Master thesis

High quality recycling of construction and demolition waste in the Netherlands

Lisanne Mulders

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Abstract

The high consumption pace of materials of the worlds population tend to cause scarcity of materials. Furthermore, the use of these materials in products have a negative impact on the environment. Once a product reaches the end of its useful life, it can again have a negative impact on the environment being discarded as waste. The building sector is accountable for a large share of the waste arising in the Netherlands, namely 40% of the total waste. Therefore, it is an important sector to take into account while reducing material use. The goal of this research is to decrease the use of primary materials in the building sector, by promoting high quality recycling of construction and demolition (C&D) waste. High quality recycling of waste is defined as waste recycling within the same product line. In this study, the current state of C&D waste recycling is assessed. With this information, more insight is gained in how high quality recycling can be increased.

The current state of the C&D waste streams in the Netherlands are studied by a material flow analysis. 90% of the C&D waste in 2012 was recycled or incinerated with energy recovery. Merely 11% of the total weight of the waste appears to be recycled within the building sector. The literature study towards re-use and high quality recycling technologies of the three largest C&D waste streams, stony materials, metals and wood, shows that there are several technologies available for this purpose. Therefore, the barriers seems to be in other parts of the system. By means of a qualitative research, the stakeholders in the C&D waste recycling system are asked for their opinion on the current C&D waste recycling system and their view towards future recycling of building materials. In general, the stakeholders concur that sorting of the materials, the economical climate and the type of building materials are the main bottlenecks that withhold high quality recycling. One important solution to these problems is co-operation of the stakeholders in the C&D waste recycling system. The findings of the MFA, literature study and the aforementioned interviews are compared to the outcome of a case study which applied high quality recycling.

In this study it is demonstrated that the C&D sector has a huge potential in decreasing material use. However, from this study it follows that a few bottlenecks exist that hamper the increase of high quality recycling.

Preface

Before you start to read my thesis, I want to take this opportunity to thank several people for making this project a success. In the first place I would like to thank Jacqueline Cramer and Sander de Vries from USI and Ernst Worrell from the UU for including me in the project Recycling van Bouw- en Sloopafval: van Cirkelstad naar Cirkelland.

Furthermore, I would like to thank the interviewees for their shared knowledge on C&D waste and their time. This also applies to the experts I spoke to in order to get a grip on the C&D waste recycling system.

Jonathan Zijlstra (van Gansewinkel) and Mark and Peter Lamers (Baetsen BV) made us come in contact with actual waste recycling. They gave us a guided tour in waste separation facilities, which was very educational.

Furthermore, I want to thank René for reading and giving feedback on my paper. Myrna the other inhabitant of our office for keeping me company. And, of course, my family for mental support.

A special thanks for my supervisor Jesús. His wise words and anecdotes regarding practising science and life in general kept me on track. Furthermore, he guided me through the process en was always available for discussion.

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Contents

1 Introduction

1.1 Background

The current pace of consumption of the earth's materials is not sustainable (Mont and Plepys, 2008). In order to lower our impact on the environment and on the opportunities of material use by future generations, a change is required. After the lifetime of a good, materials end up as waste. Of all the waste produced in the European Union (EU) in 2010, 34% – approximately 860 Mt – has its origin in the construction and demolition (C&D) sector (Eurostat, 2012). For the Netherlands, this rate was even higher, namely 40%, see figure 1.1, which is 23.8 Mt of waste in 2010 (CBS, PBL, Wageningen UR, 2012a).

C&D waste is, according to the European Commission (EC), waste that arises from activities as construction and demolition of buildings and civil infrastructure (EC, 2012). The large amount of C&D waste and the high potential for re-use and recycling of these materials are the reasons why the EC has given this waste stream high attention (EC, 2011a). The European directive regarding waste (EC, 2008), sets the re-use and recycling rate of C&D waste to a minimum of 70% by weight to be achieved in 2020.

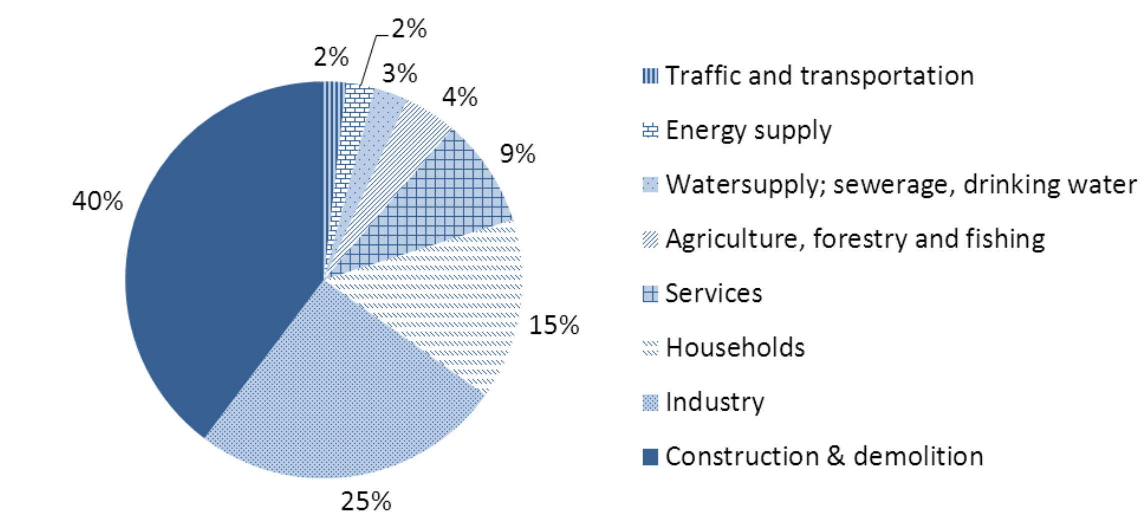

Figure 1.1 – Source of waste in the Netherlands 2010, by weight (CBS, PBL, Wageningen UR, 2012a).

In this study, C&D waste refers to the waste that appears after construction, renovation and demolition of buildings. In contrast to the definition of C&D waste of the European Commission, civil infrastructure is not included in this study. The emphasis is on buildings, in order to place recycling of aggregates into road basement outside boundaries of this study. Furthermore, the current study is linked to the project "van Cirkelstad naar Cirkelland", in which housing corporations are the initiators for the demand for demolition. The project is an upscale of the project Cirkelstad. This project is an initiative in Rotterdam, started in 2009, covering demolition projects which are executed sustainable.

There are three phases of the building material life cycle, figure 1.2 (Kim *et al.*, 1998). During the first phase, the pre-building phase, raw and manufactured materials are extracted, processed, packaged and shipped. It captures the production and delivery of the materials up to the point of installation. Second, the building phase, corresponds to the building's life, which is built and needs maintenance. The last phase is the post-building phase, the building is demolished and materials are released as waste. In a circular economy, materials are recycled and enter the pre-building phase again. Alternatively, the materials are re-used entering the building phase. Box 1 elaborates further on the concept circular economy. It is possible that the materials enter another system after recycling. This is, however, not preferred when aiming at a circular economy. Another option, the less preferred, is that the materials are discarded as waste.

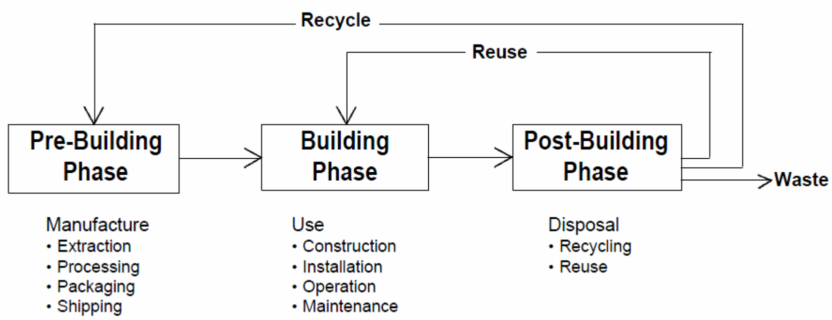

Figure 1.2 – Life cycle of building material in three phases (Kim et al., 1998).

The pre-building phase is energy and material intensive, which implies a large environmental impact (Kim *et al.*, 1998). For example, according to the Dutch Ministry of housing, spatial planning and environment – current ministry with this portfolio is the Ministry of infrastructure and the environment – (VROM, 2010a), the environmental impact of stony building material is relatively high. This is mainly due to high energy demands during the production phase (VROM, 2010a).

Box 1 – Circular economy

Circular economy does not have a clear origin or definition in literature. According to Yuan (2008), it was coined by scholars in China in 1998. However, the idea to decouple economic growth from growing waste streams and unsustainable management of earth's resources has been put forward before, for example in *The limits to growth* by Meadows *et al.* (1972). The framework of the circular economy has its similarities with other approaches like Industrial Ecology, Biomimicry and the closing-loop (Yuan *et al.*, 2006; Kok *et al.*, 2013). The idea is to move away from the linear economy that has been the main driver of society since the start of the industrial revolution. The main adage in a linear economy is to "make, use and waste" (Circle Economy, 2013).

However, the circular economy is aiming at optimal resource use. Biological materials are designed to return to the environment. Synthetic materials are aimed to be of high quality with a long life. When products reach the end of their life-cycle, they are disassembled and the materials are re-used or used as input for another product process. The target aims of circular economy are short cycles in which material resources circle (e.g. little transport), keep materials as clean as possible and the quality of the material as high as possible over the longest possible period of time (Kok *et al.*, 2013). Expected is that by pursuing a circular economy, an efficient economy will be achieved with lower or, in the ideal case, no environmental impact. Getting there requires a reform of the current system of human activity (Yuan *et al.*, 2006).

In this study, on recycling of C&D waste in the Netherlands, the aim is to reach a circular economy in the building sector. The preferred option of material treatment is to close product chains. Meaning that the waste material should be used within the product chain it already is part of. This can be in the form of a raw material or part of the production process.

In 2010, the recycling of C&D waste rate in the Netherlands was 94% and 3.5% had a useful purpose by retrieving energy in 2010 (Rijkswaterstaat, 2013b). This percentage is seemingly the result of two policies in the Netherlands. First, the "Ladder van Lansink" has been brought into Dutch waste policy by Ad Lansink in 1979. Second, which resulted from the Ladder of Lansink, a landfill tax and a landfill prohibition were introduced in the Netherlands, in the years 1995 and 1997, respectively (Linderhof and Bartelings, 2006; overheid.nl, 1997). Together these concepts prevent the waste being discarded without a useful application.

Even though there is a rate of recycling documented, it is yet unclear in which way the waste is recycled. Recycling is defined as a "useful application in which waste materials are reprocessed into products, materials or substances, for the original purpose or another. Energy recovery and processing waste materials into secondary fuel are excluded" (Rijkswaterstaat, 2013b). LAP2 – "Landelijk afvalbeheerplan 2009-2021" – the national policy for waste treatment in the Netherlands, gives minimal requirements for waste treatment. For example, incineration is the "standard" treatment for some materials, e.g. wood (VROM, 2010b), even though wood of quality A can be recycled. In a circular economy, waste materials are re-used and recycled within one sector, preferably on a small scale. This will lead to efficient use of materials, which reduces the environmental impact of products, by reducing raw material use, energy use and CO_2 emissions. In addition, it brings economic advantages, as the supply chain is working together in order to re-use and recycle the materials.

When the world is considered in three different layers, the natural system, social system and the economic system, the latter is usually seen as the most important (Cochran, 2007). However, actions that have an economical benefit can have a large impact in other sectors. For example, sending waste to a landfill is in some cases the cheapest discard option. This requires land-use, and might lead to contamination of the area, which can affect local inhabitants and nature. The discrepancy between the actual costs and hidden costs of a material is in disadvantage for the environment and society (Tietenberg, 2006). The hidden costs for nature and society which are a result of disposal of waste material and/or production of new material are ideally included in the costs of building material. When these hidden costs are included, the efficient level of recycling increases, since the cost of disposal increases which enables some space for recycling costs. Inclusion of the hidden cost of material disposal would lead to an increased recycling rate and enlarge the useful economic life for non-renewable recyclable resources (Tietenberg, 2006).

1.2 Problem definition

From section 1.1, it can be argued that the potential of recycling of C&D waste sector at a higher quality is large and can, therefore, contribute to a more sustainable sector. The definition of high quality recycling, as used in this research, is waste that is returned into the building sector as a construction material, preferably in the same product line, substituting virgin, primary material. To support the circular economy of the building sector, this research is aimed at increasing knowledge on the current status of C&D waste treatment and where improvements can be implemented to get to a circular economy. Current reliable data on recovery and recycling rates of the waste in the EU is not available (EC, 2011a). Earlier studies on C&D waste streams have already been reported for the situation in the Netherlands (AgentschapNL, 2012; Ansems *et al.*, 2009; Corsten *et al.*, 2010) as well as other countries (Franklin Associates, 1998; Department for Environment Food and Rural Affairs, 2011; EC, 2009). The aforementioned studies depict the amount of waste in broad categories, except EC (2009) for metals, and give limited information on the end-processes of the materials. In general, the recycling categories given in the studies are "*recycling*", "*landfill*", "*incineration", "energy recovery*", and "*others*".

We argue that in order to build a circular economy within the building sector, the focus should be on promoting high quality recycling of C&D waste. Therefore, a deeper analysis on types of treatments for more specific material streams is conducted. Furthermore, the viewpoints of stakeholders in the C&D waste recycling system regarding factors that impede high quality recycling were gathered. The main research question of this study is: *How can high quality recycling be promoted within the Dutch construction and demolition waste system?*

In order to answer this question the following sub-questions are formulated:

1) What is the current state of construction and demolition waste recycling in the Netherlands?
2) How can C&D waste flows be recycled within the construction sector?
3) Which barriers impede high quality recycling of construction and demolition waste?
4) What are the reasons to participate in a high quality recycling project?

This thesis is organised in 6 chapters (see figure 1.3). Each chapter contains a method and a discussion section. Chapter 2 presents the material flow analysis (MFA) of Dutch C&D waste. The included waste stream, waste treatment options and the method for constructing the MFA are given, followed by the results and discussion. Chapter 3 gives an overview of technologies available for C&D waste recycling within the construction sector. Chapter 4 entails a qualitative study regarding the experienced barriers by stakeholders that hamper high quality waste recycling. Chapter 5 includes a case study, in order to give insights in incentives to recycle building material at a high quality. Chapter 6 is devoted to the conclusion and overall discussion.

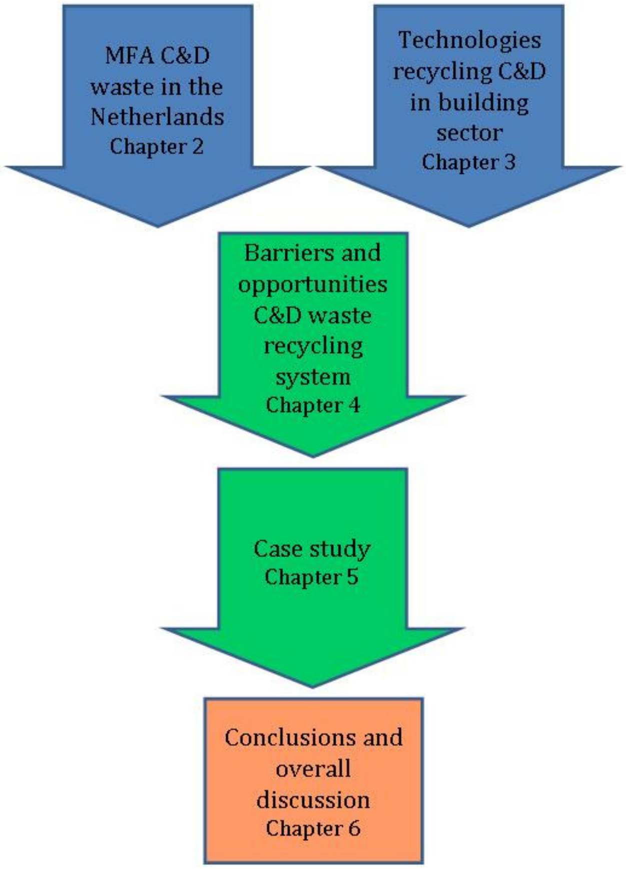

Figure 1.3 – Flow diagram of the thesis.

2 Construction and demolition waste in the Netherlands

In order to stimulate high quality recycling, the current amount of C&D waste and their treatment processes in the Netherlands are examined. An MFA is constructed to quantify and trace the material that is researched. By following the materials stocks and flows the life cycle, or a part of it, can be visualised. The MFA is constructed in order to give answer to the first sub-question: *What is the current state of construction and demolition waste recycling in the Netherlands?*

This chapter first starts with describing the C&D waste materials that are included in the MFA. Followed by a description of the waste treatment options that are currently in use and included in this study. In section 2.3 the method for constructing the MFA is explained. Followed by the results of the MFA. This chapter ends with a discussion regarding the MFA.

2.1 C&D materials in the Netherlands

The materials that are included in this MFA are grouped by type. The materials included in the MFA are in general based on the European List of Waste (LoW). In the Netherlands, it is referred to as Eural "Europese afvalstoffenlijst". The LoW is accepted by the European Commission and in use in the Netherlands since 2002 (VROM, 2001). However, for some materials the LoW is rather broad. The list used in this study was therefore extended with other materials based on other literature and expert knowledge. For the present MFA the following material categories are distinguished: "*stony material*", "*wood*", "*metals*", "*glass*", "*paper*", "*plastics*", "*insulation material*", "*asbestos containing material*", "*furnishing*", "*mixed materials*" and "*sorting residue*". In the remainder of this section the categories are explained.

2.1.1 Stony material

The bulk of the mass of C&D waste is stony material (Ansems *et al.,* 2009). In buildings different kinds of stony material are used. Examples of stony materials include concrete, masonry, bricks, gravel, sand-lime brick, roof tiles, asphalt roofing, gypsum based material and rubble. In demolition, a large part of the stony material consists of mixed content. It is not sorted on their substances, but it will be crushed to a particular size, depending on the demand, before it is used in a next process. In the LoW, a distinction is made between concrete, bricks, mixtures of stony material, here called rubble, tiles and ceramics, and gypsum based material. In this thesis, the same subdivision as in the LoW is maintained for stony materials. Even though it is mandatory to separate asphalt roofing on the demolition site (Rijksoverheid, 2011) it is registered as asphalt. It was not possible to filter the roofing material out the asphalt category. Since the focus of this research is on buildings, this category of asphalt waste is left out.

Concrete

Concrete is the basis of the urban environment (World Business Council for Sustainable Development, 2009). Block of apartments and offices are primarily constructed of concrete. Concrete is a mixture of aggregate (stone, gravel and sand), cement and water. There are different kinds of concrete, depending on the way it is produced and whether or not additives are included in the concrete. Some examples are: concrete stones, reinforced concrete and autoclaved cellular concrete (ACC) (de Haas & Partners, 2003). Most of the concrete is mixed with other types of stones during the demolition phase (O. Friebel, Personal communication, 13 December 2012). ACC is preferred to be grouped separately. Whereas ACC contains sulphates, which can leach into the soil and damage the environment in case the material is re-used in the environment (VROM, 2010b).

Bricks

This type of stones includes masonry, sand-lime bricks, and other types of bricks. Bricks are used in large quantities in the Netherlands, mainly for dwellings (de Haas & Partners, 2003). Masonry includes bricks, sand-lime bricks, and mortar, which contains cement, lime and aggregates.

Rubble

In case the stones are not separated by type on-site, the material is part of a mix called rubble. These mixed stones will have a different composition depending on the stones that are part of the building that is constructed or demolished. It is also possible that other, not stony, material is part of rubble.

Tiles and ceramics

This category contains ceramic, slate and clay floor tiles, slate roof tiles and ceramics.

Gypsum based material

Gypsum based material is made from plaster, water and additives. An example of an additive is paper, which is the additive of plasterboard. Plasterboard is used for interior walls and ceilings. Gypsum based materials need to be collected separately since they contain sulphates. As stated before, these sulphates can harm the environment when the material is ending up as base material under roads.

2.1.2 Wood

In the LoW, all wood waste is considered as a single category. In practice, wood is divided into 3 quality categories, namely: wood A, B and C (VROM, 2010b). All three types are (mainly) produced from virgin wood. Wood A is untreated wood, for example wooden pellets on which transport takes place. Wood B has been painted or glued and may contain nails, e.g. doors, frames, chipboard (Dusseldorp b.v., 2012). Wood C has been treated in a way that long life is ensured (wood preservation), containing hazardous substances. Wood C is used for outside constructions such as sheds. The difference between wood A and B is sometimes difficult to observe. Companies that ask for wood A allow it to contain some percentage wood B. Next to that, wood A sellers can make more profit by selling relatively clean wood B as wood A. Therefore, in this report the category wood A will be named wood AB, since it is difficult to state that it is pure wood A.

2.1.3 Metals

Metals are the most monetary valuable materials in the C&D waste. There is a large number of different metals that can be distinguished. The division made by the LoW is containing the following categories: ferrous metal and steel, copper, bronze and brass, aluminium, lead, zinc, tin, mixed metals, contaminated metals and cables. Some applications of metal: copper, zinc and lead are used in the building industry in facades and roofs (Stichting Duurzaam Bouwmetaal, n.d.). Copper is also used for tubes. Steel is used for making the construction of the building more firm and in reinforced concrete. Even though the LoW distinguishes six different types of non-ferrous metals, the metals were grouped into ferrous metals, non-ferrous metals and cables in this research. This is a result of different aggregation levels in the data used for the MFA.

2.1.4 Glass

Glass is used in window frames and doors. By selective demolition, the glass can be separated from other C&D waste materials. In case glass is not separated on-site, most of the glass will end up in rubble.

2.1.5 Paper

Paper is mostly used on construction sites as packaging material.

2.1.6 Plastics

Plastic comes in several forms. PVC (Polyvinyl-chloride), EPS and PUR (Plastics Europe, 2010), are the common used plastics in the building sector. The last two are partly covered in the next category "*insulation*". PVC is used for window frames, floor and wall coverings, piping, etc. (Plastics Europe, 2010). For the MFA, the LoW codes are the source of information retrieved on plastics. Therefore, all different types of plastic are taken together. This means that also PE (Polyethylene), PET (Polyethylene terephthalate), PP (Polypropylene) can be included in this category.

2.1.7 Insulation material

Insulation materials are mainly used to decrease heat loss of the inner side of a building to the outer side. It can, however, also be used for acoustic purposes and for fire prevention. The array of materials that is used for insulation is large. De Haas & Partners (2003) make a division which contains the four most used insulation materials in the Netherlands: stone wool, glass wool, PUR (Polyurethane) and EPS (expanded polystyrene). In the past, asbestos containing material has also been used for insulation. However, that material is included in the category "*asbestos containing material*".

Glass wool consists of sand, calk, soda and resin which is used as binder. It can also be made from recycled glass, which is a common source for glass wool in the Netherlands. Knauf Insulation, for example, uses 70% recycled glass for producing new glass wool (Knauf Insulation, 2013). Stone wool consist of volcanic stone, or recycled stone wool and other secondary stony material (Mineral Wool Association, 2013). EPS is made of pre-expanded polystyrene drops. PUR is manufactured by a reaction of di-isocianaat and polyol (SVI, n.d.).

All insulation materials (except asbestos) are regarded one group in this research, in compliance with the LoW no distinction per material type is made.

2.1.8 Asbestos containing material

In the Netherlands, it is obliged to start demolition with an inventory regarding the asbestos containing material in the building. It is forbidden to use asbestos since 1993, because it causes danger for public health (Inspectie SZW, 2012). The small silicate fibres can cause (lung)cancer. It has, however, extensively been used in buildings up to 1993, due to its specifications of fire resistance, durability and low price (Inspectie SZW, 2012). Therefore, by demolition of buildings build before 1993 asbestos will appear and need to be handled carefully. Asbestos has been used for example as insulation and in eternity (fibre concrete).

2.1.9 Furnishing

All materials that are not needed for keeping the construction up, but which are necessary in the use phase of a building are referred to as furnishing. These materials will come free in renovations or demolitions. It includes carpets/textiles, plumbing fixtures, porcelain, boilers, and electrical appliances. It appears that these materials will only be separated in demolition if there is a demand for it (Personal communication with: M. Dobbeling, 6 March 2013; H.B. Dieterman, 5 March 2013). In the waste hierarchy, re-use is an important feature. Information on material re-use is even more disperse than information on material recycling. Therefore, the focus of this research is on material recycling.

2.1.10 Mixed materials

Material that is not sorted on-site is collected in a mixed container. These needs to be sorted in a material recovery facility in order to retrieve mono material streams.

2.1.11 Sorting residue

Most of the mixed materials from C&D sites are transported to sorting facilities. The material is sorted into different aforementioned material streams or, in case the sorting facility is not able, or does not want, to extract more materials out of it, it will become sorting residue.

2.2 Recycling methods in the Netherlands

Current recycling methods in the Netherlands are briefly discussed in this section. The recycling methods are grouped according to the Ladder of Lansink (table 2.1). The upper step is the preferred waste treatment option, rather preventing the waste to arise. Second, it is preferable to re-use the material as a whole, for example re-use of a window frame in a new or renovated house. Third, recycling of the material into other purposes is preferred. Next is energy recovery, burning the material and extracting energy from this process. The following step downwards is incineration without energy recovery. The lowest step of the Ladder is landfill, which should be avoided if possible. In the Netherlands, this last option has already been forbidden for a long time to stimulate recycling and incineration of materials (VROM, 2010a). Since the aim of this research is increasing the recycling quality of C&D waste within the construction sector, we propose to include a new step in the Ladder of Lansink. Namely step 3a: recycling material within the building industry. Recycling of material reduces the energy requirement as explained in section 1.1. Therefore, it is preferable to recycle the material within the building sector in order to reduce the environmental impact of this sector.

Table 2.1 – Adjusted Ladder of Lansink, including step 3a - high quality recycling.

1	Prevent waste
2	Re-use
3a	Recycle material within building industry
3b	Recycle material
4	Energy recovery
5	Incineration
6	Landfill

2.2.1 Prevent waste

Waste in the building sector can, for some materials, be decreased by considering the end-of-life of the building in the planning phase, when an architect is developing the building. This can, for instance, be performed by considering re-usable materials or design a building with a long life-time. This phase of the Ladder of Lansink is not discussed in this part of this study, since the topic is recycling options for C&D waste.

2.2.2 Re-use

Some materials are valuable or useful enough to sell them in the form they appear in recovery to another party. These materials can be used in another project. For example, steel or wooden beams can be re-used in new constructions. Even bricks can be re-used for renovation in case, but requires careful demolition. After questioning in the field, the general opinion is that C&D waste is only being re-used on demand sporadically. As stated before, re-use is not included in this research.

2.2.3 Recycle material within building industry

Closing the circle, recycling material in one sector, meaning using the waste from the C&D sites and re-enter it into the production of the product, is the preferred recycling option in the study. There are several industries that use secondary material in their production, mentioned below. These options, however, do not imply that the materials are 100% re-entering the building sector.

Metals recycling

Metals are well recyclable. Production of new steel can be performed entirely of waste steel. For other metals, a share of virgin material is required.

Gypsum recycling

If gypsum based material is burned, the hydrates that were formed in the hardened material break. The residue that is left is gypsum powder, which can be used to make gypsum material again.

Aggregate concrete industry

Concrete aggregates can be used to supplement primary aggregates, like sand and gravel, in order to produce new concrete. According to Katz (2003), this implies no quality loss. In the industry, there is currently a discussion regarding the share of secondary aggregates that can be added in the production of concrete without loss of desired properties.

2.2.4 Recycle material

For some materials the bulk of recycled material is not re-entering the building sector. This is due to different quality of the recycled material.

Chipboard industry

Wood that is of good quality, wood AB, is crushed into small pieces and used for making chipboard. When wood is recycled into chipboard it leaves the building sector, since it can not be used as a load-bearing wall or window frames.

Plastic recycling

Plastic, also hard plastic is recyclable. In general, plastic is downgraded by recycling.

Glass recycling

Glass can be recycled into glass wool or new glass, not only for buildings. Therefore, it can not be stated that the material is re-used in the construction sector.

Paper recycling

Paper can be used in the production of new paper.

Recycling into base material under roads

Stony material that is broken into aggregates can be used for foundation and embankment of roads (Corsten *et al.*, 2010). The aggregates are substituting primary gravel and sand. In order to use aggregates for base material the material should comply with the European NEN-EN standards.

Unknown type of recycling

As the treatment of waste material is indicated to be recycling, or recycling as building or construction material, the precise recycling option is not clear. Therefore, materials which have received this treatment label are grouped under recycling material, not recycle material in building sector.

Export unknown type of recycling

Even though it is possible that exported recycled materials return into the building sector. No specific notion of their purpose is set. Therefore, these recycled materials with unknown treatment are grouped, similar to the previous recycling treatment, in the material recycling treatment.

2.2.5 Energy recovery/incineration

Incineration with (green) energy recovery

In this waste treatment process, the material is burned. The twelve waste incineration plants (WIP's) in the Netherlands all have the R1 status, which means that they recover electrical energy or heat in the process (Rijkswaterstaat, 2013a). Therefore, incineration is seen as a useful application. In case the incinerator only burns biomass-based materials, the energy that is recovered is labelled as renewable energy. The capacity of the WIP's is large enough to prevent burning material ending up on a landfill (CBS, PBL, and Wageningen UR., 2012b). On the other hand, the large capacity is competing with other recycling options of materials. For example: chipboard makers are negatively effected by the economic support that woody biomass retrieves in case it is used as a fuel (EP, 2010). As a result, the price of woody material has risen in Europe. Wood recyclers are negatively affected by this, since the price of their base material increased.

Secondary fuel

From fluff material and other small waste particles of high caloric value, like plastics and paper, pellets can be made. These pellets can replace fossil fuels in a cement or steel factory. Unfortunately, the capacity to use these pellets in the Netherlands is small, since there is only one cement producing factory in the Netherlands: ENCI (part of HeidelbergGroup). Therefore, secondary fuel is usually exported.

Export energy recovery/incineration

Even though the number of incineration plants in the Netherlands is high, it is possible to export materials in order to use it for energy recovery. In case the material is exported for incineration with the purpose of material removal, no energy is generated. This is called export incineration in the MFA.

Export unknown useful application

Exported waste materials which are assigned to having a useful end-phase can be incinerated with energy recovery or recycling regardless of the recycling quality. Therefore is this treatment process added to the energy recovery/incineration step of the Ladder van Lansink.

2.2.6 Landfill

Landfill

A landfill is a place where material is dumped as an end-stage. In the Netherlands, it is forbidden since 1997 to dump waste on a landfill in case it is possible to re-use, recycle or incinerate the material (Overheid.nl, 1997). There are a couple of exceptions for materials for which no useful application is available and which are hazardous to incinerate, like asbestos and preserved wood treated with chromated copper arsenate (Overheid.nl, 1997). Next to these exceptions, there is also the opportunity to request for an exemption, to dump waste that are in first instance not allowed to be landfilled. Since January 2012, the tax on landfill is abolished, which have seemingly counteract the improvements in that sector (LAP2, 2013).

Unknown

Even though it is not known what is happening with the materials, this end-phase is grouped in the worst category. In the worst case scenario the materials are landfilled.

Export unknown

Exported materials that have an unknown end-phase are included in this category. This is also grouped in the worst category, since the waste treatment is unknown.

2.3 Method construction of MFA

The MFA accounts for C&D waste released and processed in the Netherlands in 2012. If data from another year has been used, it has been indicated. The main input for the sizes of the streams was data received from the LMA, "Landelijk Meldpunt Afvalstoffen", the Dutch registering body for waste. LMA follows the LoW (European List of Waste) codes for registration of waste. The accuracy of the data from LMA has been indicated by other researchers (e.g. Corsten *et al.*, 2010) as an area in which opportunities for improvements appear.

LMA aims at following C&D waste from its origin (sorting process) to its final stage (end-use). Not all companies that treat C&D waste, e.g. companies that only process metals or plastics, are obliged to register their activities to the LMA, which makes tracking the materials a challenging task. Appendix B explains the registration process of C&D waste into the LMA. The waste treatment methods included in LMA's database are limited. In order to enlarge the C&D waste treatment processes, other sources of information were consulted. For example, experts were consulted to increase the knowledge on the material flow for wood and stones.

In order to calculate the total amount for the different C&D waste streams, data from the LMA was used. Within LMA, C&D waste is registered according to the sorting process, namely "on-site" or "off-site". The documents used were:

- "On-site" sorting – LoW chapter 17 sections 01, 02, 04, 06, 08 and 09 (see Appendix C)
- "Off-site" sorting – LoW chapter 19 section 12, on mechanical treatment of waste (see Appendix D)
- "Off-site" sorting – Shipment announcements (SA).

For information on export of C&D waste, information is gathered from the EVOA, which stands for "Europese Verordening Overbrenging Afvalstoffen". EVOA is the Dutch body that regulates the EU export waste shipment regulation. The most recent registers on waste are from 2010. Some rules for registration into EVOA have been changed between 2010 and 2012. The main changes do not affect the way the material flow analysis was carried out. For instance, gypsum is at present not allowed to be exported to Germany to be used in mines to prevent collapse, since Germany has decided that this is no useful application anymore. In 2010, a large part of Dutch gypsum waste was exported to Germany. However, at that time it was not mandatory to register export of gypsum, since it was on the Green list. Therefore, data on high gypsum export in 2010 is not included in the MFA for 2012. According to the ministry of Infrastructure and Environment (B. van Huet, Personal communication, 3 March 2013), other changes made into the EVOA registration process are not of high concern for this research.

For determining the end-process of the waste materials, the reported waste treatment options given by the LMA and EVOA were studied. LMA lists thirty-one process options (see Appendix E). These options are grouped by codes. It has been found that some codes are ambiguous. Treatments energy generation and landfill (grouped by the codes F and G) are insightful and clear. The processes grouped as recycling/re-use (code B) are difficult to understand, since recycling the material does not give insight in the way the materials are recycled. Furthermore, the category transhipment/storage (code A) and mechanical treatments (code C) are stages before the end-phase. They reveal that the material is being stored or sorted, rather than the end-treatment of the material. The material that is sorted, will appear in data on the off-site sorting. The categories chemical/physical treatment (code D) and microbiological treatment (code E) are not common treatments options for C&D waste. Waste registration to the EVOA requires another list of processes, which is defined in the Waste Framework Directive (2006/12/EC), this list is enclosed in Appendix F, which sums up different types of useful applications for the waste and types of removal.

In the data received from the LMA, a large part is registered as transhipment. Since this is no end-phase for the waste, other sources were used in order to gather more knowledge on these (i.e. expert interviews and data from LAP2[1]). For some materials, such as metals, glass and paper, the end-phase is unknown. If in LAP2 (VROM, 2010b) the minimum standard for that material is recycling; as it is the

[1] LAP2 is "Landelijk afvalbeheerplan 2009-2021" – the national policy for waste treatment in the Netherlands

case for metals, glass and paper; it is accepted that all recovered materials are recycled if no indication of other treatment processes is picked up.

In the MFA, the way of treatment of the waste is shown in respect to the total weight. The MFA is built upon tables per waste category, which contain the C&D waste materials (section 2.1) in the upper row and the recycling options (section 2.2) in the first column. The quantities of the materials are evaluated by weight, in kilotonnes (kt) and percentages of the total weight.

2.4 The material flow analysis

Combining the information retrieved from LMA, EVOA, LAP2, experts, and other documents, the constructed current picture of C&D waste recycling in the Netherlands is depicted in figure 2.1. Waste streams smaller than 40 kt are left out in the Sankey diagram in order to maintain clearness. The Sankey diagram is based on table G.1, shown in Appendix G, which included the waste streams smaller than 40 kt.

The materials in this MFA are grouped and explained according to the categories described in section 2.1. The materials are mapped from their sorting point up to the recycling process they follow. C&D waste sorted “on-site” represents 69% from the total waste registered, whereas 31% corresponds to “off-site” sorted waste. Some materials are only separated on-site, for example stones and insulation material. Streams smaller than 40 kt, which is less than 0.2% of the total weight, are left out in the MFA picture in order to maintain clarity. The treatment options of the materials are grouped according to the waste hierarchy in table 2.1, which includes the circular economy step (3a). The highest step displayed in the MFA, i.e. recycle material within the building industry, has a light colour. This colour is darkened while reaching treatment options in the category landfill.

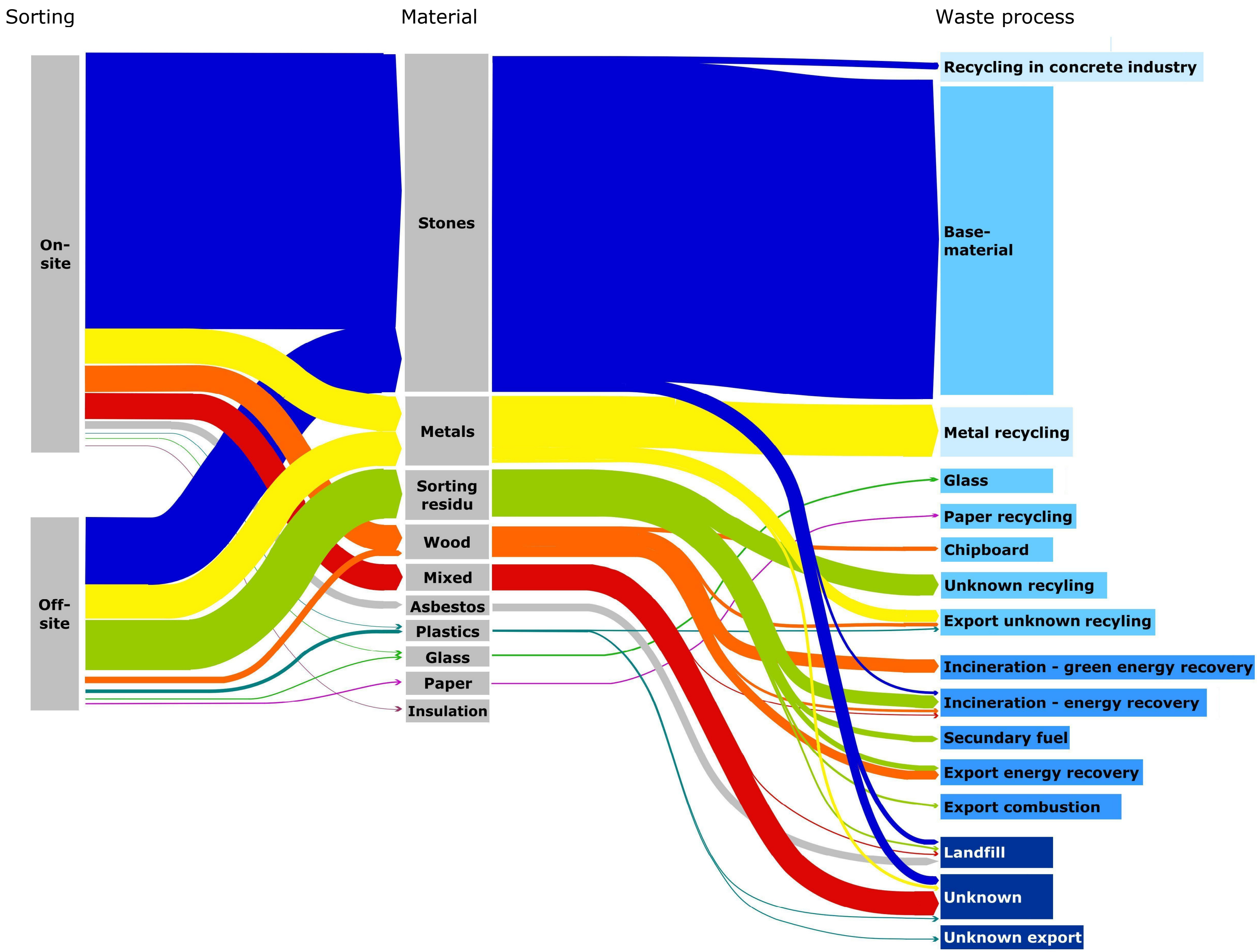

Figure 2.1 –Sankey diagram showing origin and recycling treatment of C&D waste in the Netherlands in 2012. Total weight of the C&D waste is 24317 kt. Several waste flows, smaller than 40 kt, are not displayed in the figure for clarity, e.g. gypsum recycling. The only exception is the sorted waste stream of insulation, which is 16 kt.

90% of the C&D waste has a useful application. The size of the C&D waste stream that is recycled is 19387 kt (80% of total C&D waste). About 10% of the C&D waste is being incinerated with energy recovery or used for producing secondary fuel. The remaining C&D waste is being landfilled (3%) or has an unknown waste process (7%). The MFA shows that the percentage of waste materials recycled within the construction sector – recycling in concrete industry and metal recycling – is small, 2753 kt (11% of total waste). The aim of this research is to support the circular economy of the building industry. The current C&D waste MFA shows a low quality recycling rate.

In the following sections, the different C&D streams identified in the MFA are discussed following the categories described in section 2.1.

2.4.1 Stony material

As can be seen in figure 2.1 and table G.1 in Appendix G, the largest part, 93%, of the stony waste material, is used as base-material for roads, replacing gravel and sand. "*Stony material*" is splitted up among the types of stones as made in section 2.1. The end-phases of materials in this category can be seen in figure 2.2, see table H.1 in appendix H for the table on which the figure is based. The largest part of C&D stones waste is entitled rubble, which is used as base material under roads (Corsten *et al.*, 2010). If sorting of stony material occurs on-site, the amount of recovered concrete, bricks and tiles will increase. These can be recycled in the corresponding industries. Regarding concrete, agreements were made in 2010 to recycle 300 kt per year in the concrete industry (ENCI, 2010). It is assumed that this goal has been reached in 2012. Of the remaining 1319 kt concrete, 79% is added to aggregates for base materials under roads and the rest, 8%, is sent to landfills. Not all separated concrete is recycled in the concrete industry, since aggregates containing concrete are valued as higher quality base material (Stet *et al.*, 2004). Therefore, a large share of the separated concrete (73%) is used for base material. Therefore, it is profitable to separate concrete. All the rubble for which the end-treatment is unclear is assumed to be used as base material (Corsten *et al.*, 2010).

It is, however, possible that not all rubble released in a particular year is used in that same year. If the demand is low, the rubble will be stored. If the demand is high, stored rubble will be used. This is not included in this research. However, it does show that, in order to get a precise view on the waste streams, an adequate registration process is important. In 2008, a gypsum covenant was signed in which the goal was set to reach 40% recycling of gypsum in 2010. According to M. Meijering (Personal communication, 22 January 2013) employee at Gipsrecycling Nederland, this goal has indeed been reached. For the other 60%, the treatment is yet unknown. A part of this material is likely to be incinerated (M. Lamers, Personal communication, 20 March 2013). For tiles, the end phase is unknown. Once again, the importance of the registration process is emphasised.

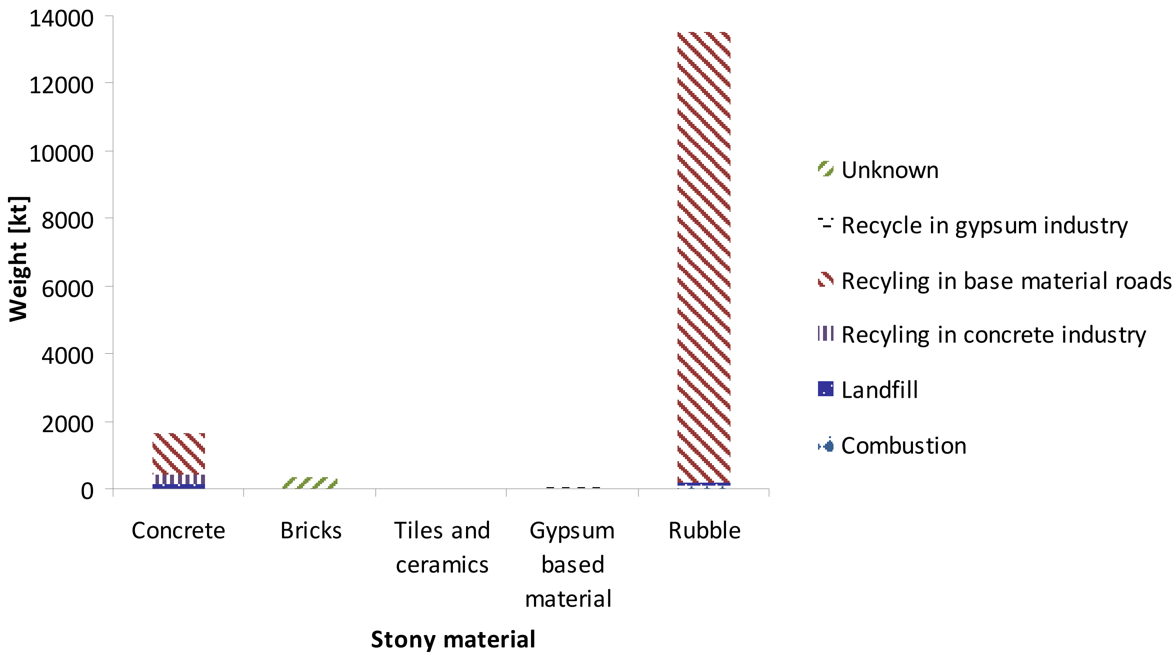

Figure 2.2 – Distribution and process treatments of stony material by weight for the year 2012 among five types of stones: concrete, bricks, tiles and ceramics, gypsum based material, and rubble. The processes included are: recycling in base material of roads, recycling in concrete industry, combustion, landfill and unknown. The material flows of tiles and ceramics and gypsum based material are too small for this graph. For tiles and ceramics, 8kt, the waste process is unknown. For gypsum based material, total weight 65 kt, 26 kt is recycled in the gypsum industry and 39 kt has an unknown waste treatment process.

2.4.2 Metals

The total amount of C&D waste metals registered by the LMA is 3131 kt, of which 95% is being recycled. C&D metal waste has traditionally been recycled in large quantities (Tam and Tam, 2006; Damgaard *et al.*, 2009; Young *et al.* 2001). The sector in which the recycled material is used is not known. This should be improved, in order to show it is indeed recycled in the building sector. Ferrous metals, non-ferrous metals and cables pertain to the category "*metals*". In figure 2.3, the sizes of the different streams and the end-phase of these materials are shown, see table H.2 in Appendix H for detailed numbers. Cables are generally shredded and separated in plastic and metals, however, no information could be gathered on this material. Therefore, the treatment is stated as unknown. For non-ferrous metal, 66% of the materials were retrieved by off-site separation. For ferrous metals 52% of the weight was retrieved from on-site separation. Metals retrieved from infrastructural work is included in this category, since it was not possible to filter these out.

Information on metals retrieved by demolition is uncertain. However, the share of metals in the total C&D waste in the Netherlands from this study (13%) and Germany (15%) (EC, 2011a), are similar. The uncertainty in information is in the first place a result of a high demand for scrap. Metal scrap can be used for producing metals and therefore substituting expensive virgin materials. It is possible that the materials are not included in the reported C&D waste, since the metal can find its own way to the recycling companies by traders. Second, in case a company only processes waste metal material, the material do not has to be registered to the LMA. Third, in 2011 the end-of-waste criteria for iron and steel scrap and aluminium was agreed by the EU (EC, 2011b). As a result, iron, steel and aluminium scrap are not considered waste when released at a demolition site. If the quality complies with the norms stated in the regulation, iron, steel and aluminium scrap are considered as materials rather than waste. Fourth, sometimes management plants do not strictly follow the coding of the incoming waste according to the origin, yet only look at the material itself (EC, 2011a). This can lead to a larger or smaller amount of metals registered as C&D waste.

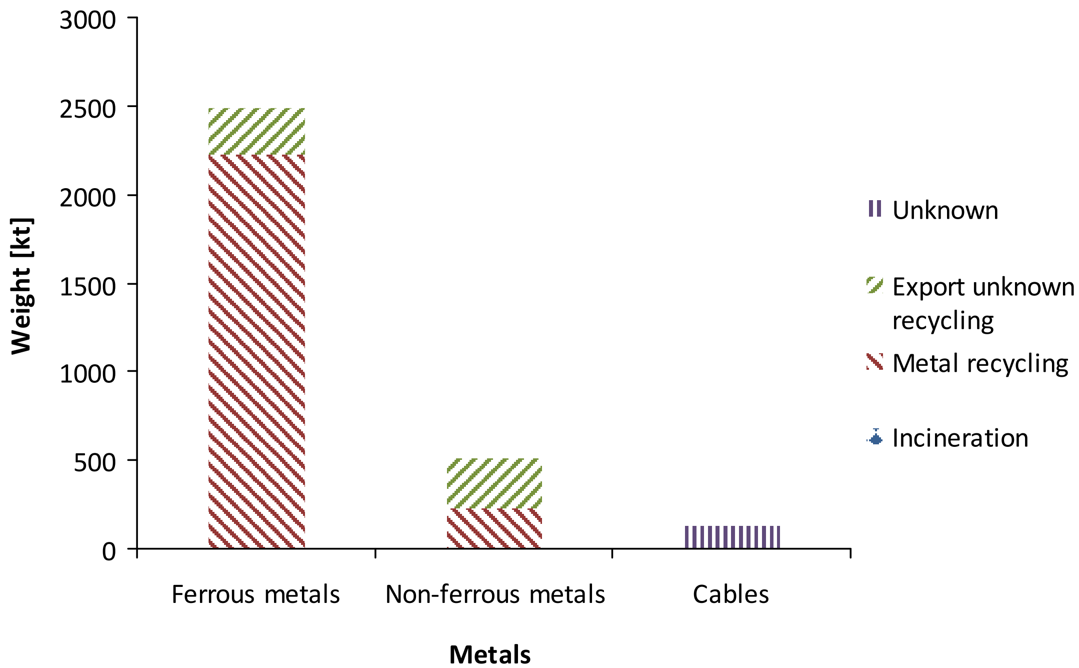

Figure 2.3– Division of total weight of metals among ferrous, non-ferrous metals and cables for the year 2012.

2.4.3 Sorting residue and mixed materials

In this section the categories "*sorting residue*" and "*mixed materials*" are assessed together. These waste streams were accountable for 14% of the total weight of C&D waste. Meaning that a considerable part of the total C&D waste is not sorted. Of these material streams, 35% is incinerated, 33% has an unknown destination, 28% claims to be recycled in an unknown way and 4% is landfilled. Even though the MFA identified 9 possible end-use processes for the categories "*sorting residue*" and "*mixed materials*", there are some voices that do not agree with the LMA data. For example, according to M. Lamers (Personal communication, 12 March 2013) and O. Friebel (Personal communication, 6 March 2013) it is likely that all sorting residue is used for energy recovery. This could, however, vary from year to year. By decreasing the share of sorting residue and mixed materials, which can be reached by intensifying sorting of C&D waste on-site and off-site, more materials are available for recycling.

2.4.4 Wood

For the category "*wood*", communication with an expert in the wood sector has led to separation of wood among three quality classifications and to figures of recycling in the chipboard industry. Wood that is categorised by LMA or EVOA as containing dangerous contents is grouped as wood C. The material with LoW code 170204, which is glass, plastic and wood containing or contaminated with dangerous substances is in total accounted to wood, since that material stream is much larger than glass and plastic in C&D waste, 1522 kt, 25 kt and 15 kt respectively.

In figure 2.4, the MFA for category "*wood*" is depicted for different wood qualities. More detailed information can be found in Appendix H, table H.3. The category is responsible for 1483 kt of waste. Of which the largest part is wood B, and is mainly used for energy recovery. It appears from this result that all AB wood is recycled. It is, however, possible that wood A is included in wood B in case the sorting company has no plans in recycling the wood. In the wood industry, there is no innovation regarding recycling of wood in new products. According to the expert, recycling into chipboard and incineration are the only end-phases for wood. For "*wood*" in total 23% is recycled, the remaining material is incinerated.

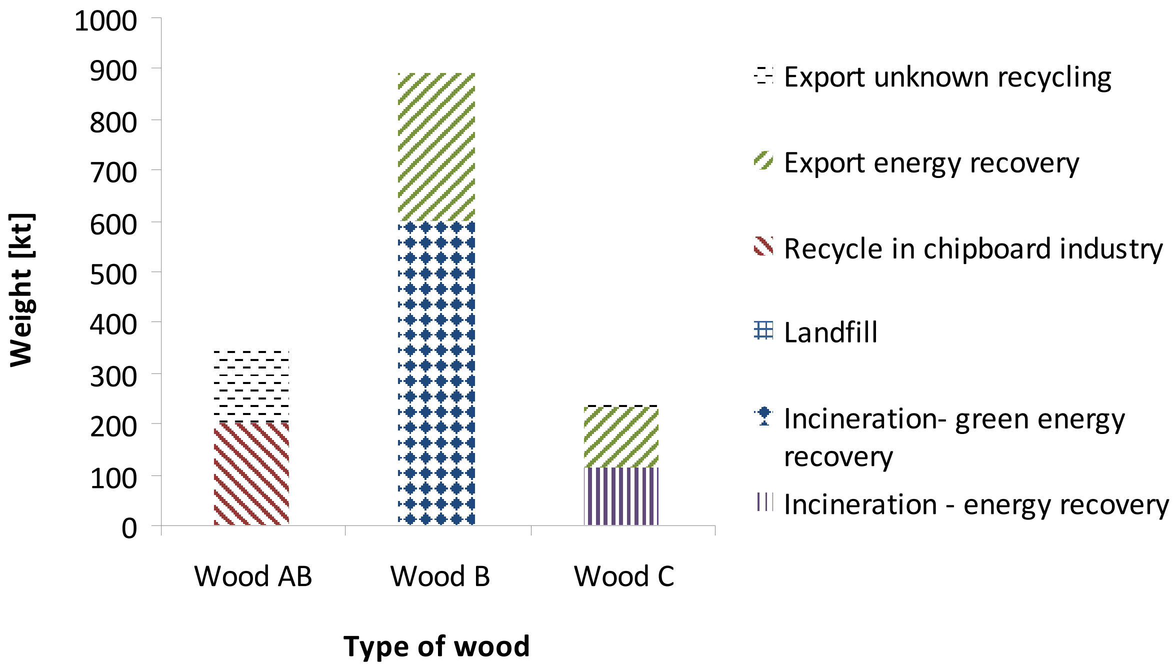

Figure 2.4 – Recovery of wood AB, B and C from C&D waste including the way they are processed.

2.4.5 Others

The other five waste streams, "*asbestos containing material*", "*plastics*", "*glass*", "*paper*" and "*insulation material*", are relatively small. Together they are responsible for less than 3% of the total weight. As can be seen in figure 2.1, all asbestos containing material, 346 kt, is landfilled. This is according to the policy in the Netherlands (VROM, 2010b). In the future, it is expected that asbestos can be dismantled by destruct of the harmful structure of asbestos and make it into reusable filler in the lime, asphalt or cement industry (Twee "R" Recycling Groep BV, 2013).

Glass and paper are in general recycled up to a high level in the Netherlands, therefore not an interesting field to make improvements for the construction sector. The end-treatment for plastic is uncertain. In case plastic is recycled, it is not clear into which process. This material should be monitored more closely in order to reveal its recycling potential. Of all the C&D waste registered at the LMA, 0.07% is of the expense of insulation material, 16 kt. From a project in Rotterdam, where 6 flats (168 households) were demolished, 0.28% of the recovered materials was stone wool (M. Dobbeling, Personal communication, 6 March 2013). This means that if insulation is sorted on-site, the amount of collected insulation will increase. However, the share of insulation remains a small part of the total C&D waste.

2.5 Discussion

As it was concluded in section 2.4, 80% of the C&D material is being recycled and 10% is being incinerated with energy recovery. This share of recycling is different than the 94% recycling in 2010, published by Rijkswaterstaat (2013b). Possible explanations for this difference will be discussed below. The high recycling rate reached in the Netherlands does not mean that the materials are optimal re-used. In order to reach a circular economy within the building sector, materials should follow a closed loop within the sector. We propose to recycle C&D waste material at a high quality within the construction sector. High recycling quality is reached as the waste material is substituting a raw material in the production process of construction material. In this way, the waste material replaces the embodied energy of the produced material.

A concise MFA for the Netherlands has been constructed. As far as we understand, there is no other flow analysis available which identifies the "life cycle" of different C&D materials from the separation site up to the recycling processes. The aim was to have a high level of aggregation, meaning to separate the C&D waste in the diverse types of materials that are used in the construction and map all the recycling treatments that are brought into practice at the moment. Even though, the level of aggregation in the MFA is lower than aimed at, due to dispersion of data, the level exceeds previous research. Several lessons can be learned from the process of building the MFA:

- The registration procedure of the LMA is ambiguous and incomplete, which could result in double counting of the waste.
- The goal of the LMA is to track (hazardous) waste materials in order to keep the overview and help companies to comply with legislation. Their aim is not to map the C&D waste streams, this can be improved if they also aim at evaluating and stimulating recycling of waste materials.
- Definitions of recycling, high quality recycling and useful application may differ from report to report. Therefore, it should be stimulated to use similar definitions among studies regarding C&D waste recycling.
- The MFA contains more recycling options and materials than are available in earlier studies on C&D waste. For further research, a recommendation to improve the recycling categories for the MFA is to include the following materials: 1) Different types of insulation, like stone wool, which can be used to make base material for new stone wool. 2) Asphalt roofing, which is not included as a material in the MFA can be recycled into new asphalt, as the companies Icopal and Biturec already practise. 3) Roof grind, which might be included in rubble, can be washed and re-used as roof grind. 4) Sand-lime bricks, can be recycled into new sand-lime bricks, as the company Calduran Kalkzandsteen BV practices. 5) Tile recycling, Mosa BV, a tile producing company, produces tiles with 16 to 45% recycled stones. These recycling options are already practiced, and therefore would enhance the accuracy of the MFA. However, the available sources for this study do not include information on these recycling options. Therefore, these recycling options are not included in the current study.
- After discussing recycling of C&D waste with different representatives in the field, several companies and visiting sorting facilities it seems that demand is the key to recycling more material, i.e. it is possible to separate more materials on-site and off-site. However, if there is no demand for secondary material, the drive for separating C&D waste on-site is low.
- The quality of sorting in sorting facilities is diverse. The top segment of the sorting facilities is able to retract useful products out of the residue of other sorting facilities (M. de Vries from BRBS, Personal communication, 28 February 2013). Next to that, depending on the cost for waste incineration, it can be cheaper to send waste to a waste incineration facility than to sort the material and sell the material to another party who can recycle the mono stream.

- The manner of sorting and/or demolition has influence on the quality of the material. For instance insulation waste, this can only be captured clean if sorting of this material is performed on-site. If it is not separately sorted, the material will become part of rubble. If this happens, the option to use the material in the production of new insulation material is not possible anymore.
- In order to increase insight in the recycling type and rate of C&D waste in the construction sector, standardisation in registration should be improved. This should be done by including more end-processes for the materials and enhance the list of recovered materials. The first step for the LMA could be adapting the waste treatment options to the list used by EVOA (which is used by the EU). The registration of LMA should be simplified in order to eliminate double counting of waste, not meaning that the waste treating companies should register less. Though, the information given, should lead to a clear view on the end-phase of the waste materials.

One inconsistency that was found relates to the total quantity of C&D waste. It appears to be higher in LMA data than data on waste data reported by Rijkswaterstaat (2013b). Between the year 2006 and 2010, the total annual amount of waste reported by Rijkswaterstaat remained fairly the same with an average of 23.9 Mt. The total waste reported by LMA was 31.79 Mt in 2012, including bituminous mixtures in order to make the totals comparable. The possibility of double counting is high in the LMA database, due to unclear procedures and the possibility of registering materials multiple times in the same LoW code chapter. Also the amount of off-site sorted material differs in size. According to an unfinished report from AgenschapNL on C&D waste in 2009, the size of the sorted waste stream is approximately one fourth of the data received from LMA on 2012. Nevertheless, in the last years the registration has been changed and improved, which makes the data more reliable according to Rijkswaterstaat (Personal communication, 19 February 2013).

According to Hofstra *et al.* (2006), the amount of C&D waste was 25.5 Mt in 2003 and heading to 39.6 Mt for the year 2025 (excluding civil infrastructure). Between the years 2006 and 2010 the total amount of C&D waste has been around 23.9 Mt (Rijkswaterstaat, 2013b). The future of C&D waste in the Netherlands is expected to grow in the coming years. Despite of the crisis in the construction industry, experts in the field expect that the activity in this sector will increase within a few years. However, it is unsure if the growth predicted by Hofstra *et al.* (2006) will be reached.

Changes in policy will have, next to the economic climate, an influence on the size and treatments of C&D waste. Currently, the crisis in the construction industry led to a decrease in the number of construction and demolition projects. A change in policy, for example a landfill ban or taxes on landfill, changes the waste treatment in a country. As mentioned in section 3.3, for some types of metals an end-of-waste criteria came into force, which assigns scrap metals and aluminium as materials, not waste. For stony aggregates, a similar policy is in the pipeline. In case this policy will be adopted by the EU the size of the C&D waste materials will decrease drastically, since the major part of C&D waste is stony material. This does, however, not mean that the amount of stony material has diminished. It does neither mean that stony material will be recycled at high quality within the building sector. It will make transport of stony aggregates less bound to rules.

Our results are in line with those from VROM (2010a), saying that currently, stony waste materials is mostly used as aggregates which replace sand and grind in base material of roads. Building roads is not as energy and CO_2 intensive as, for example, producing cement. Besides, when striving for a circular economy, namely aiming at recycling and re-using materials in the sector where the materials are released, the use of stony waste material in production of cement or concrete is preferred.

3 Technologies for construction and demolition waste recycling within building sector

As the MFA in chapter 2 has shown, around 24 Mt of C&D waste were generated in the Netherlands in 2012. Only 11% of this waste was high quality recycled. In this chapter the sub-question "*How can construction and demolition waste be recycled within the construction sector?*", will be answered. By studying the re-use and recycling options of C&D waste within the building sector, insights in whether technologies and processes are available to increase the share of recycled materials in the sector are available.

This chapter reads as follows: first the method of research for this part of the study is deliberated. In section 3.2 more information on waste sorting is given, since sorting is a vital part of high quality recycling. Re-use options for C&D waste are explained in section 3.3, followed by recycling options in section 3.4. The re-use and recycling options are compared with each other in section 3.5. This chapter is concluded with a discussion.

3.1 Method

In order to get insights into which technologies are available for recycling within the construction sector, a literature study was conducted. This information was supplemented with information retrieved from experts and already executed projects to see which best practices already have been conducted. In the MFA, re-use was not included in the system. For the optimal technologies re-use is taken into account, since re-use is higher on the ladder of Lansink than recycling (see table 2.1).

Only the largest waste streams are included in this literature study. The Pareto principle, also known as the 80-20 rule, implies that about 80% of the effects are a result of 20% of the causes (Koch, 2008). Therefore, we focus on the group of materials responsible for the major part of the waste generated in the C&D. The MFA in section 2.4 shows that stony material, metals and wood are accountable for 83% of the total C&D waste generated in 2012 in the Netherlands. Improvements in the recycling and re-use rate of these materials will consequently have a large influence of the total C&D waste treatment. Even though sorting residue and mixed materials are large C&D waste streams, together 14% of the total, they are not included in the recycling and re-use chapter. These streams contain diverse materials, e.g. wood, paper, plastics, which – in general – will be incinerated with energy recovery as end treatment. Reducing these waste streams will be more effective than recycle them. In order to stress the importance of decreasing these waste streams, the first section, section 3.2, is devoted to proper sorting.

3.2 Sorting

Sorting of waste materials is a crucial step in recycling. Waste materials need to be clean in order to be suitable for inclusion in the production of (building) products. By separating a larger number of different materials on-site, the amount of rubble and mixed materials will theoretically decrease, as is shown in figure 3.1 (DDC, 2003). Separation close to the source will prevent the waste being mixed with other wastes, and increases the amount of materials suitable for recycling (Edge Environment, 2011; Del Río Merino *et al.*,2010; Poon *et al.*, 2001). As included in the Building Regulation "*Bouwbesluit*" of 2012 (Rijksoverheid, 2011) at least the following fractions of demolition waste need to be separated on-site when they arise in volume larger than 1 m^3: dangerous materials in that are noted in chapter 17 of the LoW (always, regardless the amount), stony material, gypsum based material, bitumen and tar roofing, asphalt, roof gravel. In case there is an approved reason, a request for separation of the waste on another location is possible.

According to M. Lamers of Baetsen BV, an off-site sorting company (Personal communication, 28 February 2013), the following material is preferred to be separated on-site: Scrap, ferrous and non-ferrous metals, cables, asbestos, gypsum, AAC, rubble, wood A, B, and C quality, glass, and bitumen roof material. If these materials end up in the mixed waste stream or in an intended mono-stream, some of them will be difficult to filter out in off-site sorting.

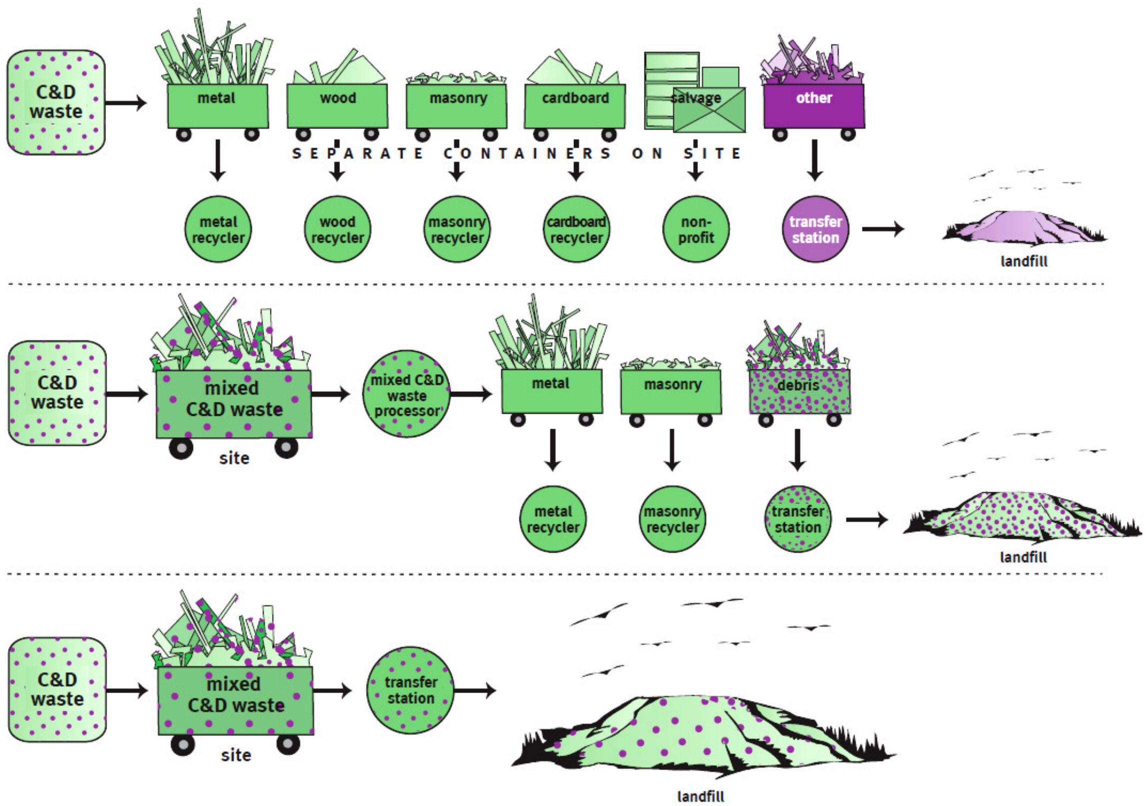

Figure 3.1 – Sorting of materials at different stages leads to different amounts of material (source: DDC, 2003). For the Netherlands, the landfill should be replaced by a waste incineration plant..

Once mixed materials are not separable anymore, the quality of the secondary material stream is lower, which complicates recycling at a high quality. The size of sorting residue of the sorting facility may increase due to improper sorting on-site. This residue is likely to be incinerated, and is therefore not available anymore for recycling. Furthermore, separation of the demolition waste is easier in case a building is designed to be taken apart at the end of its life. Therefore in the design phase of the building deconstruction should be considered (Edge Environment, 2011).

3.3 Re-use

Since re-use is higher on the Ladder of Lansink (see table 2.1) re-use is preferred over material recycling. In this section, re-use options for wood, stony material and metals are discussed.

3.3.1 Ceramic clay bricks

Bricks can be re-used in their original purpose, use in the masonry of a construction. In order to prepare the brick for re-use a temperature treatment can be practised or the mortar can be manually removed from the brick. Figure 3.2 shows bricks recovered from a demolition with mortar attached. Treatment of bricks at a high temperature leads to strains built up in the brick and mortar. This causes shear stress on the mortar, since the mortar is on the interface of the brick (Mulder *et al.*, 2007). As a result, crack formation on the interface sets the brick free. The recovered bricks are of the same quality as before heating, complying to the Dutch standard NEN 2489 and the Dutch Building Materials Decree. Van Dijk (2004) shows that cement dominated mortar requires a temperature of 540 °C for separation of the mortar and the brick. Higher temperatures are required for separating brick and mortar containing lime. A higher temperature results in more cracks in the bricks. This will especially be the case if the masonry debris is presented in large lumps. The critical quartz solid phase transition temperature of the ceramic clay brick is 573 °C, in case a higher temperature is required for mortar separation the chance of fractures in the bricks increases. In order to lower the cracking percentage, the bricks can be separated mechanically before heating. For the cement based mortar, Mulder *et al.* (2007) found that the recovery rate was 36% of the total mass of masonry input. In the test for the other mortar, containing lime, 2200 kg of bricks where mechanically separated before heating at 650 °C. The recovery rate was 41%. The latter is higher, but the treatment is more labour-intensive, due to pre-treatment.

Figure 3.2 – ceramic clay bricks with mortar. The brick can be re-used in case the mortar is removed.

There are some examples of initiatives to re-use bricks. It is, however, not clear in which way the mortar has been removed from the clay bricks. The first example is a project in Oregon, US, where a demolition project of seven buildings, including a parking garage, retail stores, and apartment building took place (United States Environmental Protection Agency, 2000). The contractor held a "Great Brick Giveaway", a program to invite citizens to take the bricks that were recovered from the demolition for re-use. This led to local re-use of the waste materials. Another example is the reconstruction of historically valuable buildings. In Eynderhoof, a museum in Nederweert (the Netherlands), local buildings that can teach the society more of the way of living around the year 1900 are carefully demolished and re-build on the area of the museum.

3.3.2 Wooden construction material

Wooden material, e.g. beams, floor board, window frames and other wooden materials, can be re-used in the same form as they are recovered. Re-use of wood means that the structural capacity of the wood is largely maintained (Goverse *et al.*, 2001). In order to increase re-use of wood, adjustments in the design and building phase can simplify full recovery of the material (Goverse *et al.*, 2001). Next to that, careful and selective demolition is required in order to maintain the specifications of the wood.

Window frames and doors can be re-used in their original purpose. They can, however, also be used as building material, for example, to build a wall see figure 3.3 (Slager and van der Veen, 2012).

Figure 3.3 – wall made of secondary doors and windows (source: Slager and van der Veen, 2012)

3.3.3 Steel construction products

Re-use of steel can be in the form of products, like steal beams or steel portal frames, but also on the complete building level. For construction products, it is important to gain information on the properties of the material and the users' history. For steel, fatigue loading is an important issue for safety (Corus, 2006).

In the UK, around 100 tonnes of steel were recycled for the building BedZed (Corus, 2006), which is a 100 home eco-village. The steel was retrieved from a railway station in the neighbourhood. The steel was inspected on dimensional and strength properties. If approved, the material was shot or sand blasted in order to clean the steel, e.g. remove coatings and re-fabricated (*ibid.*). The last step before re-use in construction was cutting the material in the desired length.

3.4 Recycling within building sector

After re-use of building materials, recycling of the material within the building sector is preferred. The embodied energy of recycled products is, in general, lower than products made from virgin material. The use of recycled materials in construction will decrease the embodied energy of the building. Using recycled materials for construction does not immediately has a positive influence on the use phase, e.g. energy efficiency of the building in the use phase.

3.4.1 Bricks

Masonry can be recycled with or without mortar separation. If the brick and mortar are not separated, the masonry is crushed to a fine grain size smaller than 0.5 mm. The aggregates are mixed with clay and fired in a kiln in order to make clay bricks. Since the mortar is still present in the added aggregates, the strength of the clay bricks will be affected (van Dijk, 2004). Van Dijk (2004), recommends based on empirical results is to use no more than 25% share of recycled masonry aggregates in brick production.

It is preferred to separate the clay bricks from the mortar in the masonry rubble, since the cement fraction will affect the strength of the brick when it is included in production of new bricks. By thermal treatment, the masonry is separated in cement and sand (*ibid.*; Tam and Tam, 2006). For different types of bricks, the added brick aggregates in production should be analysed on strength and quality. In the experiment of van Dijk (2004) where brick aggregates were added to bronze firing clay, from a Dutch river, was shown that from 70% brick aggregates with 30% bronze firing clay, a good quality clay brick can be produced.

In Spain, masonry aggregates are used as a substitute for virgin aggregates for different types of stones (Del Río Merino *et al.*, 2010). In order to separate the masonry with contamination, all small particles were eliminated from the waste stream. The material stream remaining is crushed to the desired size while impurities are removed by the most common used method in Spain, the dry method: large size impurities are manually removed in an early phase of crushing.

3.4.2 Sand-lime bricks

The technology to include sand-lime bricks aggregates in the production of new sand-lime bricks is available. Production of sand-lime bricks runs as follows. Sand, lime and water is mixed in a reactor, in which the lime and the water react to a substance that sticks together (H. Verkleij, Personal communication, 31 May 2013). This substance is pressed together and is placed in an autoclave, i.e. a pressure vessel, in which the temperature rises to 200 °C. The chemical reaction between the lime and sand that occurs in the autoclave, leads to hardening of the material to a sand-lime brick. The strength of the brick can be adjusted to the intended use of the brick, between 14 and 40 N/mm^2 (*ibid.*).

Aggregates from stony material can be used for production of sand-lime bricks as replacement for virgin sand. The aggregates are made by a (mobile) crusher (figure 3.4) to the desired size. The production of sand-lime brick can remain the same when including recycled aggregates in the product (H. Verkleij, personal communication, 31 May 2013). The preference is, however, to include sand-lime brick aggregates or concrete aggregates, not masonry, since masonry will lead to a notable colour difference of the product (*ibid.*).

Figure 3.4 – Mobile crusher. On the left rubble is inserted in the crusher. In the middle ferrous-metals are separated from the rest of the stream. The output on the right is aggregates, which can be used to replace grind or sand in the production of stony building material.

3.4.3 Concrete

Concrete aggregates can be used for substituting grind in concrete production. Use of up to 20% concrete aggregates as substitute of grind has a low influence on concrete properties and workability. Concrete with or without recycled content should comply to NEN-EN 206-1[2] and NEN 8005[3]. Aggregates that are included in the concrete, for example, sand, gravel or concrete aggregates, need to comply with the NEN-EN 12620 and NEN 5905[4]. In case the portion of added concrete aggregates is 21% or higher, the concrete should comply with the CUR-recommendation 112[5]. Use of more than 50% of concrete aggregates for concrete production, requires adjusted calculation methods for the use of the concrete.

There are several technologies to prepare concrete for recycling. The following 4 technologies will be discussed: Crushing, sifting and washing, Advanced Dry Recovery (ADR), thermal treatment and smart crushing. Crushing, sifting and washing is the most commonly used method in the Netherlands, the other are in development and executed on pilot level (L. Dekker, Personal communication 3 June 2013).

Crushing, sifting, with or without washing

This technology consists of the processes crushing, sifting and cleaning of the material. In the first step, crushing, the range of size of the material is chosen, usually 0 to 32 mm (Betoniek, 2011). The most common used crushers are the cone crusher and the jaw crusher. After crushing, ferrous metals and light weight materials are removed from the material stream by a magnet and a wind sifter, respectively. The light weight materials, e.g. wood, plastics and plaster, contaminate the aggregates, in case they remain in the material stream. A small amount of these contaminants remaining in the material stream can degrade the strength and durability of concrete produced with these recycled aggregates (Meyer, 2009). The remaining aggregates are sifted into two size categories, 0 to 4 mm and 4 to 16 mm or 4 to 32 mm depending on the demand. To eliminate possible remaining contamination the aggregates are washed. Several washing techniques are available, ranging from rather simple to complex systems (Betoniek, 2011). The remaining materials are clean aggregates that can be used in concrete production,

[2] These standards are on specification, performance, production and conformity of the concrete
[3] Dutch validation of the European norm NEN-EN 206-1
[4] Dutch validation of the European norm NEN-EN 12620
[5] CUR-recommendation 112 is about concrete produced with concrete aggregates as coarse aggregate

and sludge which needs to be landfilled (Betoniek, 2011). In figure 3.5 the crushing, sifting, washing method is depicted in a diagram.

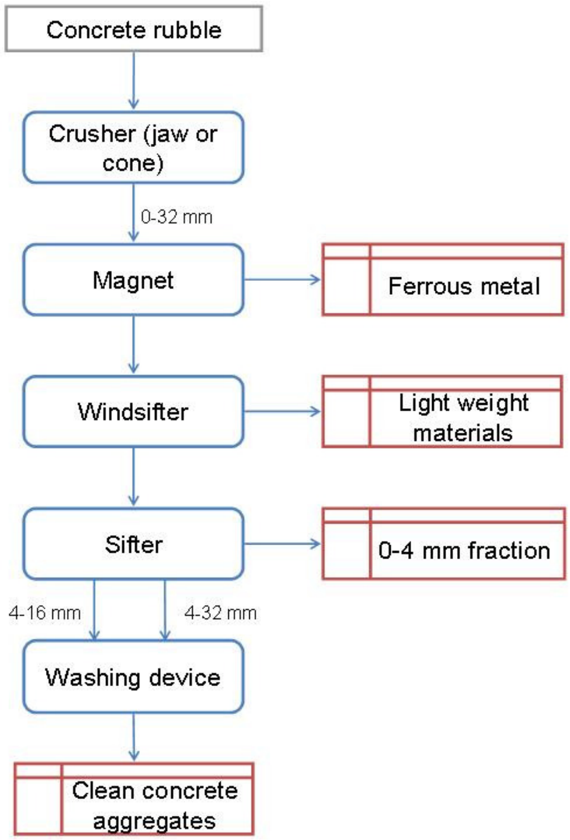

Figure 3.5 – Crushing, sifting, washing method for preparing concrete aggregates for recycling.

Advanced Dry Recovery

For the ADR technology, the focus is on reducing the amount of fines within the waste material. It is expected that for larger grain-sizes, contamination of ferrous metal is easily removable by magnets, while eddy current separators are able to separate non-ferrous metals (de Vries *et al.*, 2009). Therefore, the ADR starts when receiving 0 to 12 mm grain-sized particles, see figure 3.6 for the diagram flow of the ADR method. The crushed aggregates, sizes 0 to 12 mm, are separated in the machine in size 0 to 2 mm, the fine fraction, and 2 to 12 mm, the coarse fraction. Materials that are considered as contamination are in general light-weight and therefore directed to the fine fraction. In the ADR unit, kinetic energy is used to break the water bond that is associated with the fine particles (de Vries *et al.*, 2009). Thereafter, the separation of the fine and course fraction is executed on the aggregates density and size (Betoniek, 2011). In general, the fine fraction hosts 50% of the initial volume of the demolition concrete. Whether the cement in the fine fraction of the crushed material can be used in the production of cement requires additional research (Betoniek, 2011). The coarse fraction can be used as concrete aggregates.

Recycling of cement by the ADR technology is the topic of the EU Research project Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste (CORDIS, 2012). This project is a collaboration between 8 European countries, and aims at investigating withholds of recycling of concrete in the concrete industry. They intent to optimize the breaker and separation process, do research on environmental and economical value of recycling, deliver background information that can be used for policy making stimulating C&D waste recycling and evolve the thermal treatment for conversion of fine cement fraction into a new cement binder (CORDIS, 2012).

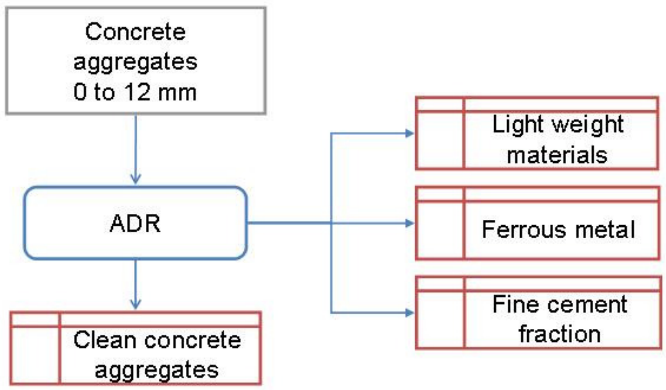

Figure 3.6 – Advanced dry recovery method for preparing concrete aggregates for recycling.

Thermal treatment of concrete rubble

In order to completely close the concrete cycle, gravel, sand and dehydrated cement can be retrieved from concrete rubble (Mulder *et al.*, 2007). Figure 3.7 shows the process for thermal separation of concrete. First, the concrete rubble is crushed into small pieces with a jaw crusher. After crushing, the material passes a magnet, which extracts the steel from the material stream. Next is a rotary kiln, in which the temperature rises to 700 °C, which thermally separates sand and gravel from other materials. Then, by a vibrating screen, coarse aggregate is separated from the material stream. By an air separator the fine aggregates are captured, leaving the cement stone at the end of the process. Whether the cement stone can be added in the production of Portland cement should be tested more thoroughly (Mulder 2007; Betoniek, 2011).

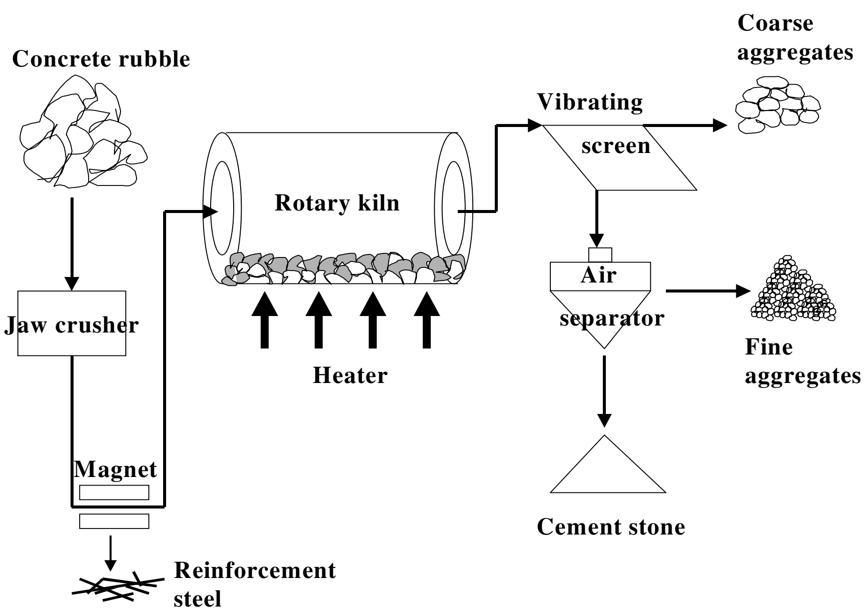

Figure 3.7 – Preparing concrete rubble for recycling by thermal treatment (Source: Mulder et al., 2007).

Smart Crusher

Another new technology that is currently being developed is smart crushing. The Smart Crusher (SC) is a technology which aims at separating the concrete in it source materials, i.e. sand, gravel and cement paste with doing minor damage to the grains (Zuokui, 2012). In contrast to traditional types of crushers, like the jaw or cone crusher, which aim at retrieving a certain grain size. Concrete consists of different components which have different strengths. The compressive strength of aggregates varies depending on the kind of rocks (Zuokui, 2012). Coarse aggregate are usually the strongest part in concrete and the cement paste the weakest. With a force smaller than $100N/mm^2$, which is between the highest strength of the cement paste and the lowest strength of the aggregates, concrete can be separated into its composite materials (Schenk, 2011). In order to exert the right force on the aggregates, crushing and grinding are combined. The fine particles, i.e. cement paste, require thermal treatment to dehydrate the material in order to be used in the production of new cement (Zuokui, 2012). This year, the SC is being introduced commercially and can manage 150 mm concrete debris (BEwerken, 2013).

There are several examples of buildings built with concrete containing a high rate of recycled aggregates. In Australia, a community building was constructed in 2008 with a load-bearing foundation slab of concrete which contains 95% recycled content (Edge Environment, 2011). This was the first construction made with this high level of recycled concrete content. Also for the Netherlands an example can be given of a building with a high concrete recycled content. In 2013 a swimming pool was opened in Maastricht, called de Geusselt. The concrete used for this construction contains 100% recycled concrete aggregates (Mebin, 2011). Actual implementation of aggregates in building material is the next step to acceptation of this product. Examples can help in this process.

3.4.4 Gypsum based material

Even though gypsum comprises a small share of the stony C&D waste material, in can be recycled. A mono-stream of gypsum is the input for the recycling process, thus separation on-site is preferred. For the recycling process, the gypsum is burned. The residue of the heated material is gypsum powder, which can be used in the production of gypsum material. Recycled material replaces mined gypsum and synthetic gypsum. In the Netherlands, the virgin synthetic gypsum is recovered via flue-gas desulfurization of a coal-fired power plant (M. Meijering, Personal communication, 22 January 2013).

3.4.5 Roof bitumen

In the MFA, roof bitumen is not separately included since roof bitumen is registered into the LMA within different categories (asphalt or stony material). Bitumen is recyclable and therefore included in this study towards technologies for material recycling within the building sector. Bitumen is used for roofing and asphalt production. It is obtained from crude oil refinery, the residue is the high viscous, black and sticky bitumen. There are three steps that are followed for bitumen recycling: control and separation of contaminants, shredder, and rejuvenation of the material (Recycling Platform, n.d.). The collected bitumen roofing should be free of tar, asbestos and other materials (e.g. metals, wood, sand). Collected bitumen with approved quality is shredded. The shredded material is treated by rejuvenation process, which decreases the viscosity of the bitumen in order to make it easy to process, as it was before (*ibid.*).

In the Netherlands recycling of bitumen is already put into practise. The company Icopal recycles used bitumen roofing into new roofing. They claim that their recycling saves 615 kg CO_2 per ton roofing (Icopal, 2013).

3.4.6 Wood

Recycling of wood would, in the optimal situation, follow a cascade of use applications as depicted in figure 3.8 (Goverse *et al.*, 2001). Wooden material, can next to or after being re-used, recycled. The wood can be recycled into another high quality wood product. If, for instance, the wood starts as a beam, after its useful life as a beam it can be used for floor board. After its life as a floor board it can be made into a window frame. Each extra step, extra life form of the wood before incineration, is enlarging its useful lifetime and therefore saving newly produced wood.

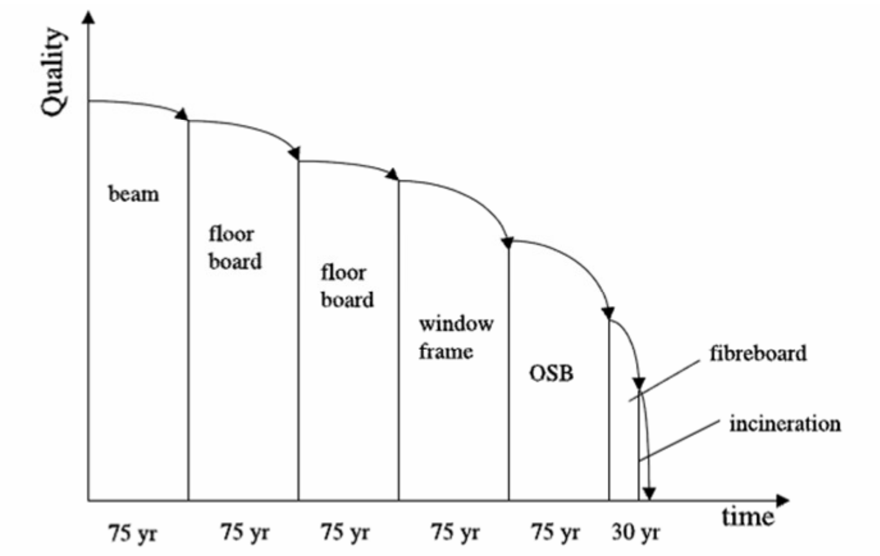

Figure 3.8 – Optimal lifetime of wood, cascade for pinewood (Source: Goverse, 2001).

Similar as for re-use of wooden materials, adjustments in the design and building phase can stimulate full recovery of the material in order to increase high quality recycling of wood (Goverse *et al.*, 2001). Separating the wood on-site will increase the amount of high quality material that can be re-used. Wood from a demolition site needs to be treated before it can be recycled, e.g. remove nails and adjust size (Tam and Tam, 2006). Whether recycled wood can be used for production of OSB (oriented strand board), which is suitable for load-bearing applications in construction, requires additional research.

Next to that, wood A and B can be recycled into chipboard. The wooden material is shred into small wooden chips, which can be used for making chipboard. Products that are made from this material do not have the same structural capacity and are therefore not usable for construction beams, floor etc. Chipboard can be used for making furniture. If furniture is considered to be part of the building sector, recycling wood into chipboard can be seen as recycling within the building sector.

3.4.7 Metals

Metals from construction have traditionally been recycled, since they are recovered in large quantities (Damgaard *et al.*, 2009). For steel, there are two modern ways of reprocessing steel: electric arc furnace (EAF) and basic oxygen furnace (BOF). In the EAF process 100% scrap is accepted. In the BOF process 25-30% of the ingredients is scrap steel, the rest is iron ore (Damgaard *et al.*, 2009).

In general, the EAF process is as follows. The scrap is preheated, were after the scrap is loaded in baskets in which furnace anodes are brought into. The energy flow to the electric arc is kept low, until they are fully submerged in the scrap. At that moment, the energy is increased up to complete melting, which is at 1600 °C (Damgaard *et al.*, 2009; Crundwell *et al.*, 2011). To obtain additional heat, oxygen can be added in early stages of the melting process. When the steel is liquefied, alloying and deoxidizing compounds can be added. After that, the steel can be used in production for any steel production.

BOF is for approximately three quarters made from molten pig iron, and one quarter of scrap steel. In the process, high-pressure oxygen is injected into the molten iron to burn out excess carbon and other combustible contamination (Kirchhoff, n.d.). Non-combustible contamination will float as slag on top of the melt, which will be removed. Energy supply to this process is from the heat of the molten iron and the heat induced by adding pure oxygen.

3.5 Comparison

In table 3.1, a summary of the available technologies discussed in this chapter is shown. For the major share of the materials, a recycling method within the sector is available.

Table 3.1 – Summary of the processes, technologies and best practices for re-use or recycling of C&D waste.

Material	Re-use option	Recycling option	Best practice
Concrete	-	Concrete aggregate for concrete production - Crushing, sifting, with or without washing - Advanced Dry Recovery - Thermal treatment of concrete rubble - Smart Crusher	Swimming pool build with 100% concrete aggregates in concrete
Bricks	- Manual removal of mortar - Heat-treatment to release mortar from brick	Use stony aggregates in production of new bricks	Making bricks available for citizens, re-build buildings with same material
Gypsum based material	-	Heat to retrieve gypsum powder which can be used for new gypsum products	-
Roof Bitumen	-	Include in production of new bitumen	Recycle old bitumen roofing in new
Wood	Re-use for similar purpose	- Enlarge life by using the wood in another product - (Chipboard for furnishing)	Constructing a wall of used doors and windows
Metals	Enlarge life by using the metal for the same purpose in another building	For steel - Electric act furnace - Basic oxygen furnace	Re-use construction parts in new building

To begin with, recycling or re-use of C&D waste materials do require good sorting both on and off-site. For material re-use, careful and selective demolition is required in order to keep the materials intact. The number of different waste streams sorted on-site should increase in order to supply clean material streams to building material producers or raw material producers.

Re-use is valued higher in the Ladder of Lansink than recycling for environmental cause. The materials do, in general, only require minor adjustments for re-use, e.g. removing nails from wooden beams, manual separating mortar from bricks or resizing metal beams. To carry out these adjustments, extra labour is required, which makes re-use of materials expensive. The ceramic clay bricks prepared for re-use by thermal treatment requisite energy input. The 540 °C that need to be reached in the treatment is lower than the temperature needed for production of new ceramic clay bricks, 1100 °C, therefore re-use requires less energy than producing a new brick. This thermal treatment of bricks has, however, not yet been put into practice. Therefore, the feasibility of this method should be examined further.

Metal recycling is practiced commonly, most of the benefits for environment and financial are acknowledged. Recycling slows depletion of natural resources, avoids mine waste products, and it decreases energy demand up to 90%, in respect to metal-from-ore production (Crundwell *et al.*, 2011). Therefore, this sector is successful in recycling. It is, however, not known if the waste metal from the building sector is indeed being recycled into building material. In order to give an estimate of this, a mass balance analysis should be executed. By comparing the demolition waste metal entering the metal production with building material leaving the production company, the average rate of construction metal waste in new construction metal can be determined.

Gypsum based material, roofing material, and bricks are small material streams in C&D waste and have a minor number of recycling technologies. Nevertheless, they are well recyclable as is illustrated in this chapter. For gypsum and roof bitumen collection strategies are available in the Netherlands. Therefore, the expectation is that these recycling methods will be used more frequently in the future.

More efforts in experiments and research, e.g. on wood or cement recycling, on improved recycling options are preferred for taking the next steps to the circular economy in the building industry. The coarse fraction of concrete aggregates can be easily implemented in production of concrete to substitute sand and gravel. As explained in section 3.4.3, adding concrete aggregates in concrete can comply with legislation regarding building material. The fine fraction that arises from crushing stones, which is 50% of the initial stone volume, has no recycling option within the building sector yet. In case more C&D stony material is used as aggregates in production of new stones, more fine material will be released. Thermal treatment of concrete rubble can separate cement paste from the fine fraction. However, this requires large amounts of heat and therefore implies a large CO_2 emission. The smart crushing technology could be a better solution. It requires no heat input and the small particles that remain are likely to be all cement paste (Zuokui, 2012). In case this material can be included in cement production, a large step towards decreasing CO_2 emission in the construction sector can be made. By an experiment, Zuokui (2012) showed that cement paste could, after thermal treatment at 800 °C, replace 20% cement in mortar without quality loss. Nevertheless, further research and projects in this field are needed in order to show that cement paste can included in new cement.

Woody material can have a long life by using the same material in different products. On the contrary, wood is a renewable resource, thus recycling of the material might not be necessary. In this study the circular economy is preferred, and that includes giving biomass back to nature or recycling the materials in their own cycle. Woody biomass can be seen as a sustainable energy producer. Since incineration of biomass in WIP's in the Netherlands is cheap at the moment, wood recycling has a feared competitor. However, it should be kept in mind that in order to call wood a renewable or sustainable resource the production forest should be maintained by certain criteria (Lattimore *et al.*, 2009). Next to that, more production of wood requires more land use, which is in some countries, like the densely populated Netherlands, an issue to be considered. Furthermore, recycling wood requires labour since nails and other irregularities should be removed. More research or projects towards successful recycling of wood should be executed to show whether it can also be economically beneficial.

3.6 Discussion

As we have seen, a limited number of recycling methods for C&D waste recycling in the building sector exists. However, this does not mean that it is not possible. Furthermore, the sector is still evolving, at the moment projects on recycling of C&D waste materials are carried out, e.g. smart crusher for concrete.

In this chapter, an overview of the most promising recycling technologies that are available or upcoming were discussed. Nevertheless, it is incorrect to conclude that all technologies have been covered. Most of the discussed methods were examined by Dutch scientists or practiced in the Dutch market. It is possible that new projects being executed in, for example, Asia where the availability of suitable aggregates for concrete production is more severe (Meyer, 2009), are existing but not included in this study. The scope in the current report is on the Dutch demolition sector, hence technologies that have been put into practice in the Netherlands were discussed. Further research may focus on international developing technologies.

Furthermore, the possibility of using C&D waste materials for other purposes in the sector than their original material is not investigated. For instance, the use of fly ash, which is the residue of (C&D) waste incineration, can also be used in concrete production (Meyer, 2009). This was not part of the current study. However, it could contribute to recycling options in the building sector. In the future, studies towards separation of complex materials should be conducted, for example regarding separation of stones contaminated with insulation materials.

4 Construction and demolition waste recycling system

The current status of C&D waste recycling has been researched in chapter 2 by a MFA. The literature research in chapter 3, regarding technologies for high quality waste recycling, showed that there are technologies available. Therefore, the barrier for high quality recycling seems to be elsewhere. In this chapter stakeholders are asked to give further insights in the barriers towards high quality recycling of C&D waste materials.

In section 1.1, we elaborated on the three distinctive phases of the lifecycle of buildings, i.e. pre-building phase, building phase and post-building phase. This system is extended (see figure 6.1) to illustrate were the main actors of C&D waste recycling interact. The pre-building phase includes raw material production and building material production (prefab material). When the building materials are available, the building is constructed. Once the building is completed, it can be inhabited. Even though users have a minor impact on the waste generated, they are included within the stakeholders because the use phase of the building is a vital part of the life cycle of the materials. The demolition phase follows after the use phase of the building has ended. The waste material recovered during the demolition - or construction - phase is sorted. This can be executed by the demolition company or by an off-site sorting company. The sorted material can re-enter (after appropriate treatment, see chapter 3) the raw material, prefab material or the construction phase. The customer, the petitioner of the demolition, is the starting point of the waste recycling system. The client has an influence on the decision-making related to waste treatment. For instance, the time available for demolition is a result of the choices made by the petitioner.

Studying the relationships between actors operating in the system, an insight regarding the possible barriers that hamper the recycling of C&D waste can be revealed. Next to that, a look into the future through the eyes of the stakeholders gives the opportunities and threats of a project like Cirkelstad. These topics are approached in order to give answer to the third sub-question: *Which barriers impede high quality recycling of construction and demolition waste?*

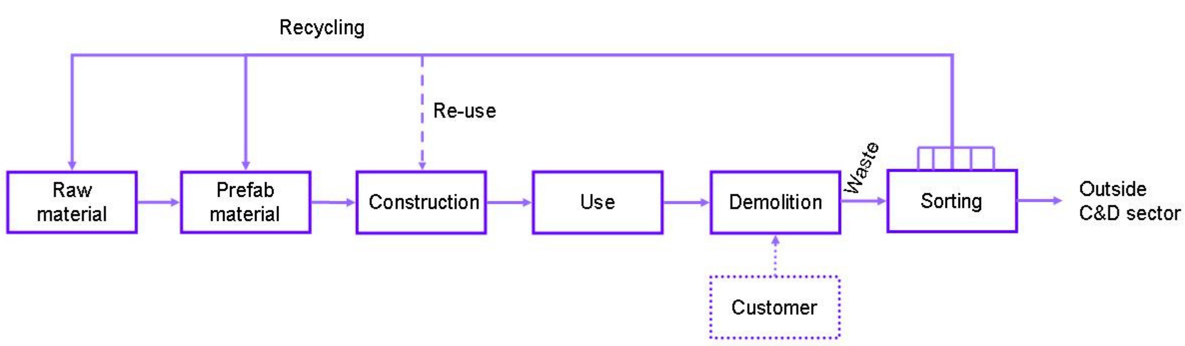

Figure 6.1 The system of C&D waste recycling. The flow of the (waste) material is depicted over different parts of the system. The customer has an influence, without interfering with the material itself.

4.1 Method

For this part, a qualitative research is conducted. The qualitative study is performed to support the quantitative study regarding the MFA and the available technologies to recycle C&D waste (chapters 2 and 3). Next to that, it provides a broad picture of the problems occurring in the C&D waste recycling sector.

The C&D waste recycling system consists of raw material producers, building material producers, construction companies, users, demolition companies, sorting companies and customers. The users do not have a representative in this study since they do not work with the material, except if they are the initiators of the demolition of a building. Demolition companies may also be responsible for the material sorting, and can therefore also be regarded as a sorting stakeholder. This leaves six different groups of stakeholders identified in this C&D waste recycling system. These groups have different views on the system, since they have diverging core businesses. For each part of the system, one or two actors were interviewed. As Flick (2006) mentions, the number of cases is less important than the quality of sample decisions on which the study depends. In general, the chosen interviewees are large players in their sector. This does not apply for all the actors; one acts as the association for producers of a specific product.

On the basis of semi-structured interviews, the opinion of different stakeholders was gathered. This type of interview was conducted, because it is expected that interviewees will discuss more freely their viewpoints on the subjects in this type of interview than in a standardized interview or a questionnaire (Flick, 2006).

The topics deliberated in the interview were the actors' perspective on the current recycling C&D waste system, the future of recycling of C&D waste and system co-operation initiatives like Cirkelstad. In Appendix I, the interview guide can be found. The interviews were held in Dutch language.

The stakeholders were free to choose whether to respond to the question in written form or by phone. This freedom of choice was made in order to remove the threshold of making time for responding. Most of the representatives had a preference for responding by phone, five of six. The stakeholders are treated as representatives for the part of the system they operate in. Therefore, they will be referred to as their position in the chain or as company A to F. The raw material producer is labelled as company A, the producers of building material are labelled as companies B and C, the construction company is company D, the demolition and on-site sorting company is company E, and the customer is company F.

After finishing the interviews, the data was analysed. In order to describe the different viewpoints of the stakeholders' C&D waste system, several topics were determined beforehand based on the questions that were asked in the interview: Current system, future recycling and co-operation in the system. From the data retrieved, important themes were clustered per category to give an overview of the barriers and opportunities in the system.

4.2 Results

In this section, the results of the interviews are given. To start with, a comparison with earlier findings, chapter 2 and 3, is made. This is followed by the stakeholders view on the current C&D waste recycling system, the project Cirkelstad and the future of C&D waste recycling.

4.2.1 Comparison with earlier findings

In general, all actors agree that the recycling rate of C&D waste is fairly high in the Netherlands. At least the largest streams, stony material, metals and to a lesser extend wood, are recycled to a sufficient degree. Nevertheless, the high quality recycling is considered to be still in an infant stage (company F). For stony aggregates, for example, manufacturer B put forward that it is cheaper and easier to use it as base material for roads. Therefore, most of the material finds its way towards this purpose. The MFA constructed in section 2.4 shows this finding, as 93% of the stony aggregates was used as base-material for roads. Wood is seen as a renewable material, implying that incineration with energy recovery is an acceptable treatment option. For smaller materials, like insulation material, the separation is more difficult since it may comprise different materials. As a result, the recycling of these materials lags behind.

Furthermore, the manufacturing companies have technologies and practical knowledge for including recycled aggregates in their production process. The most used method for secondary aggregate preparation is crushing, sifting and washing. Other methods are still in development, but have high expectations, like the smart crusher (see section 3.4.3). Hence, technologies for recycling are available or in development, the cause of the low recycling rate within the sector seems to be at another point in the system. Therefore recycling technologies are not assigned as a problem regarding high quality recycling. Almost all stakeholders do, however, indicate that separation and sorting of the waste as starting point of improving the quality of the material. Less contaminated material is easier to process in building material production processes. They expect that, in case separation of the C&D waste provides clean mono-streams of materials, high quality recycling of building material will increase.

4.2.2 Current system

According to the stakeholders the current C&D waste recycling system is being hampered by the economic crisis, the availability of suitable waste materials and the project planning.

Economic climate

All actors mention that the current economic climate makes it difficult for the sector to recycle C&D waste materials. Due to the crisis, the price of raw materials is rather low. At least, it is lower than the price of secondary materials, except for metals. As a result, secondary aggregates which are designated for use in the production of concrete are piled up having a difficult market position, at least according to company D.

Another consequence of the lower economic activity is the decrease of construction and demolition projects in the Netherlands. This leads to a stagnation of the amount of C&D waste that is released and the projects in which the C&D waste can be recycled.

Availability

Manufacturer B and C claim that, next to the price, not enough suitable aggregates are available to include secondary aggregates in their production process. Two barriers are mentioned for the low availability of proper aggregates. First, the materials are preferred to be separated correctly. The materials included in production processes require certain quality, which can be reached by good separation. Second, for stony aggregates, it is cheaper to recycle the material as base material (company

B). In order to use stony aggregates as base material, lower requirements are set to the composition of the aggregates. The stony material may contain concrete, masonry, other bricks, glass etc. Leaving minor amounts of clean aggregates for recycling at high quality.

Another barrier to promote high quality recycling is that incineration is cheap at the moment (company E). Thus, attempts towards recycling of combustible materials, e.g. plastics and wood, have to compete with the low disposal costs of waste incineration plants.

Planning

There is a contrast in the plan of action regarding construction and demolition, in the opinion of demolition companies. For construction each step is included in a time plan. In case the space of the newly constructed building is occupied by an old building, the latter is needed to be demolished in a short amount of time. This leaves no time for careful material separation. According to company E, the attitude of customers for demolition towards demolition is disrespectful. This needs to be changed in order to be able to demolish buildings sustainable, which requires more attention and time.

4.2.3 Cirkelstad

In order to close the life cycle of building material, all actors within the system should work together. Cirkelstad is seen as a project to demonstrate chain co-operation and aims at creating a circular economy. The project Cirkelstad is showing that bringing together material producers, demolition company and the customer/initiator around one table would tend to recovery, re-use and recycling of C&D waste materials. “The front and the back of the lifecycle of building materials should work together” (company D). Furthermore, interaction among stakeholders can lead to joint responsibility. That is, also according to company F were interaction among stakeholders should lead to.

However, according to company A, not all materials should be seen as scarce. In a project like Cirkelstad, all products are aimed to remain in their own product line. While in case the aim is not the recycle at high quality but reduce, for example CO_2 emission, this is not the best option. For stony aggregates, transport distance is a component to consider when looking at CO_2 emission and environmental impact. Therefore, some parties are convinced that viewing materials in absolute cycles is not the ideal way of treating the materials. As company C said: “road construction also needs stony aggregates. In case all the aggregates are used for making building materials, aggregates need be imported to supply the demand in the road industry. As a result, more lorries will have to travel longer distances to meet the demand.”

Furthermore, the producers of raw materials (A) and producers of building materials (B and C), agree on the fact that the emphasis in such initiatives is mainly on the largest waste stream: stones. As shown in chapter 3, recycling options for these materials are available. As a result, the stakeholders assume that large steps towards a circular economy can be made in rather un-exploited recycling fields for smaller material streams, i.e. insulation material.

4.2.4 Future

Regarding the future, the actors have several points of attention: the economic crisis, material availability, scarcity, technologies, labour and changes in building material.

Economy

All stakeholders expect that the economic climate will improve. This will lead to an increase of the price of raw materials. Therefore, secondary materials will become more competitive to be used in production of building materials. The difference in price will extend financial tools for material recycling (company D). Furthermore, an improved economic climate will result in more building demolition in order to make place for the new buildings. At the moment refurbishment is more popular than constructing new buildings. Consequently, minor C&D waste material is available for recycling. According to company C, it might be better to demolish buildings and construct new ones instead of renovation, in order to make the buildings comply with modern wishes.

Furthermore, economical benefits of high quality recycling may be enhanced by including hidden costs in the price of building materials (company E). As a result the price of primary materials increases, which narrows or overcomes the gap between the costs for primary and secondary materials.

Availability

The expectation is that the financial climate will improve and the number of projects in the building sector will increase. As a result, more C&D waste material will be released. Additionally, the prediction is that road construction will decrease (Hofstra *et al.*, 2006). Consequently, more stony aggregates will be available for inclusion in production of stony material, since the capacity for cheap and easy treatment, base material for roads, will decline. To prevent large stocks of stony material, this material may be recycled in concrete and brick products.

Scarcity

The recycling of metals is already executed on large scale. The material is scarce, which makes secondary material for production of new metals financially beneficial for the producer. It is expected that more materials will become scarce in the future, leading to larger efforts in re-using and recycling waste materials. Company D expects that the waste will not be considered as waste in the future, but as building material. In order to accelerate this change in mindset, hidden costs should be included in the total costs of raw materials. In general, building materials are cheap at the moment, making recycling not beneficial (company E).

Technologies

It is expected that separation methods will develop in the future. This is, according to several actors, the main issue that needs to be solved to recycle more materials. This improvement should be made on-site and off-site. However, separation costs time and money. A solution, for financing the extra costs for material separation, by company B, was to include a fee similar to the removal fee ("verwijderingsbijdrage") for electric appliances in the Netherlands[6]. The removal fee was included in the purchase price of the appliances. In case a separation fee is included for materials that require additional efforts for separation, the funding is solved. Next to that, it will acclaim the use of simple building materials in construction.

Labour availability

[6] In February 2013 the removal fee has been abolished. This is a result of the WEEE directive revision in 2005 (de Roos, 2013)

"*Nederland kennisland*" – the Netherlands, a country of knowledge – is what the government of the Netherlands propagates. Knowledge is manifested as the greatest good, and therefore studying to gain scientific knowledge is encouraged. Consequently, the number of workers in the building sector is decreasing. Additionally, the sector is at the moment badly affected by the economic crisis. When the moment arrives that the activity in the building sector increases, there will not be enough labour available for refurbishment requests (company B). To decrease the required labour hours, company B expects that buildings will be demolished in stead of refurbished and new buildings will be constructed with prefab materials.

Building material

Even though most of the actors are positive about the future, demolition companies observe some problems. Old buildings, which are currently being demolished, contain rather simple materials. These can be sorted into separate base materials. Current construction projects include more sophisticated materials, which consist of more types of materials, e.g. plastic and wood, which are difficult to separate. Also the use of polyurethane as insulation material is seen as an inconvenient addition in a building. It can be used in several areas in a building. Once it is connected to stony material, it will be difficult to separate the two materials. As a result company F said: "the future of C&D recycling will become even more difficult". Separation of the waste materials will become more complex and will require more effort, in time and money.

4.3 Conclusion and discussion

Considering the circular economy as the ultimate goal, the current status of recycling and the initiatives towards high quality recycling are not yet sufficient to see this happening within a foreseeable period.

Similar to the conclusion of chapter 3, the stakeholders agree that high quality recycling options for large waste streams are available and separation of the materials needs to be stimulated. The main opinion of the stakeholders is that when the better economic times return, recycling of C&D waste materials will get a boost. This can be either be initiated by higher prices of raw material, implementation of new technologies or an initiative that makes money available for separation.

Only one stakeholder (company E) mentioned that policies regarding inclusion of a certain share of recycled material in new building products might be an idea to stimulate high quality recycling. Therefore, it seems that the system is convinced that self regulation will increase the rate of high quality recycling.

All actors that were interviewed had the opinion that the C&D waste recycling system was doing quite well. The Dutch recycling rate is one of the highest in the world, thus need to get some credits. However, when the aim is high quality recycling, the system is still in the starting phase. The actors all appointed another phase, than their own, in the C&D waste recycling system where changes should be made, in order to improve the recycling quality of the materials. For instance, the time restriction on demolition projects was only accounted by the demolition company (E), which is forced upon the demolition company by the inquirer for demolition. The image was sketched that the problems always lay at someone-else's. Therefore, it is important that the stakeholders sit together and work on a joint responsibility. Hence, it would be interesting when projects like Cirkelstad should communicate their findings on the project, especially on the co-operation between the different actors. Information that can be retrieved from monitoring the project is valuable for future collaborations.

Only two actors (demolition stakeholder and customer with sustainability high on its agenda) have indicated that new developments in building materials could form a threat for future recycling. The rest of the actors do not mention this problem, they have the opinion that separation of the materials is the key to improving the system. However, the new types of building materials may complicate this step separation step even further. As demolition companies are experts on this field, it is good to consider demolition plans already in the design and construction phases of a building.

The stakeholders have all different interests, e.g. deliver good quality and cheap products, optimizing living comfort and demolish a building fast and cheap. This all is done, with their own financial gains in mind. High quality material recycling does not seem to be profitable (see section 4.2.2). As a result, most of the rubble is being used as base material for roads and is wood being incinerated with energy recovery. These waste treatment processes have shown that they are effective, and therefore the familiar road is usually taken.

Some stakeholders do not advocate the idea of closing the material loops. The raw material producer is, naturally, not in favour of using less primary material. However, also other stakeholders (companies B and E) point out that closing the cycle may not always be the best option energetically. As the main goal of this study is to stimulate the circular economy of the building sector, recycling of rubble as road base material is not seen as a favoured option. The ambition is to reduce the material use in the construction sector, not in other sectors.

The interviewed stakeholders are already engaged with sustainability. Therefore, the actors have knowledge of C&D waste recycling. However, not all companies they represent have the same vision. Therefore, the results of the interviews are more in favour of high quality recycling than the represented stakeholders visions. Nevertheless, getting insights in the barriers and opportunities in the system, can be appointed best by stakeholders which are already conducting this type of recycling.

For further research, we advise to pursue research in the C&D waste recycling system. The current study aimed at giving insights in the C&D waste recycling system, not to generalise. By interviewing more actors, a more general picture of the system can be researched. Next to that, the C&D waste recycling system could be enhanced in further research with other stakeholders. An example of a stakeholder that could be included is the government. Policies have influence on waste separation, waste treatment and material use. Furthermore, the main barriers are researched in this study, the solutions to overcome these barriers is a topic that could be researched in future projects.

5 Business case

As concluded from the insights given by participants in the C&D waste system (chapter 4), there are several barriers that hamper high quality recycling of C&D waste. Furthermore, chapter 4 showed that improvements in recycling of C&D waste within the sector can be made in different sections of the C&D waste system. Separation of the streams was pinpointed as one of the requirements in order to improve the circular economy of C&D waste materials. By means of a case study regarding a sustainable demolition project, a comparison among the theoretical findings and a sustainable demolition project is made. Furthermore, some insights in the financial part of demolition and recycling are generated. The question that is central in this chapter is: *What are the reasons to participate in a high quality recycling project?*

5.1 Method

The business case under study is chosen, because it has been one of the first large sustainable demolition projects in the Netherlands. Sustainable demolition is a demolition project in which waste materials are separated thoroughly and is high quality recycled. The project comprises the demolition of 15 buildings. The customer requested the highest possible high-quality recycling rate. In the end it was claimed that the project reached 96% high quality recycling rate. This is larger than the 11% average in the Netherlands in 2012 (see section 2.4). By describing the project, from the creation of the idea up to the execution, lessons can be learned from this demolition.

Similar to the method of chapter 4, data was gathered by a semi-structured interview. The interviewee was the project manager of the company that was the initiator of the demolition. The reason for using a semi-structured interview is again the higher possibility for receiving their viewpoint on the case in comparison to other interview methods (Flick, 2006). In Appendix J the interview guide is added. The demolition project was carried out in 2011 and 2012, thus completed during the current study. The topics discussed in the interview were: the incentive for the sustainable demolition project, how different treatment options of the case compare with findings in chapter 2 and 3, what the benefits and costs of sustainable demolition were and which lessons were learned by doing the project.

5.2 Case description

In this section, a description of the case as followed from the interview is given. The subjects dealt with are the creation of the project, execution of the project, monitoring of the recycling treatments, costs and benefits and learning points.

Creation of the project

The company under study claims to have sustainability high on its agenda. Demolition causes a lot of waste, which should be treated correctly. Therefore, a straightforward result was to also include sustainability in their demolition projects. The project comprised a set of buildings, 15 in total, which were likely to be demolished within three years. This gave the company the opportunity and space to include certain sustainability criteria in the demolition contract. The aim was to reach the highest rate of high quality recycling of the C&D waste. The definition of high quality recycling, according to the company, reads "*returning the materials to manufacturers in order to use them for similar purposes*" – for example used concrete would be used as a base to make new concrete. The first requirement to which the demolition company should comply was showing for –at least – minimal eight products recycling contracts with building material producers. The materials released by demolition should be sent to these producers, for inclusion in the production of the same product. To compare the subscribed demolition companies plans on their sustainability level, the rate of high quality material recycling was taken as measure unit. The applicants for the contract are obliged to include a percentage of high quality recycling in their project enrolment. This percentage of material recycling was also to be included in the final contract. Inclusion of CO_2 emission in the contract was considered. However, during the process this appeared to be too complex to be included in the contract. Therefore, the high-quality recycling rate was chosen as single measurement for sustainability.

Demolition companies which meet first the requirement can apply for the project. All applications were compared on:

- the price for demolition
- high quality recycling percentage of all the materials

The party that scored highest including both criteria received the project. In the final contract, a recycling percentage (by weight) of 96% was included.

Execution of the project

Sustainable demolition can be regarded as building backwards. All materials need to be retrieved from the building separately. As it was a demand of the customer, all materials were sorted on-site. For the following materials separate containers, or assigned areas to stock the material were available on-site:

- Concrete
- Masonry
- Roof bitumen
- Ferrous metal
- Non-ferrous metal
- Wood A
- Wood B
- Wood C
- Glass
- Plastics/insulation material
- Electrical appliances

The separated streams are similar to the streams that were depicted in the MFA. Different types of stones were separated on-site. Gypsum material, however, was not separated during this demolition. The building contained only a minor amount of this material. Small shares of gypsum may be added to other stony waste streams, since these may contain a small share of contaminants (<<1%). In order to reach the 96% of high quality material recycling, the materials were separated thoroughly. The sorted materials were transported to the material producers under contract with the demolition company. However, the precise treatment methods of the waste material streams were not open for investigation.

Monitoring

In this project, it was mandatory for the demolition company to demonstrate that the waste leaving the demolition site was delivered to the producers with whom the demolition company had contracts. By sampling, several shipments were tracked, in order to check the treatments of these waste streams.

However, verifying what happened to the waste streams in the treatment facility did not have a high priority. Therefore, it was only assumed that material streams that arrived at the producer's site, were recycled maintaining a high quality.

A penalty was enclosed in the contract in order to show that the company requesting the demolition was genuine about the recycling percentages by which the applicant enrolled. In case the percentage was not met, a penalty of €2500 per 0.1% was imposed. At the end of the project, no penalty was given, since the target was reached.

Cost and benefits

Due to extra labour time that sustainable demolition requires, because of removing the materials one by one, the time needed and the price for the demolition increases. On the contrary, the materials retrieved from the building can be sold for recycling. An estimation regarding the extra costs for sustainable demolition was made at the start of the project. The costs for demolition, excluding thorough removal of asbestos and materials contaminated with asbestos, would increase by 10 to 15%. The removal of asbestos accounted for the main part of the budget (60%) and spent time for demolition. Therefore, the total costs for demolition would maximal increase with 6% by making the choice to demolish the buildings on a sustainable way. As a result, the extra costs and time needed were accepted. Nevertheless, the company tried to diminish the total cost by enlarging the volume of the project. As stated before, there were 15 buildings to be demolished with a high probability, within three years time. The high certainty of the constant generation of income over three years was attractive for demolishers to enrol for this project.

The company claims that the higher demolition costs made the team more creative. Due to the high costs, they looked beyond the project, trying to use the waste material in other projects. For example the concrete aggregates could be used in the area. This may prevent new sand and grind mining and transportation over a longer distance of (secondary) aggregates. The team working on the sustainable demolition seemed "more focussed on sustainability in all facets of their profession" and the project "changed the mindset within the team".

Learning points

This project was the first demolition project, for the company in place, which was executed with high quality recycling as a goal. The following demolition projects will be executed sustainable also, if the materials in the building make it worth being recycled. "The policy of our company is to demolish buildings sustainable, but the degree of high quality recycling will depend on the materials in the building." Time and energy that separation of the materials require are to be considered in respect to the benefits for the environment.

According to the company that initiates the demolition, several lessons were learned in this project:

1) Connecting projects. It saves money and transportation costs, as in fuel and CO_2 emission, if projects in the same area are connected. Not all loops can be closed yet, for example if a demolition project is followed by a construction project, it would be preferred to close material loops. If company G recycles the concrete aggregates it is risky or inconvenient for the customer to demand from the construction company use of concrete from company G. The responsibility of the materials, e.g. supply and quality, it then the inquirers responsibility, not the construction

company'. In order to stimulate high quality recycling, changes in the system are needed. The responsibility should be in the hands of several stakeholders, not one.

2) The requirement was that the demolition company proved that the material streams went to certain building material producers. This transport should be the evidence of high quality recycling. However, this claim cannot be made with a 100% certainty. Therefore, in future contracts the demolition companies will be forced to prove that the material is being recycled in the high quality they claim.
3) Recycling and separation of some materials appeared to be costly. The recovered insulation material consisted of several different materials, for example plastic and wood. It was time consuming to separate these materials, and the benefits in terms of costs and environment was debatable. In future projects, conclusions from the material inventory towards possible recycling methods will become more accurate, since their knowledge has increased.

5.3 Conclusion and discussion

The main driver behind conducting a sustainable demolition was to live up to the sustainability objectives the company has. They complied to these objectives since they consider themselves a role model. Additional costs for sustainable demolition were in this project lower than 6% of the total costs. Due to the large amount of asbestos in the buildings, these costs were acceptable for the customer. In this particular case, the amount of asbestos present in the building was large and therefore demanded a large share of the costs and time for demolition. In case the building contains less to zero asbestos material, the additional costs for sustainable demolition will comprise a larger share, probably 10-15% of the costs. These increased cost could be a barrier for a company to request for sustainable demolition of a building.

Furthermore, the company of the case study was able to reduce the costs by increasing the size of their project. They had several buildings that were likely to be demolished. This volume enhancement is not applicable for all projects. Next to that, labour costs were decreased by stimulating use of persons with a distance to the labour market. The government supports these initiatives and therefore these employees are less expensive due to subsidies.

Sorting of the materials was performed properly in this case. In order to discuss whether the demolition was carried out sustainable, the treatment options of the waste material should be compared with their definition of high quality recycling and recycling technologies mentioned in chapter 3. Since we were not allowed to know to which companies the materials were brought for their recycling treatment, we can not give statements on the recycling methods and the quality of recycling of waste in this case. It is possible that the recycling processes are secret. On the contrary, there is the possibility that the recycling methods did not meet the definition of high quality recycling they pursue. Either way, we are not in the position to say whether this was a sustainable demolition or not.

The unit of measure for sustainability was the amount of high quality recycling. By means of a penalty there should be a control over the demolition company, to make sure he is complying with the recycling target set in the contract. There was however, no conclusive prove whether the material was being recycled in the way the demolition company states or aimed at. Therefore, the fact that there was no penalty given at the end of the project does not necessarily mean that 96% of the material was actually recycled at high quality level. Monitoring of the recycling treatment is a difficult task. As the company under study mentioned, in future projects it will be compulsory for the demolition companies to show how the waste materials were treated.

Connecting local projects, for example the re-using stony aggregates for road basement, does not comply with their own high quality recycling definition. It is, however, considered by the company. Therefore, it seems like there are other criteria playing a role in decision making, besides high quality recycling. This could in this case be lower CO_2 emissions, by reducing transportation of the aggregates, or reducing costs since the stony material is already in possession of the company.

Whether hidden costs are included in the company' consideration to pursue high quality recycling is not clear. On the one hand time, energy and financial investment are compared with on the other hand possibility of high quality recycling and benefits for the environment. However, what these environmental benefits comprise is not clear. Therefore, this can not be evaluated.

According to Salzmann (2005), case studies have the following two important disadvantages; the evidence presented is often not hard enough, and case studies are often only valid for a specific sector or company. The data is indeed retrieved by a qualitative research. This does, however, not mean that the data can not supply additional knowledge to the rest of the paper. The case study encloses a demolition project which aims at maximizing the high quality recycling rate of C&D waste, as is similar to aim of this thesis. Therefore, the case is an example of real implementation of the gained knowledge in previous chapters. The way of tackling the project can give inspiration for other demolition cases, and address points of attention for sustainable demolition.

6 General conclusion and discussion

In the Netherlands there is a high recycling rate of C&D waste materials. However, it was not known what this recycling comprises and which methods were used for this recycling. In this study the aim was to research how a circular economy in the building sector could be reached. Primary material use should be reduced by increasing the high quality recycling of C&D waste rate. Therefore, the main research question was: *How can high quality recycling be promoted within the Dutch construction and demolition waste system?*

In order to answer this research question, several methods were used. First an MFA was build. The MFA showed that currently 80% of the C&D waste material in the Netherlands in 2012 was recycled and 10% was incinerated with energy recovery. Focusing on recycling in the building sector, only 11% of the total weight of the waste is recycled within the building sector. C&D waste is rather difficult to track, since it can have several intermediate stops before it reaches its end treatment. For the materials stones, metals and wood, re-use and recycling options were investigated by a literature study. The most promising high quality recycling process is including of cement paste in production of new cement, which is recovered from concrete aggregates by smart crushing.

A qualitative study was carried out regarding the C&D waste recycling system. Stakeholders were asked for their viewpoints on the system. In general, sorting of the waste materials, the economical climate and the type of building materials used are the main barriers for high quality recycling according to stakeholders. One important solution for these barriers is co-operation of stakeholders in order to create joint responsibility for the C&D waste process.

The findings of the MFA, the literature study and the stakeholder interviews were compared to the outcome of a case study. The demolition project aimed at a large share of high quality waste recycling. They company attempted to achieve this by sorting all waste materials on-site. Their drive to conduct a high quality recycling project was that sustainability is one of their pillars, they aim to act social responsible in environmental, social and economic dimension.

High quality waste recycling can be stimulated by engaging all stakeholders of the C&D waste recycling system for this purpose. For example agreements on the time and effort that can be spent for separation, the building materials used in construction can be made and the demand for secondary materials can be aligned. Next to that, it appears that without proper sorting of the materials, high quality recycling is hampered. Furthermore, high quality recycling has to have an economic benefit for stakeholders, which would induce supply and demand of high quality recyclable waste materials.

Recommendations for further research

In this thesis, the focus was on recycling secondary C&D material within the construction sector in order to substitute primary materials. There are also other pathways that can be taken in order to increase the sustainability in the C&D sector. For example, research towards the embodied energy of building materials may help in making an assessment towards which building materials should be used for construction. Next to that, hidden costs of building materials may be included in research in order to assess proper recycling options or material use in construction.

Technologies for recycling in the construction sector were restricted to the materials stones, metals and wood, since these materials are responsible for no less than 80% of the weight of C&D waste. Therefore, they will have a large impact on the environment when not correctly treated. For voluminous materials, like stones, transportation of the material is responsible of a considerable share of the energy use and environmental impacts of the product. Nevertheless, it would be interesting to do further research regarding small material streams like insulation material. The impact of these materials and proper recycling options are not well studied. Some of these materials might be difficult to separate.

Furthermore, research towards how recycled materials may be included in constructions is a necessary next step towards an increased recycling rate of building materials. It is possible to use 100% concrete aggregates for construction. The construction methods slightly differs when using recycled concrete (CUR-recommendations 112). Not all architects and constructors have this knowledge. Furthermore, not all recycled building materials have described methods for use.

In this study it is demonstrated that the C&D sector has a large potential in decreasing primary material use. However, a few bottlenecks exist that hamper the increase of high quality recycling. These barriers are a subject to be solved in future research.

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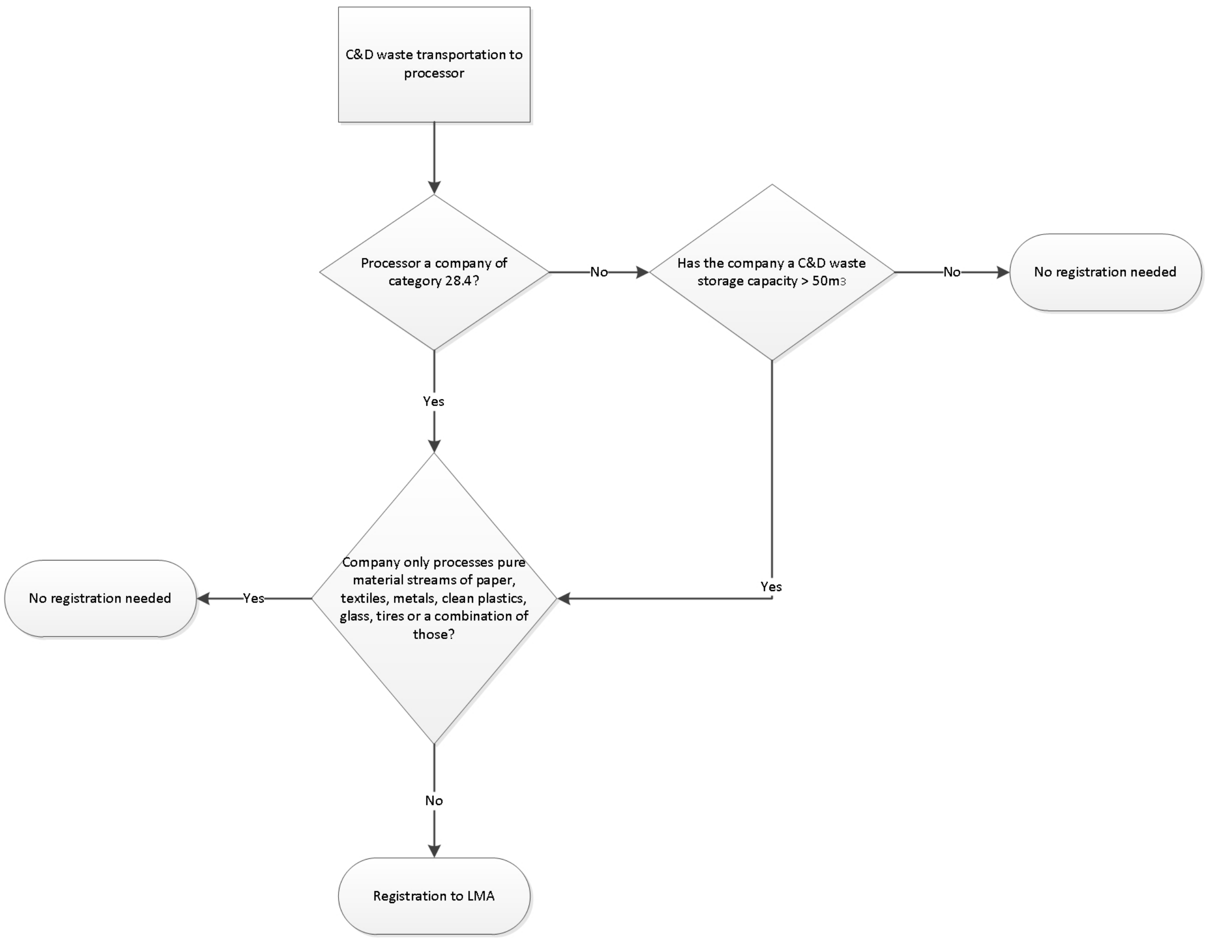
Appendix A – Glossary of acronyms

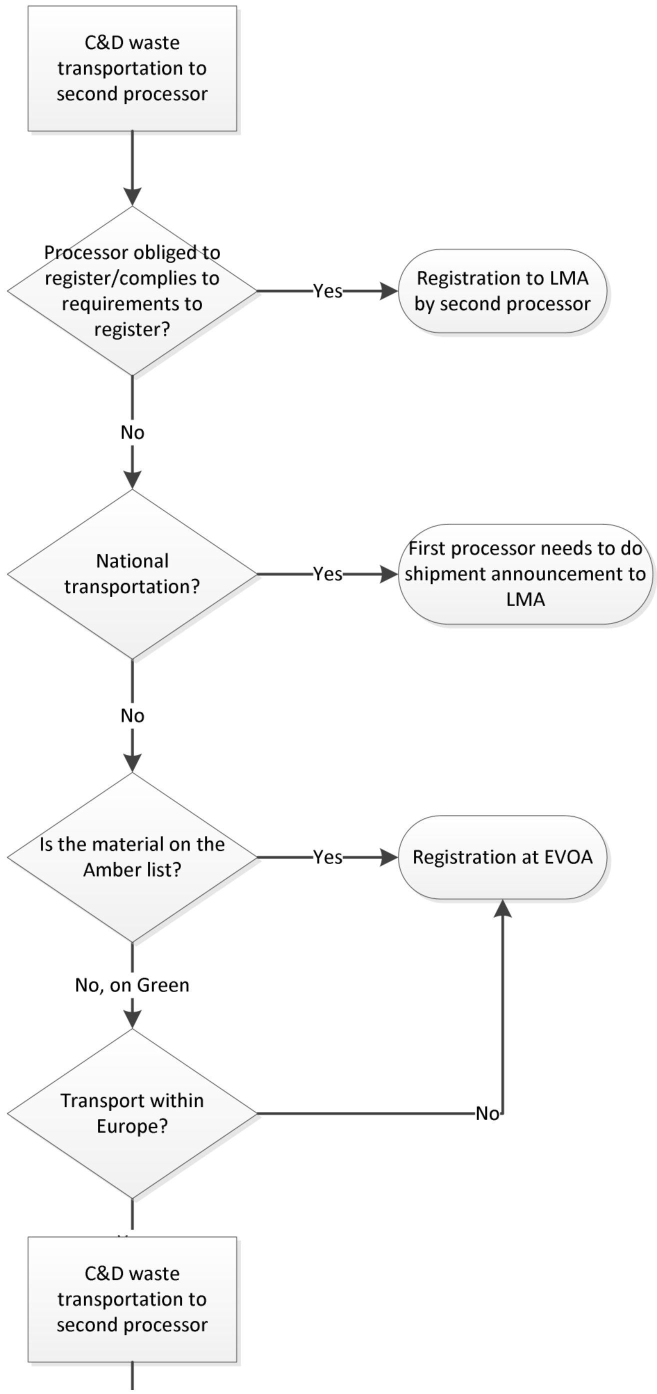
ACC	Autoclaved cellular concrete
ADR	Advanced Dry Recovery
C&D	Construction and demolition
EC	European Commission
EP	European Parliament
Eural	Europese afvalstoffenlijst
EVOA	“Europese Verordening Overbrenging Afvalstoffen” – the Dutch body that implement the EU export waste shipment regulation
kt	Kilotonnes
LAP2	“Landelijk afvalbeheerplan 2009-2021” – the national policy for waste treatment in the Netherlands
LMA	“Landelijk Meldpunt Afvalstoffen” – the Dutch registering body for waste
LoW	European List of Waste
MFA	Material flow analysis
SA	Shipment announcements
SC	Smart crusher
WIP	Waste incineration plant (in Dutch AVI – “afvalverbrandingsinstallatie”

Appendix B – LMA

Registration at LMA works according to the following, simplified, decision trees. For entries of chapter 17 of LoW the first decision tree applies. For entries of chapter 19 section 12, decision tree 2 applies, which involves a second waste processor.



Decision tree 1 – Registration process for materials that are in chapter 17 of the European List of Waste.



Decision tree 2 – registration process of materials that are send to a second processor. Who should register the waste and to which agency? (Chapter 19 section 12 materials of the European List of Waste)

Appendix C – Chapter 17 of European list of Waste

The list is retrieved from EC (2000).

Chapter 17 – Construction and Demolition waste (including excavated soil from contaminated sites)
17 01 concrete, bricks, tiles and ceramics
17 01 01 concrete
17 01 02 bricks
17 01 03 tiles and ceramics
17 01 06* mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances
17 01 07 mixture of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
17 02 wood, glass and plastic
17 02 01 wood
17 02 02 glass
17 02 03 plastic
17 02 04* glass, plastic and wood containing or contaminated with dangerous substances
17 03 bituminous mixtures, coal tar and tarred products
17 03 01* bituminous mixtures containing coal tar
17 03 02 bituminous mixtures containing other than those mentioned in 17 03 01
17 03 03* coal tar and tarred products
17 04 metals (including their alloys)
17 04 01 copper, bronze, brass
17 04 02 aluminium
17 04 03 lead
17 04 04 zinc
17 04 05 iron and steel
17 04 06 tin
17 04 07 mixed metals
17 04 09* metal waste contaminated with dangerous substances
17 04 10* cables containing oil, coal tar and other dangerous substances
17 04 11 cables other than those mentioned in 17 04 10
17 05 soil (including excavated soil from contaminated sites), stones and dredging spoil
17 05 03* soil and stones containing dangerous substances
17 05 04 soil and stones other than those mentioned in 17 05 03
17 05 05* dredging spoil containing dangerous substances
17 05 06 dredging spoil other than those mentioned 17 05 05
17 05 07* track ballast containing dangerous substances
17 05 08 track ballast other than those mentioned in 17 05 07
17 06 insulation materials and asbestos-containing construction materials
17 06 01* insulation materials containing asbestos
17 06 03* other insulation materials consisting of or containing dangerous substances
17 06 04 insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05* construction materials containing asbestos (18)
17 08 gypsum-based construction material
17 08 01* gypsum-based construction materials contaminated with dangerous substances
17 08 02 gypsum-based construction materials other than those mentioned in 17 08 01
17 09 other construction and demolition waste
17 09 01* construction and demolition wastes containing mercury
17 09 02* construction and demolition wastes containing pcb (for example pcb-containing sealants, pcb-containing resin-based floorings, pcb-containing sealed glazing units, pcb-containing capacitors)
17 09 03* other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04 mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

Any waste marked with an asterisk (*) is considered as a hazardous waste pursuant to Directive 91/689/EEC on hazardous waste, and subject to the provisions of that Directive unless Article 1(5) of that Directive applies

Appendix D – Chapter19 section 12 of European list of Waste

The list is retrieved from EC (2000).

Chapter 19 – Wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use
Chapter 19 section 12 – wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising) not otherwise specified

19 12 01 paper and cardboard
19 12 02 ferrous metal
19 12 03 non-ferrous metal
19 12 04 plastic and rubber
19 12 05 glass
19 12 06 wood containing dangerous substances
19 12 07 wood other than that mentioned in 19 12 06
19 12 08 textiles
19 12 09 minerals (for example sand, stones)
19 12 10 combustible waste (refuse derived fuel)
19 12 11 other wastes (including mixtures of materials) from mechanical treatment of waste containing dangerous substances
19 12 12 other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11

Appendix E – Waste treatment codes LMA

This list is in Dutch and is retrieved from LMA (2011).

A. Bewaren / overslag (geen verandering van de afvalstof zelf, tijdelijk karakter):
A.01 = Bewaren
A.02 = Overslag / opbulken

B. Direct toepassen of direct hergebruiken (geen verandering van de afvalstof zelf, definitief karakter, vervangt een primaire grondstof):
B.01 = Inzetten als veevoer
B.02 = Inzetten als meststof
B.03 = Inzetten als bouwstof
B.04 = Inzetten als brandstof
B.05 = Overig inzetten als grondstof

C. Mechanisch / fysisch behandelen (procesmatig, geen chemische omzetting, is een bewerking – vergt nabehandeling –, geen gewichtsreductie van het afval):
C.01 = Breken
C.02 = Shredderen / knippen
C.03 = Sorteren/scheiden
C.04 = Immobiliseren voor hergebruik

D. Chemisch / fysisch behandelen (procesmatig, niet vallend onder rubriek C, E of F):
D.01 = Chemisch/fysisch scheiden
D.02 = ONO is ontgiften, neutraliseren en ontwateren
D.03 = Destilleren
D.04 = Metaal terugwinnen (chemisch)
D.05 = Extractief reinigen (grond)
D.06 = Oxidatie onder hoge druk

E. Microbiologisch behandelen (procesmatig, chemische omzetting door micro-organismen):
E.01 = Vergisten
E.02 = Composteren, anaeroob
E.03 = Composteren, aeroob
E.04 = Biologisch reinigen (water)
E.05 = Biologisch reinigen (grond)

F. Thermisch behandelen (procesmatig, verhitting):
F.01 = Verbranden in roosterovens
F.02 = Verbranden in draaitrommelovens
F.03 = Pyrolyse
F.04 = Vergassen
F.05 = Uitgloeien (grond)
F.06 = Verbranden met terugwinnen materiaal (chloor, zwavel ..)
F.07 = Verbranden met terugwinnen energie (bijstoken)

G.Storten (niet procesmatig, definitief karakter, eindverwerking):
G.01 = Direct storten
G.02 = Immobiliseren

Appendix F – Disposal and Recovery operations EU

Disposal and Recovery operations used by the EU and EVOA (Retrieved from EC, 2008.).

Disposal Operations

D 1 Deposit into or on to land (e.g. landfill, etc.)
D 2 Land treatment (e.g. biodegradation of liquid or sludgy discards in soils, etc.)
D 3 Deep injection (e.g. injection of pumpable discards into wells, salt domes or naturally occurring repositories, etc.)
D 4 Surface impoundment (e.g. placement of liquid or sludgy discards into pits, ponds or lagoons, etc.)
D 5 Specially engineered landfill (e.g. placement into lined discrete cells which are capped and isolated from one another and the environment, etc.)
D 6 Release into a water body except seas/oceans
D 7 Release to seas/oceans including sea-bed insertion
D 8 Biological treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 12
D 9 Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D 1 to D 12 (e.g. evaporation, drying, calcination, etc.)
D 10 Incineration on land
D 11 Incineration at sea (*)
D 12 Permanent storage (e.g. emplacement of containers in a mine, etc.)
D 13 Blending or mixing prior to submission to any of the operations numbered D 1 to D 12 (**)
D 14 Repackaging prior to submission to any of the operations numbered D 1 to D 13
D 15 Storage pending any of the operations numbered D 1 to D 14 (excluding temporary storage, pending collection, on the site where the waste is produced) (***)

(*) This operation is prohibited by EU legislation and international conventions.
(**) If there is no other D code appropriate, this can include preliminary operations prior to disposal including pre-processing such as, inter alia, sorting, crushing, compacting, pelletising, drying, shredding, conditioning or separating prior to submission to any of the operations numbered D1 to D12.
(***) Temporary storage means preliminary storage according to point (10) of Article 3

Recovery operations

R 1 Use principally as a fuel or other means to generate energy (*)
R 2 Solvent reclamation/regeneration
R 3 Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes) (**)
R 4 Recycling/reclamation of metals and metal compounds
R 5 Recycling/reclamation of other inorganic materials (***)
R 6 Regeneration of acids or bases
R 7 Recovery of components used for pollution abatement
R 8 Recovery of components from catalysts
R 9 Oil re-refining or other reuses of oil
R 10 Land treatment resulting in benefit to agriculture or ecological improvement
R 11 Use of waste obtained from any of the operations numbered R 1 to R 10
R 12 Exchange of waste for submission to any of the operations numbered R 1 to R 11 (****)
R 13 Storage of waste pending any of the operations numbered R 1 to R 12 (excluding temporary storage, pending collection, on the site where the waste is produced) (*****)

(*) This includes incineration facilities dedicated to the processing of municipal solid waste only where their energy efficiency is equal to or above:— 0,60 for installations in operation and permitted in accordance with applicable Community legislation before 1 January 2009, — 0,65 for installations permitted after 31 December 2008, using the following formula: Energy efficiency = (Ep - (Ef + Ei))/(0,97 × (Ew + Ef)) In which: Ep means annual energy produced as heat or electricity. It is calculated with energy in the form of electricity being multiplied by 2,6 and heat produced for commercial use multiplied by 1,1 (GJ/year) Ef means annual energy input to the system from fuels contributing to the production of steam (GJ/year) Ew means annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year) Ei means annual energy imported excluding Ew and Ef (GJ/year) 0,97 is a factor accounting for energy losses due to bottom ash and radiation. This formula shall be applied in accordance with the reference document on Best Available Techniques for waste incineration.
(**) This includes gasification and pyrolisis using the components as chemicals.

(***) This includes soil cleaning resulting in recovery of the soil and recycling of inorganic construction materials.
(****) If there is no other R code appropriate, this can include preliminary operations prior to recovery including re-processing such as, inter alia, dismantling, sorting, crushing, compacting, pelletising, drying, shredding, conditioning, repackaging, separating, blending or mixing prior to submission to any of the operations numbered R1 to R11.
(*****) Temporary storage means preliminary storage according to point (10) of Article 3

Appendix G – MFA table

Table G.1 – The MFA for all the material categories. Showing the sizes and end-process per waste category with.

C&D waste materials / Waste process	Stony material		Woody material		Metals		Glass		Plastics		Paper		Insulation material		Asbestos containing material		Sorting residue		Mixed material		Total	
	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%
Incineration - energy recovery	117	1	115	8	4	0			4	2			2	10			600	26	45	4	887	3,6
Incineration - green energy recovery			600	40																	600	2,5
Landfill	224	1					0	0	2	1			8	53	346	100	82	4	52	4	714	2,9
Unknown recycling	0	0							31	17			6	37			953	42	5	0	996	4,1
Base-material	14511	93																			14511	59,7
Recycling in concrete industry	300	2																			300	1,2
Metal recycling					2453	78															2453	10,1
Glass recycling							77	100													77	0,3
Paper recycling											53	100									53	0,2
Recycle in gypsum industry	26	0																			26	0,1
Recycle in chipboard industry			200	13																	200	0,8
Secondary fuel																	260	11			260	1,1
Export energy recovery			409	28					1	1							231	10			641	2,6
Export combustion																	97	4			97	0,4
Unknown export									43	23							36	2			79	0,3
Export unknown recycling			154	10	543	17			61	33							14	1			772	3,2
Export unknown useful application			6	1																	6	0,0
Unknown	388	2			131	4			44	24									1083	91	1646	6,8
Total	**15566**	**100**	**1483**	**100**	**3131**	**100**	**77**	**100**	**186**	**100**	**53**	**100**	**16**	**100**	**346**	**100**	**2273**	**100**	**1185**	**100**	**24317**	**100**

Appendix H – MFA tables for stony material, metals and wood

The tables that are constructed for the material categories "stony material", "metals" and "wood" are shown here. The first table, F.1. is about stony material, the total weight per category and their specific end-treatment options. Table F.2. shows this information for metals and table F.3. for wood.

Table H.1 – Current end-phases for different stone categories

C&D waste materials / Waste process	Concrete		Bricks		Tiles and ceramics		Gypsum based material		Rubble		Total	
	kt	%	kt	%	kt	%	kt	%	kt	%	kt	%
Combustion									117	1	117	1
Landfill	129	8	1	0	0	1	0	0	94	1	224	1
Recyling in concrete industry	300	19									300	2
Recyling in base material roads	1190	74							13321	98	14511	93
Recycle in gypsum industry							26	40			26	0
Unknown			341	100	8	99	39	60			388	2
Total	1619	100	342	100	8	100	65	100	13532	100	15566	100

Table H.2 – Current end-phases for metals material

C&D waste materials / Waste process	Ferrous metals		Non-ferrous metals		Cables		Total	
	kt	%	kt	%	kt	%	kt	%
Combustion	4	0	0	0			4	0
Metal recycling	2222	89	230	45			2453	78
Export recycling	262	11	281	55			543	17
Unknown					131	100	131	4
Total	2488	100	512	100	131	100	3131	100

Table H.3 – Current end-phases for different wood categories

C&D waste materials / Waste process	Wood AB		Wood B		Wood C		Total	
	kt	%	kt	%	kt	%	kt	%
Incineration - energy recovery					115	49	115	8
Incineration- green energy recovery			600	67			600	40
Landfill					0	0	0	0
Recycle in chipboard industry	200	57					200	13
Export energy recovery			291	32	118	50	409	28
Export unknown recycling	152	43			2	1	154	10
Export unknown useful application			6	1			6	0
Total	352	100	897	100	235	100	1483	100

Appendix I – Interview guide for stakeholders in C&D waste recycling system

Begin dit jaar hebben we elkaar al eens gesproken over duurzaam slopen en het recyclen van bouw- en sloopafval. De huidige afvalstromen met verwerkingsmethoden in Nederland en de technisch mogelijke recycling methoden heb ik in kaart gebracht. Om het beeld compleet te maken zou ik graag de visie van verschillende stakeholders over het recyclen van bouw- en sloopafval willen horen. Van ieder onderdeel van de keten (grondstofproducten, bouwmateriaal producent, bouwbedrijf, sloopbedrijf en sorteerbedrijf) wil ik graag weten hoe er vanuit hun eigen oogpunt wordt gekeken naar recycling van bouw- en sloopafval. Vandaar dat ik u graag enkele vragen hierover zou willen stellen.

1. Wat is uw mening over/visie op de huidige manier van bouw- en sloopafval (BSA) recycling in Nederland?

Bent u bekend met het project Cirkelstad naar Cirkelland? Cirkelstad is een project in Rotterdam waar hoogwaardige recycling en hergebruik van BSA in de bouwsector zelf wordt gestimuleerd. Het sluiten van kringlopen wordt steeds belangrijker geacht en wordt ook steeds meer in de praktijk gebracht. Het project van Cirkelstad naar Cirkelland wil het project opschalen naar heel Nederland.
2. Wat zijn volgens u succes- en risicofactoren van het sluiten van de bouwkringloop?

3. Hoe verwacht u dat de toekomst op langere termijn (2030) eruit gaat zien voor BSA recycling?

Bedankt voor het beantwoorden van mijn vragen.
Zou ik de antwoorden morgen gebruiken in mijn verslag met haar/hem als referentie?
Eindigen met vertellen dat ik het verslag naar haar/hem opstuur (eind juli).

Appendix J – Interview guide case study

1. *Kunt u beschrijven hoe het project is verlopen?* opdrachtgever, aannemers, planning

2. *Kunt u wat meer vertellen over het slopen en de materiaal/afvalverwerking?*
   Op welke manier werd er gesloopt (met een sloopkogel oid?)
   Welke materialen werden er on-site en off-site gescheiden?
   - Steen
     - Beton
     - Gasbeton
     - Bakstenen
     - Kalkzandsteen
     - Gips
     - Dakbedekking (bitumen)
   - Metalen
     - Ferro
     - Non-ferro
   - Hout
     - Hout A
     - Hout B
     - Hout C
   - Asbest
   - Plastics
   - Glas
   - Papier
   - Isolatiemateriaal
   - Mixed

Verwerkingsmanieren
- Hout
  - Hergebruik
  - Spaanplaat
  - Andere bouwmaterialen
- Steen
  - Granuleren van materiaal met mobiele breker? Daarna zeven wassen of ADR of thermische behandeling?
  - Betongranulaat voor wegfundering
  - Beton granulaat voor in betonproductie
  - Hergebruik van hele baksteen (op welke manier schoongemaakt?)
  - Gips recycling?
  - Bitumen als aanwezig, geshredderd en verhit?
- Metalen
  - Electric arc furnace
  - Basic oxygen furnace
- Andere materialen
  - isolatiemateriaal?
  - Asbest → stort
  -

Heeft u een verdeling van de materialen die vrijkwamen en de verwerking daarnvan?

3. *Wat levert duurzaam slopen op en wat kost het? (hoge kwaliteit afvalstoffen? Geld besparing? Meer tijd voor het slopen? Meer arbeidsuren? Leidde dit tot extra personeelskosten? Kosten voor materiaal te recyclen?)*

4. Zou u bij een volgend project weer duurzaam slopen? Zo ja, welke redenen heeft u daarvoor? Economische redenen om het duurzaam te slopen?

5. *Wat zijn de leerpunten van eerste duurzame sloop op de Uithof?* Welke problemen kwam u tegen. (Waarom is aanbesteding bij aardwetenschappen en Went anders verlopen)

6. *Wat is uw mening over/visie op de huidige manier van bouw- en sloopafval (BSA) recycling in Nederland?*

7. *Hoe verwacht u dat de toekomst op langere termijn (2030) eruit gaat zien voor BSA recycling?*

Vraag of ik het interview en zijn naam + de case mag gebruiken in mijn verslag.