-scenarios were modelled. The most extreme sub-scenario, combining scenario's 1-5, resulted in a reduction of 91% of the virgin abiotic material demand compared to the baseline. But with the combination of the urban mining, wooden structure and halving the parking space under high-rise buildings a reduction of 73% is achievable, just enough to reach the absolute circularity goal.

OTHER SOLUTIONS AND APPROACHES

Apart from the quantifiable material impact, additional solutions can support the transition toward a circular construction sector, the main one being a different building method. Currently the construction practice is not designed for alterations or demolition, because this is not part of the business-case of architects and contractors. Also, in the interviews a more flexible and adaptable design method was one of the most acclaimed solutions. However, the impact is not as direct as other solutions and could not be quantified in this thesis. Furthermore, because the average lifespan of a building is longer than 10 years, we will not notice the effects in the short term. But, according to the experts, the impact in the long run could be significant. This solution can be seen as a system change, while the other solutions only try to reduce the impact of the current, linear, way of construction.

GLIMPSE TOWARD 2050

The main challenge for reaching a fully circular residential construction sector in 2050 is establishing stable high-rise buildings, especially in their foundation and basements, because currently these elements require a large proportion of concrete and steel. The stability in high-rise is now supplied by a concrete base and elevator shaft. Although high-rise buildings with a fully wooden structure do exist (Block, 2019), this needs to be further researched.

Another challenge is the foundation of all building types. As constructor N. Breuer (Personal communication, July 13, 2020) stated, in Leiden on average pile foundations are used, with an average pile length of 18,5 m. Historically foundation piles were constructed of wood but due to subsidence, decay and limited length these were gradually replaced with concrete. And as seen in step 1, foundation piles result in on average 67 kg/m2 GFA which is 6% of the total concrete demand.

INTERPRETATION OF THE GOAL

The goal is stated as an absolute goal by the Dutch government in the report "Circular in 2050" (2020) and was therefore as such interpreted in this research. However, this results in a confusing goal for practice for which a relative goal is possible easier to follow as this is more straightforward. However, the absolute goal in this research demand a reduction of 72% of the virgin abiotic material demand, which is much more ambitious as the 50% reduction the relative goal would provide (see section 3.4.1). It can be questioned that with the expected growth of dwelling demand a relative goal should be implemented stricter to reach the same result as the absolute goal. The overall conclusion is that a relative goal is easier to reach with the growing dwelling demand but harder to reach if the housing market would crash due to Covid-19.

The absolute goal, set by the government, was based on 2016 because in a couple sources this was named. However, this has not been widely announced by the government themselves, yet. A difference in base year would also have a significant impact on the goal, especially for the residential sector, because construction has increased. Also, on national level there might have been build more or less relatively to Leiden, which also changes the goal.

SCALE UP TO NATIONAL LEVEL

Because this study focused at the local level with specific building plans, the outcomes cannot precisely be extrapolated to the national level. However, they do tell us something about trends and the overall impact of different scenarios should be more or less the same.

After Den Haag, Leiden is currently the most urbanized municipality of the Netherlands and is therefore forced to densify at an earlier stage compared to other Dutch cities. Therefore, of the total floor area plans of Leiden 80% are constructed as high-rise buildings, which is much more than in other Dutch regions, especially rural regions (Neprom, 2018) Because high-rise is responsible for the largest material demand so without this the goal should be easier to reach.

As a large part of the material demand is caused by the high-rise plans of Leiden, which are also needed because the city is situated in the middle of the 'green heart'. This 'green area' is the rural space between the four major cities that together constitute the Randstad (Amsterdam, The Hague, Rotterdam and Utrecht) in which no more grass land will be given up for the building of cities or villages. This means that new housing and commercial buildings need to be realized within the city limits.

FURTHER DISCUSSION POINTS

The wooden structure scenario (2) especially, but also scenario 3, rely heavily on the production of wood and/or other biobased materials. These solutions do not deplete finite resources, but these materials do have environmental impact notwithstanding (a fact also stated by many interviewees). Furthermore, it raises the question whether there is enough production forest and cultivation land in the Netherlands to supply the wood and other biobased alternatives needed for these structures.

In recent years several large construction companies have stated that at this rate the urbanization plans will not be reached by 2030 (Neprom, 2018; NU.nl; 2019). The Corona crisis will likely make the expected shortfall even worse. Therefore, the urbanization ambitions may not be fully realized, which means that the absolute circularity goal will also be easier to be reached.

4.2 Previous studies

No previous study has compared the impact of circular construction solutions. Therefore, no comparison could be made pertaining to the key result. The intermediate results, however, can be compared. In this subchapter will look at three intermediate results: 1) The material intensity of derived from the BIM models; 2) Results of the urban mining scenario; and 3) the wooden material intensity of the wooden structure scenario.

4.2.1 MATERIAL INTENSITIES BASELINE

The results for the material intensity data are shown in table 11. In which MF stands for multiple-family dwelling and SF for single-family dwelling.

Overall, the total material intensity that this thesis has calculated is higher when compared to other studies, especially with respect to concrete. The main reason may be that the countries that previous studies cover use a different construction method or that the density of concrete of this study is indeed too high. In contrast to the material intensity of concrete that of brick is lower than most previous studies, whereas the material intensity of wood is further compared to previous studies in 4.2.3.

Table 11 – Material intensities from previous studies

Source	Case study	Year data used	Type of residential building	area type, unit	Concrete	Steel	Brick	Glass	Ceramic	Bitumen	Wood	other	total
Müller (2006)	Netherlands	1900-2100	average	UFA	2000								
Bergsdal et al. (2007)	Norway	1900-2001	average	UFA	621						72		
Heeren & Hellweg (2018)	Switzerland	2015	average	Not defined	920	33	280				40		
Gontia et al. (2018)	Sweden	1880-2000	SF	GFA	217	40	0				49	59	365
			MF concrete	GFA	749	135	38				19	37	
			MF wood	GFA	295	428	0	5			44		
Marinova et al. (2020)	World	1970-2050	Residential	UFA	1053-1726	30-106							
Ortlepp et al. (2018)	Germany	1918-2010	Residential and utility	Not defined	389-1336								
Han&Xiang (2013)	China	2000s	Urban area	Not defined	970	40	180	2			15		
Kleeman et al.(2016)	Oostenrijk	after 1970	average	Gross volume	127	5					3		
Ortlepp et al. (2018)	Germany	1991-2010	MF	Not defined	962	126	972			11	26		2231
Sprecher et al. (2020)	Netherlands	1945-1970	UM average	GFA	908	4	392	20	21	13	111	6	1487
			UM SF	GFA	686	4	388	20	21	12	157	6	1308
			UM MF	GFA	1129	3	397	20	21	13	64	6	1666
current study	Netherlands	2020	average all	GFA	1240	80	111	10	29	0	52	129	1666
			average lowrise (SF)	GFA	927	48	163	11	44	0	79	154	1399
			MF concrete	GFA	1711	129	33	7	6	0	12	93	1987

Sprecher et al. (2020) conducted a thorough evaluation of the material intensities in the secondary literature, which is used for the first comparison of previous studies. The most thorough evaluation could be done for concrete, as shown in Figure 19, which led to the on average 63% (detached dwelling) 88% (high-rise apartment) material intensity share in the model. Other material intensities are available for wood, steel, minerals, brick ceramic and glass.

The only study specifically for the Netherlands is Müller (2006) focusses mainly on concrete. It states that for concrete the mass per floor area has intensified from 0 in the year 1900 to 2000kg in the year 2000. This is almost twice as high than the average material intensity (of 1240 kg/m^2) of this thesis, but comparable when limited to high-rise apartment buildings (1910 kg/m^2). However, the results from Müller (2006) are in UFA instead of GFA used in this study. When multiplied with the UFA/GFA ratio the material intensity results in an average of 1700kg/m^2, which is still lower than Müller, but closer to it.

Marinova et al. (2020) predict the mass of the worldwide material demand until 2050. All their material intensities were in line with the averages in my study except for glass, for which my result was three times as high. However, it was easier to compare, because they provided a range instead of just one number.

Heeren and Hellweg (2018) quantify the future construction material demand for Switzerland between 2015 and 2055. When the total material input for 2015 is divided by the total floorspace their results are lower than the average of my analysis (1530kg/m^2 compared to 1670kg/m^2). Their material intensity does fit well with the low-rise model of my thesis. Especially for concrete (922kg/m^2) they almost equal my own results (927kg/m^2). The other material categories differ too much to make sense of, However, their average also includes renovation practices (20% of total area), which overall lead to lower material intensities (EIB,2020).

Gontia et al. (2018) examined the material demand for residential buildings in Sweden between 1880 and 2010. Interesting about this study is that it differentiates for different years and types of structures and dwellings. When the multiple-family concrete structure was compared, the numbers matched up really well, except for concrete, which was considerably lower than my average. This can be explained by two factors: the concrete density Gontia et al. (2018) is significantly lower (2100kg/m^3 instead of 2500 kg/m^3) and there is not always a (concrete) basement. Finally, Gontia et al. (2018) results in a lower brick material intensity because in Sweden in the 2010s the only façade material was wood and plaster.

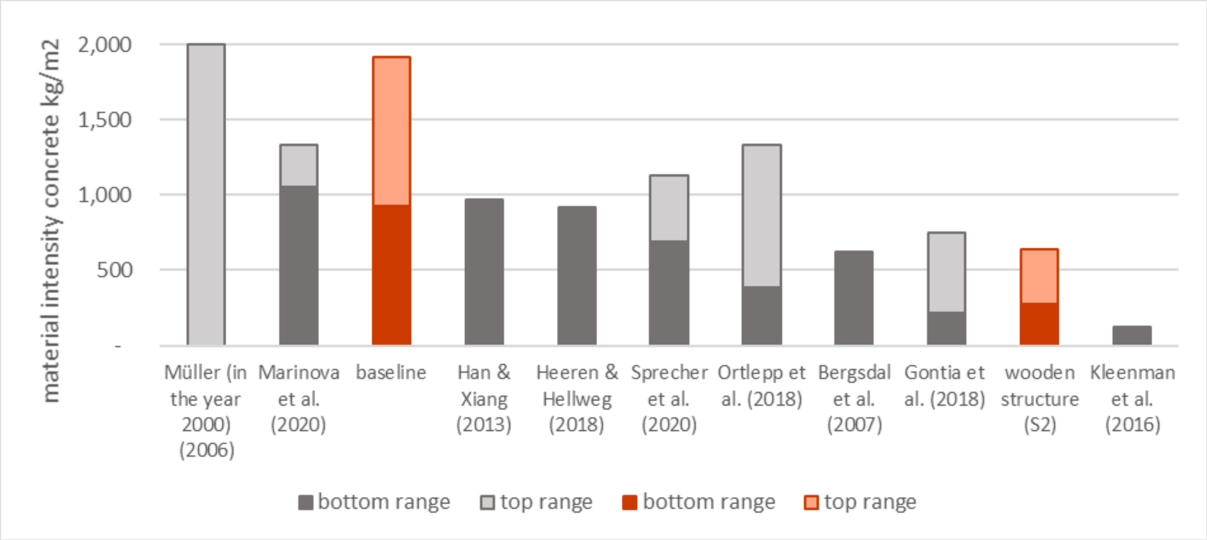

Figure 19 – Material intensity of concrete of previous studies compared to this thesis [kg/m2]

The overall higher concrete in my thesis could also be explained by the fact that parking garages are included in the high-rise apartments material intensity, which share in the total volume of concrete is 28%, which is comparable to Gontia et al. (2018) who mention a share of 35%.

Han & Xiang (2013) analyzed the change in material stock between 1978 and 2008 and their average material intensity for residential buildings in urban areas (using 2000s data) only partially matches with mine. In their case the total demand is lower, mainly due to a significantly lower concrete demand.

Bergsdal et al. (2007) studied the material demand of Norway's dwelling stock between 1900-2100 in which they used data of the range 1991-2001. Probably due to a different type of construction their material intensity does not fit with the average of my thesis. More on this in 4.2.3.

Ortlepp et al. (2020) examined the material in and outflow of multiple-family dwellings in Germany between 1918 and 2010, split into five different age categories. The material intensities of the most recent decade (1991-2010) is higher (2.2 tons/m^2) than the average of my model, However, the concrete is lower (962 kg/m^2) than my calculations. Brick is much higher, but this is explained by the fact that this material is used for building structures, whereas only lightweight concrete is used. The value for brick in table 11 is in fact a mix of brick, mortar and plaster.

Moreover, the overall higher material intensity of concrete can be explained because in my own model because I assume a 50-50 split between low-rise apartments and high-rise apartments, while these can also be interpreted as rowhouses that are split up into two apartments according to data controller of the Municipality of Leiden (D. Lucassen, Personal Communication). But in the new dwelling plans of Leiden such dwellings are not included. However, in previous studies these could still be included as these studies focus on a different time frame.

4.2.2 URBAN MINING POTENTIAL

The results in the Urban Mining scenario are based on a study by Verhagen et al. (2020), in which the Urban Mining potential was also examined for Leiden. This section compares the urban mining potential results of this thesis with Verhagen et al. (2020).

Verhagen et al. (2020) concluded a reduction in total virgin material demand (not per se abiotic material) of 40%, whereas in my model I assume a lower value, namely 19%. However, this difference can be explained quite easily. Verhagen et al. (2020) did not have access to current construction data, so instead gathered demolition data from Sprecher et al. (2020) as second best. The material for demolition data is, however, slightly lower and have a different material composition (see previous section on material intensities). This led to a lower total material intensity for almost all building types (see 4.2.1), resulting in a relatively low material demand. Next, this study took into account a more precise Waste Material Collection Rate. Whereas Verhagen et al. assumed 95% for all material, of which Personal Communication showed that this is often lower. At the same time there are different material categories in my model than in Verhagen et al. (2020), causing more of a mismatch of materials. Nevertheless, the material intensity in my study is more representative for the current construction needs and therefore offers a more realistic picture of the urban mining potential.

A study from the Economic Institute of the Built Environment (2020), analyzed the material streams in the Netherlands relating to the construction sector and concluded that in 2014, 41% of the building material could technically be used for new construction, a share that could increase to 59% by 2030. This is much higher than the assumptions in my model, which is can be explained by the fact that EIB (2020) included utility buildings as well and left out a loss in material within the recycling process. Another explanation could be that when looking at a national scale the fluctuations are relatively small and that the mismatch of supply and demand of material would therefore decrease.

4.2.3 WOODEN STRUCTURE

The most important uncertainty of the scenarios of my model is the assumed CLT dimensions for the construction of high-rise buildings in the second scenario, because only basic numbers could be found. In this section the material intensity of wood in the second scenario is evaluated. Figure 20 shows the wood intensities of some previous studies in which wood was taken into account. It shows that the literature is divided on the material intensity but that overall, the wooden structure scenario is higher than the average. The range of wood intensities found in the literature is rather wide, as shown in Figure 20. Some revolve around 100kg/m2 while others start at 20kg/m2. In my model a baseline for material intensity of 50 kg/m2 was calculated and these are in line with Heeren and Hellweg (2018) Han and Xiang (2013) and with the bottom ranges of Marinova et al. (2020) and Ortlepp et al. (2018).

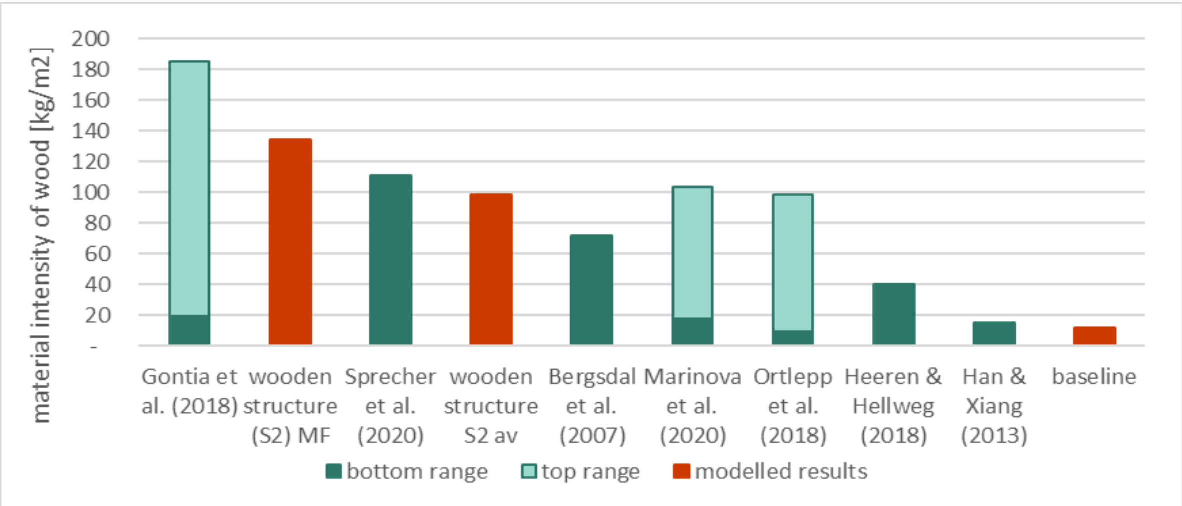

Figure 20 – Material intensity of wood of previous studies compared to this thesis [kg/m2]

However, the wood material intensities in the higher range are much more in line with the wooden structure scenario (S2). Interesting is that Gontia et al. (2018) and Bergsdal et al. (2007) both mention rather low concrete material averages, which is also in line with the second scenario. This can explained by the fact that the wooden structure is more common in Sweden and Norway, countries on which these studies are focused.

The study by Gontia et al. (2018) divided its results in material intensities for different structure types for multifamily dwellings, the overall result being a wooden material intensity of 180kg/m2, which is higher than the average in my model. Finally, in the wooden structure of Heeren et al. 2015 the mass was half of that of the massive (concrete) variant, which is quite similar to my model (58%).

4.3 Limitations

While this research fills a certain data gap in literature there are, like any study, clear limitations.

The main limitation of this study is that the material intensities rely on data of one project, which is especially for mid- and high-rise apartment buildings insufficient to describe the variety of construction methods and building shapes and sizes (J. Roeleveld, Personal Communication, June 15, 2020; Gontia et al., 2018). In an attempt to make it more inclusive, certain aspects were changed in the model to better represent the practice construction sector (more on this in 2.3.2). Nevertheless, a range of different projects would have given a better overview of the material demand.

Furthermore, when adapting the buildings in the scenarios four and six, the floor space in or outside the apartments is altered, resulting in a shift of UFA/GFA ratio. This ratio, however, was too complicated and project specific to alter based on one project and was left unchanged. Future research looking into downsizing floor area should take a closer look at this.

Even though the goal of this study was defined to find out how to reduce the absolute virgin abiotic material demand, this only portrays a part of circularity. The total environmental impact is something different and when we would have taken that into account, the results would have been different. Where the main mass can be ascribed to the structure, a big part of the environmental impact is attributed to installations (EIB, 2020).

This links with the next limitation, which is that in the 3D BIM models used to quantify the material intensities, the installations (and other small elements) are not included. These installations are often modelled in a separate model in a later stage of the project and were not included in the models evaluated in this research. This does not really impact the results of this research but does have implications for further research on the environmental footprint.

Furthermore, not taken into account is the total material consumption related to this product. The assumption is that the ratio of the final material demand and the resources extracted are similar. However, in reality this is not the case. The easiest way to take this into account is by including a Life Cycle Assessment (LCA) approach, but in my model cutting waste and construction waste is not taken into account.

Another limitation is that this study, due to time and data restrictions, only takes into account new buildings and not renovated ones, while this represents 30% of the total dwelling procurement. According to EIB (2020) renovation accounted for 8% of the material demand in 2014, which is relatively low as structure is kept intact, but the environmental impact (29%) was much higher. Again, this is due to the high impact of the installations which are almost always replaced when a building is renovated. Furthermore, in my model no attention is paid to the height of the building. Overall, the higher the building, the more material is needed for the structure and the less material for roof covering is needed. This is not included at the moment. However, in Leiden not many of the projects will be higher than nine floors.

A limitation of my Urban Mining scenario is that it is largely based on Verhagen et al. (2020) who used different construction plans and did not include the fall-out rates, due to the fact that construction projects were not executed. This resulted in 22% less dwelling units in my model and a lower supply of urban mined materials.

Another limitation regards the baseline, in which standard recycling rates of virgin material are not taken into account. This means that when for example glass wool contains 40% recycled glass, this is not reflected in the material intensity.

In the wooden structure scenario, a main drawback is that no averages were found for a CLT high-rise structure. And that for apartments the same material intensity is used as that of terraced houses. Although these can be built with the same structure, according to Technical Designer from Sustainer Homes M. Oskam (Personal Communication, July 8, 2020), the material intensities can still differ.

A limitation of the third scenario, which analyses the material related to the fit-out, the assumption was made that the biobased insulation materials would have the same volumes as the abiotic variant. However, the insulation value was overall slightly lower and around 1.1 times extra weight would have to be added.

Finally, a drawback of the combination of solutions in scenario six is that the uncertainty grows when multiple solutions are combined. This does not apply for all the solutions but for example the wooden structure. Thus, the exclusion of parking basements under high-rise apartments might not be possible when the wooden structure depends on it for stability. However, this is something that should be evaluated when put in practice.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This thesis revolves around the question how the circularity goals (50% virgin abiotic material reduction compared to 2016) as well as the urbanization goals (1 million new dwellings between 2016 and 2030) could be met by 2030. This thesis has tried to answer the main research question

To answer this question the city of Leiden was taken as a case study and answers the main question *"How can the circularity and urbanization goals be reached for the city of Leiden by 2030 and what circular solution has the biggest impact?".* The following three steps were taken to answer the main research question: 1) create a baseline of the total material demand for the residential sector, starting from the assumption that we continue to build in a linear way; 2) examine the consensus of circular solutions among experts; and 3) quantify the impact of certain circular solutions compared to a business-as-usual scenario.

The result of these steps is that the two goals are achievable only when multiple solutions are combined. The total virgin abiotic material demand for an average year between 2020 and 2030 would be around 155,000-tons in the business-as-usual scenario. The biggest impact came from switching the concrete loadbearing structure to a wooden (CLT) alternative, which leads to a reduction of 46% on the virgin abiotic material demand. The second largest impact resulted from converting the low- and high-rise apartments into micro-apartments in combination with downsizing the single-family dwelling size by a quarter, which leads to a reduction of 27% of the virgin abiotic material demand. Similar to this solution is excluding basements for parking under high-rise apartment buildings, which gives a 24% reduction. This is followed by the Urban Mining scenario, in which the released circular demolition waste is recycled/reused. This scenario had an impact of 19% on the total virgin abiotic material demand but is less difficult to implement compared to downsizing living space or parking spots. The scenario with the lowest impact was replacing abiotic material in the fit-out of a building, which only reduced 7% of the virgin abiotic material demand. When all solutions were combined the total reduction resulted in 91%, which clearly transcends the needed reduction, in case of an absolute goal, of 69%.

These results relate to an absolute goal, which is only one interpretation of the circularity goal. This research concluded that the interpretation of the goal has big implications for the impact of the solutions. The other form studied in this thesis is the relative goal which was concluded to be easier to reach in case of a growing dwelling demand. However, there is still a lot of confusion about the interpretation which does not support the implementation.

The results of the quantified part of this thesis were in line with the results from the interviews, where changing the structure was mentioned as "the biggest fish" by M. Schokker and changing the fit-out "rumbling in the margins".

Overall, the main impact is to be found in switching the concrete structure to a wooden (CLT) alternative. This solution in combination eliminating half the parking lots under high-rise buildings and moving toward urban mining as the standard demolishing process, in which as much secondary material is high-grade reused or recycled, would ensure that the absolute circularity goal is reached.

5.2 Recommendations

5.2.1 POLICY RECOMMENDATIONS

My recommendations for the sector to transition into a circular construction sector are to focus on the three main strategies.

First, pertaining to materials, to focus on the concrete structure. Replacing the structure by a (partly) wooden alternative has resulted in the biggest reduction with respect to the virgin abiotic material demand, in which swapping the floors with CLT makes the largest difference. This has a much larger impact than changing any other part of the building.

Second, would be to use what is already there by making urban mining a common part of the construction process and to standardize the product to increase the implementation in the market.

Thirdly, reduce the parking demand by moving toward different forms of mobility, such as more shared cars and more public transport to benefit the circularity goals. In total 28% of the weight of high-rise buildings is related to the parking garages in the basement. Especially one could consider reducing parking space in the immediate vicinity of the central train stations.

Fourth, change the design strategy. This solution is harder to apply and would demand systemic change. However, it is necessary for an economically viable circular construction sector in the future. The important part is that elements are standardized and that the design becomes more flexible, meaning that if the needs change, the structure remains the same.

Finally, the fifth solution would be to look into downsizing a part of the new dwellings and research the possibility for shared living for young professionals. Even though this solution is not socially and politically desirable, the impact could be substantial.

Furthermore, there is still a lot unclear about the circularity goal which should become clearer. First and foremost is the base year to which the 50% circularity goal is referring. Secondly whether the goal should be interpreted as an absolute or a relative goal, because a relative goal of 50% less material per kg/m2 would have less of an impact compared to 50% material demand compared to 2016, due to the growing dwelling demand. Also the indicator is important, because this can be interpreted as mass, volume or environmental impact (CO_2-eq.).

The most important chance for the municipality is creating an ambitious circular tender request. Here the highest aims can be set, and success stories and best practices gained, in order to move the remaining market toward a circular construction sector. In the interviews this also came forward as most important task for the municipality.

Another import chance for the municipality is to look into facilitating a construction material HUB for the region to help improve the business case of urban mining. This is already successfully realized in Amsterdam and Utrecht (Beelen, 2019).

5.2.2 FUTURE RESEARCH

This study is a step in the right direction However, it also resulted in more questions. This section will discuss possible further research.

Even though the material intensity data are sufficient for a first step in the analysis, there is much to be improved. A model could be made to more easily assess BIM data and gather more data points to improve the material intensities provided by this study. Also, data should be gathered from different construction companies as each company might build slightly different. Especially for high-rise buildings the uncertainty is larger, due to multiple ways of construction. The height of the building is now not taken into account, and the same is true for a wider variety in design compared to row houses. Also, the cutting waste and surplus waste on the building site is not considered. Another aspect that I left out, is the demand for raw materials instead of the final product. However, this is considered when incorporating the embodied emissions.

Which takes me to my next point: in future research the embedded emissions should be taken into account because this will result in different impacts and therefore alters the recommendations. As M. Schokker stated in the interview: “after concrete, glass and installations have the biggest environmental impact” (see appendix X), something that is not visible when only looking at the abiotic material demand. It could be interesting to see if this could also be coupled with the BIM models as is done in Rezaei et al. (2019).

This study has focused exclusively on new buildings, due to time and data limitations, However, renovation is an important part of the urbanization task and so is the energy transition. In 2014 this resulted in 8% of the material demand, and in 29% of the environmental impact of construction materials.

The main questions resulting from the scenarios is: is using CLT indeed the better option when taking the whole lifecycle into account? Can we produce enough wood for the construction sector, or should we rely on other countries for this supply and can this be considered ‘sustainable’?

Moreover, the scenarios are based on what is possible at this moment, but research in how to improve the current solutions could increase the impact of them. Especially within urban mining and wooden structure there is still a lot to gain.

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Sustainer Homes

M. Oskam, Technical Designer at Sustainer Homes, personal communication, July 8, 2020

Interviews

Tom Blankendaal, Project manager Circular Economy, Advies en Engineering at BAM

Marijn Sauer, Beleidsadviseur Circulaire Economie, Gemeente Leiden.

Floris Schiferi, Partner and Designer at Superuse

Dora Vancso, Circular Building Consultant at WE Adviseurs

Menno Schokker, Consultant at Merosch

Written sources

DATABASES

Municipality of Leiden

Excel spreadsheets called:

- 'Nieuwbouwmonitor' (NBM)
- 'Realisatielijst'

BAM

3D BIM models, drawings and calculations from building types:

- High-rise (124 dwelling units)
- Apartment building (48 dwelling units)
- Low-rise project containing (21 row houses, 2 semi-detached and 1 detached dwelling)

(specific project name not published but know to author)

Sustainer Homes

- "MPG – Detached Dwelling"
- "MPG – In-between dwelling"
- "Bill of Materials – In between dwelling"

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APPENDIX A – ADDITIONAL INFORMATION AND RESULTS

3.1.1 MATERIAL INTENSITIES

Material property data

Table 1 – Material density data			
code	**Weight in kg/m3 or kg/m2**	**unit**	**Source**
concrete	2500	kg/m3	BAM
concrete (basement)	2500	kg/m3	BAM
aerated concrete	1000	kg/m3	
steel (reinforcement)	7800	kg/m3	Engineering toolbox
Steel (structure elements)	7800	kg/m3	Engineering toolbox
aluminum	2700	kg/m3	Engineering toolbox
eps	53	kg/m3	Gontia et al. (2018)
PF-foam insulation	34	kg/m3	Gontia et al. (2018)
glass wool	60.00	kg/m3	Gontia et al. (2018)
Woodfibre insulation (rigid)	156.00		NDB
flax	33.66	kg/m3	Nibe
glass HR++ [m2]	22.5	kg/m2	Suppliers data *
triple glass	32.5	kg/m2	Suppliers data *
glass	2580	kg/m3	Gontia et al. (2018)
CLT wood	420	kg/m3	Brander et al (2016)
wood (window frame)	650	kg/m3	Brander et al (2016)
wood (spruce)	455	kg/m3	Gontia et al. (2018)
solid wood	780	kg/m3	Suppliers data *
multiplex	427	kg/m3	Gontia et al. (2018)
chipboard	600	kg/m3	Nibe
Gypsum board	732	kg/m3	Gontia et al. (2018)
Cempanel	1250	kg/m3	Suppliers data *
volspaanvulling	190	kg/m3	Proxy from brick
brickstrips	2000	kg/m3	Proxy from brick
cempanel + brickstrips	1625		Proxy from brick and cempanel
chalk mortar	1600	kg/m3	Gontia et al. (2018)
brick	2000	kg/m3	Douveren (personal comunication, 2020)
mortar	50	kg/m2	Douveren (personal comunication, 2020)
trespa	1400	kg/m3	Suppliers data *
wood finish	510	kg/m3	Suppliers data *
Sand-lime brick	1900	kg/m3	Gontia et al. (2018)
gypsum block (normal)	800	kg/m3	Suppliers data *
gypsum block (heavy)	1260	kg/m3	Suppliers data *
RVS	7930	kg/m3	Suppliers data *
Clay bricks	1200		Nibe

paintwork	1600	kg/m3	Gontia et al. (2018)
Tile (floor)	1700	kg/m3	Nibe
Tile (wall)	2650	kg/m3	Nibe
Screed layer	2150	kg/m3	Suppliers data *
Sand-lime brick	2275	kg/m3	Suppliers data *
bitumen	1,050	kg/m3	Suppliers data *
rooftiles	48	kg/m2	Suppliers data *
EPDM	1,237	kg/m3	Suppliers data *
gravel	1850	kg/m3	Gontia et al. (2018)
holonite	1860	kg/m3	Suppliers data *

* links to supplier data can be found in appendix B, tab prop

Go-GFA ratios per building type (from BAM models)

Table 2 – GO/GFA ratio per building type					
Building type	High-rise apartement	apartment	row	semidetached	detached
UFA/GFA ratio [%]	48%	67%	94%	83%	83%

Material intensity per element per building type

Table 3 - Material intensity per element per building type

Table 3 - rate of material intensity per function						
	high-rise apartment	high-rise apartment	low-rise apartm	row	semidetached	detached
structural basement	26.6%					
structural	60.9%	83.1%	82.5%	70.6%	63.6%	61.9%
Facade	1.5%	2.1%	3.6%	10.6%	16.3%	21.0%
Floor finish	3.6%	4.9%	7.3%	8.8%	8.2%	6.8%
Interior walls	6.7%	9.2%	5.6%	4.5%	7.5%	6.2%
Roof	0.3%	0.5%	0.8%	5.2%	4.1%	4.0%
elements	0.3%	0.4%	0.3%	0.4%	0.3%	0.1%
total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Distribution concrete per building type

Table 4 - Distribution concrete per building type					
concrete	concrete in high-rise apartment	concrete in low-rise apartment	concrete in row house	concrete in semidetached	concrete in detached
Basement foundation poles					
Basement walls	35.86	-	-	-	-
Basement floors	552.14	-	-	-	-
Foundation piles	163.12	31.51	50.91	57.66	97.32
Foundation	39.59	42.61	83.42	105.91	50.70
Walls	139.29	192.77	240.88	160.60	214.41
floor	897.55	1,062.38	357.17	414.11	621.21
column	26.40	-	-	-	-
prefab	84.20	48.32	-	-	-
mastiekrand	-	0.34	-	-	-
dekvloer	80.35	129.55	102.82	105.00	117.74
Walls (interior)	-	0.34	-	-	-
total	2,018.50	1,507.82	835.20	843.29	1,101.38

3.1.2 DWELLING DEMAND

Distribution dwelling demand per year [m2 GFA]

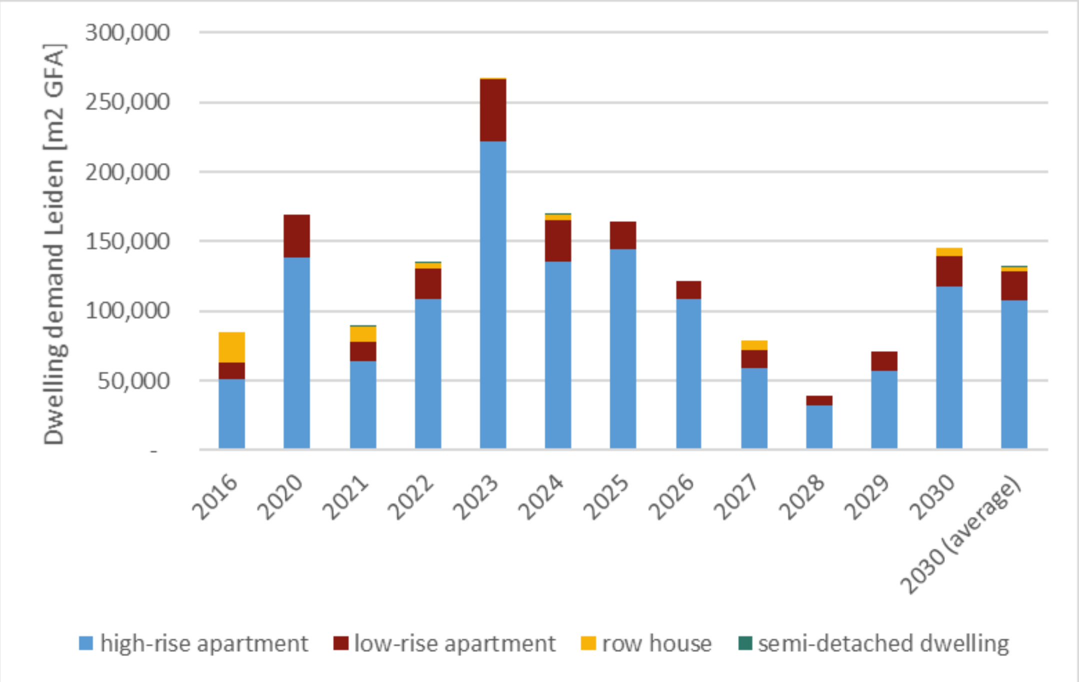

Figure 1 - Distribution dwelling demand per year [m2 GFA]

3.1.3 MATERIAL DEMAND

Below the material demand per dwelling type as defined by municipality of Leiden is given.

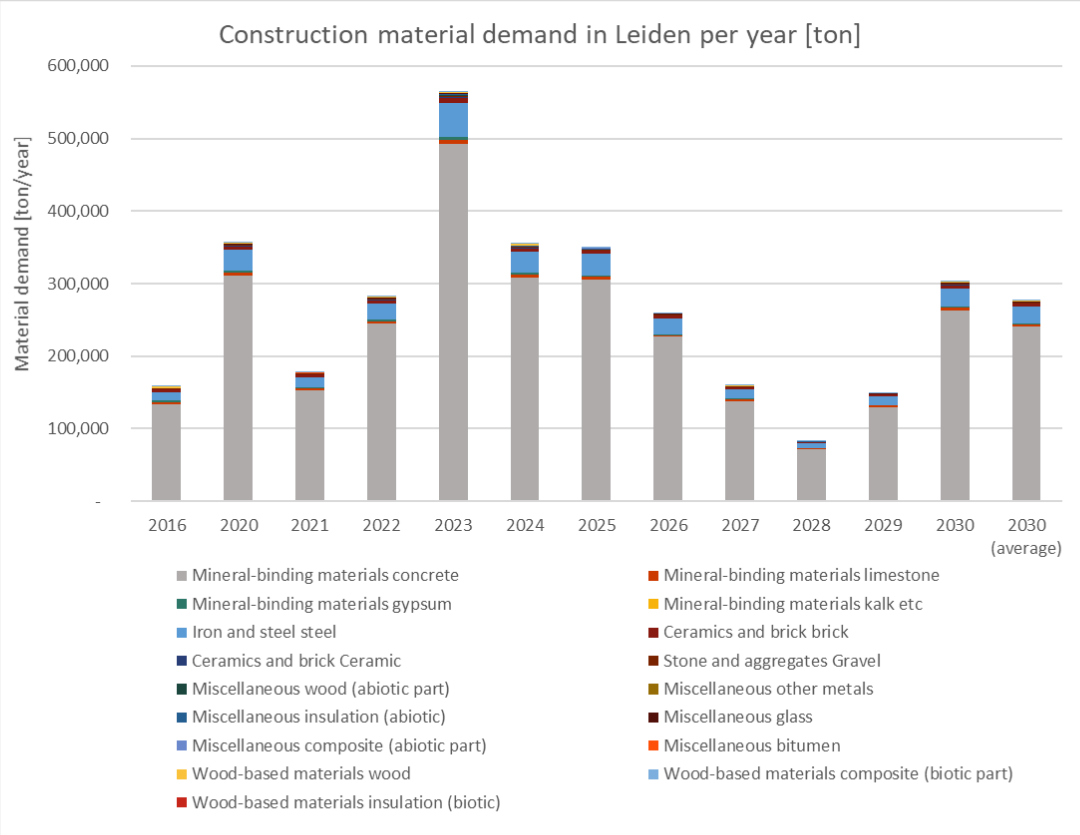

Figure 2 - Construction material demand in Leiden per year [ton]

3.3 Modeling impact solutions

3.3.1 URBAN MINING

	Recover y rate (%)		Recycled content UM (%)	Recycled content other waste (%)	
Concrete	99%	Hiskemuller van der Zijden, pers com. (2020)	60%		Hiskemuller van der Zijden, pers com. (2020)
Brick	99%	Coumans pers. com. (2020)	45%	55%	Coumans pers. com. (2020)
Wood	90%	Van Hoye, pers. com. (2020)	80%	15%	Van Hoye, pers. com. (2020)
Roof gravel	100%	Verhagen et al. (2020)	0%		Verhagen et al. (2020)
Aluminiu m	36%	Verhagen et al. (2020)	85%		Naaikens, pers com. (2020)
Steel	52%	Verhagen et al. (2020)	85%		Naaikens, pers com. (2020)
Glass	91%	Verhagen et al. (2020)	40%		Dubios et al. (2013)
Ceramic	80%	Verhagen et al. (2020)	0%		Coumans pers. com. (2020)
Gypsum	83%	Wouda, pers com. (2020)	50%		Wouda, pers com. (2020)
Bitumen	88%	Den Hartog, pers. com. (2020)	28%		Den Hartog, pers. com. (2020)
Cast Iron	52%	Verhagen et al. (2020)	85%		Naaikens, pers com. (2020)

C&DW	100%	Verhagen et al. (2020)	0%		Verhagen et al. (2020)

3.3.4 SCENARIO 3 – REPLACING THE FITOUT WITH BIOBASED ALTERNATIVES

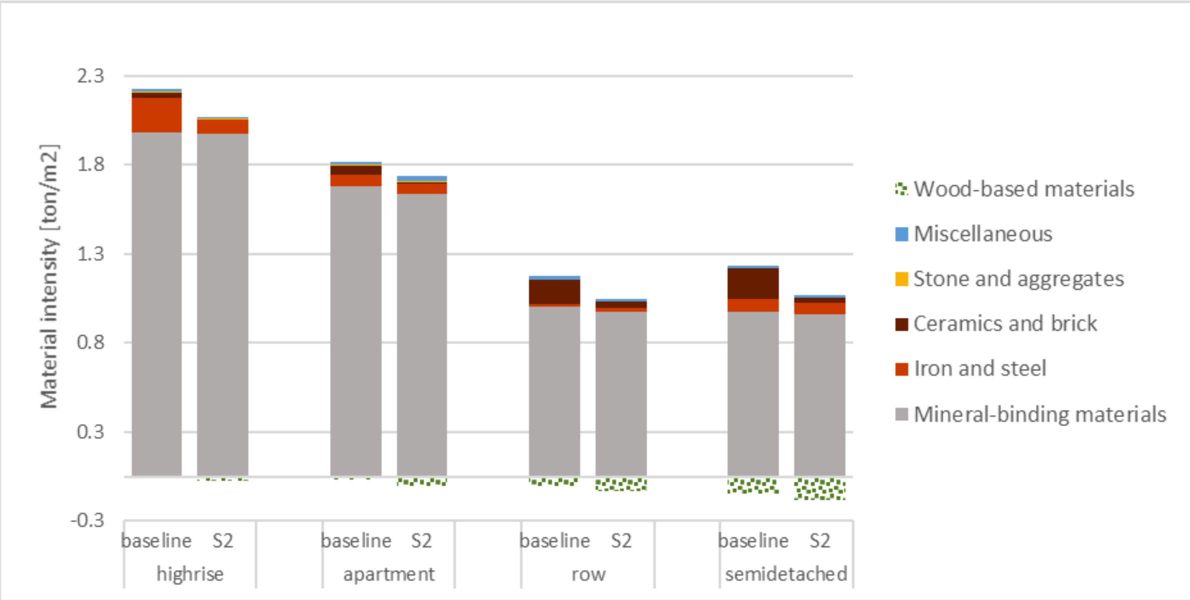

Figure 3 - Material intensity per building type - scenario 3: biobased other materials [tons/m2]

APPENDIX B – MATERIAL INTENSITY EXCEL

APPENDIX C – BASELINE AND SCENARIOS MODEL

APPENDIX D – INTERVIEW RESULTS

APPENDIX E – CONSENT FORMS INTERVIEWS