Closed-loop Economy: Case of Concrete in the Netherlands

4413INTPGY Interdisciplinary Project Groups

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Executive Summary

Concrete is the second most consumed material after water and completely shapes the built environment in the Netherlands (WBCSD, 2009). When a building is demolished, the concrete in it is currently downcycled to be used as a road filling material. In the future, the supply of end-of-life (EoL) concrete in construction and demolition waste is expected to grow significantly, whereas the demand for road fill will stay behind. Since landfilling is not allowed in the Netherlands, a new purpose for the concrete waste needs to be found (Rijksoverheid Nederland, 1997). With the development of technologies that can separate EoL concrete into its constituents, it will be possible to recycle concrete into new building materials. This report has been written with the purpose of finding out what needs to be done in order to close the loop of concrete in the Netherlands by 2050. A backcasting analysis has been conducted at the end of the report to provide an answer to this. Preceding the backcasting, four different analysis of the technological development, environmental impact, economic climate and social situation are executed to serve as input for the backcasting. The remainder of this executive summary will state the main findings of this report.

The technology assessment has shown that the two most promising technologies for concrete recycling are C2CA and SmartCrusher (SC). Of these two, SC has shown to be at a more advanced level in terms of separation, as it has proof that it is able to separate the fines (0-4 mm) into unhydrated cement, hydrated cement and sand. The advantage of C2CA on the other hand is that it includes the development of sensor technologies, which are able to detect contaminants and monitor the quality of input and output streams. Regarding the readiness of the technologies, both C2CA and SC have been given a TRL level of 3 (experimental proof of concept). The ADR technology of C2CA is quite far in development and has already been tested in a niche project in Groningen, but the sensor technology is still in an early phase of development. SC has been validated in laboratory and has worked well at small-scale pilot projects, but the dust problems need to be eliminated and a quality check of output needs to be made.

The environmental analysis has been built around a quick and dirty Life Cycle Assessment. The LCA looked at the impact caused by the production of 1 tonne of concrete in the conventional way compared to recycling by the SC technology. Overall, the results show that recycling concrete can reduce the impact by more than 50% for each of the impact categories. Moreover, the CO_2 emissions can even be reduced by almost 75% when concrete is recycled. The biggest share of the impact reduction can be contributed to the lower direct emissions during the production of Portland cement and the lower amount of energy (fossil fuels) needed for the production of input materials. Hence, the environmental burden of the concrete production industry can be significantly lowered when concrete is recycled instead of produced from virgin materials.

The economic analysis has indicated that the Netherlands is not self-sufficient by far in extraction of the raw materials for concrete production, but at the same time there is also no established market for recycled concrete material. Therefore, the Netherlands is highly dependent on neighbouring countries like Germany and Belgium for raw materials needed to make cement and concrete. The comparison of C2CA and SC on their economic performance shows that they both have the potential to make more value than the business-as-usual (BAU) scenario for concrete recycling. Compared to the BAU scenario, C2CA lowers the cost per tonne of concrete by 2 euro, while increasing the revenue by 0.80 euro per tonne. SC can realize even more value, as it decreases the cost of recycling by 6 euro and increases the revenue by 7.20 euro. Further analysis indicates that it is mainly because of its high mobility

that C2CA is able to reduce (transportation) costs, while still maintaining a competitive throughput rate. SC creates most of the profits by effectively breaking down the EoL concrete into the most valuable materials, such as the unhydrated cement that can be used as a raw material in cement production. Because the two technologies compete on a different basis, it might be possible that there is room in the market for both of them to mature.

The FIS analysis has brought up some interesting aspects of the concrete industry. The concrete and cement sectors appear to be very conservative in nature and can be characterized as closed and non-transparent. For entrepreneurial initiatives like the SC it is therefore hard to grow and secure a place in the industry. Initiatives like C2CA and the Green Deal are very fruitful in encouraging collaboration between key players in the industry. The influence of mobilization of resources on entrepreneurial activities is also limited, because many resources are directed towards projects to find alternatives for cement instead of recycling concrete waste and closing the loop. At the moment, the lack of market formation negatively impacts the amount of entrepreneurial activities and mobilization of resources. However, the government has the means to change this, as their construction projects are responsible for nearly half of the demand for concrete in the Netherlands. A stricter implementation of the government's policy of sustainable procurement could be a crucial factor in establishing a market for recycled concrete.

Bringing together the main findings from the technological, environmental, economic and social system analyses, the formulation of a development pathway towards the desired future of 100% recycled concrete by 2050 can be constructed in a backcasting assignment. This pathway has been broken down into five progressive seven year intervals, each of which encompasses critical stepping stones that work toward the final goal. The initial assessment of the present situation in relation to the desired future was measured against the defined criteria for sustainability. A list of 19 solutions were identified using a multidisciplinary approach and weighed according to the likelihood of implementation and impact. These solutions were then subjected to different scenarios that represented the critical uncertainties, namely economic growth and sustainability awareness. Through this elaborate selection process, three possible sets of solutions are envisioned for which a pathway is constructed.

The first pathway is a combination of multiple solutions. It encompasses a gradual market creation and maturation of the C2CA technology. The storyline describes a future where the government's sustainable procurement programme and the pre-fab industry increase demand for recycled concrete. The recyclability building materials (RBM) label that is introduced for every newly constructed building in the Netherlands will facilitate transition to a circular concrete economy. This label describes the composition of the materials present in the building, which makes it clear to building owners how much profit they can make from selling these materials to recyclers. Furthermore, the practice of aggregate packaging is increased in order to reduce the amount of cement used in the concrete recipe. The most important solution in this pathway is the maturation of the C2CA technology. A lot of research and development activities need to be devoted to finishing the laser technology by 2022, achieve separation of the fines by 2029 and scale up the technology for large-scale implementation by 2036.

Because maturation of the C2CA technology is an uncertain factor in the previous backcasting pathway, an alternative has also been devised. This solution combination also consists of market creation by governmental procurement and the pre-fab industry, RBM labelling and aggregate packaging, but it assumes that C2CA fails in developing its technology and SC fills its place in the industry. The solution envisions a pathway where SC is able to acquire funding to prove its claims regarding the composition and quality of the output streams in 2022. In 2029, the SC has fully proven that the concept works and attracts further funding to scale up the technology. The next step will be to complement the SC technology with laser sensor technology in order to check the wet content of the feed stream. In the final phase towards 2050 the recycling practice is implemented on a large scale by building more production facilities.

The third solution requires a carbon tax to be imposed by the EU. This type of regulation forces cement producers in Europe to reduce carbon dioxide emissions significantly. If they decide not to change their production practices, their carbon tax payments can become a lot higher than that of competitors, which negatively impacts their competitive position and could even jeopardize the continued existence of their business. The expectation is therefore that cement producers will adopt the practice of recycling cement and start investing in technologies that create cements with low emissions. Based on the calculations, the carbon tax needs to be 50 euro per tonne of carbon dioxide emissions in 2050 in order to be effective. However, given the negative impact that the introduction of the tax has on the economy, it will be implemented gradually over the years. The pathway describes that the carbon tax will be increased by 10 euro per tonne every seven years, starting with 10 euro per tonne in 2022.

Each of the three proposed pathways will be able to realize the goal of complete recycling of EoL concrete in the Netherlands by 2050. However, all of the solutions have their specific drawbacks. The first pathway of market creation and C2CA maturation is uncertain from a technological point of view, since C2CA needs to find a method to recycle the fine fraction of the EoL concrete. A lot of research needs to be focused on this issue. The alternative of the SC has a more advanced technology with regard to fines separation, but it has more difficulties in finding funding and support from the industry. Participation in industry-wide sustainable initiatives, such as the Green Deal Beton, could help SmartCrusher to find suitable partners with the right intentions from the concrete and cement industry. Finally, although the carbon tax pathway seems to be a simple solution to implement at first sight, it has the disadvantage of having a negative economic impact and is threatened by strong opposition from the cement industry. Nevertheless, according to the findings of this report, the three presented pathways present the best and most feasible course of actions to reach a complete recycling of end-of-life concrete by 2050.

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- ADR - Advanced Dry Recovery
- BAU - Business as Usual
- C&D - Construction and Demolition
- C2CA - Concrete to Clean Aggregate
- CA - Concrete Aggregate
- CDW - Construction and Demolition Waste
- CFC - Chlorofluorocarbon
- DCB - Dichlorobenzene
- EAF - Electric Arc Furnace
- ECP - European Concrete Platform
- EM -Electromagnetic
- EoL - End of Life
- FIS - Function of Innovation System
- FORTH - Foundation for Research and Technology Hellas
- FP7 - Framework Program 7
- HSI - Hyperspectral Imaging
- IS - Innovation System
- LCA - Life Cycle Analysis
- LIBS - Laser Induced Breakdown Spectroscopy
- MLP - Multi-level Perspective
- NEN - Normalisatie en Normen
- NIR - Near-Infrared
- NMVOC - Nonmethane Volatile Organic Compound
- PM - Particulates Matter
- R&D - Research and Development
- RBM - Recyclability Building Materials
- RCF - Recycled Concrete Fine
- ROHS - Restriction Hazardeous Substances
- SC - SmartCrusher
- SUC-CON - Sustainable Construction
- TRL - Technology Readiness Level
- UV-B - Ultraviolet -B
- VAR - Veluwse Afval Recycling
- VOC - Volatile Organic Compound

Introduction

The concept of circular economy has become increasingly popular in recent years among scholars, policy makers and even in business. In current business the common pattern is the one that the Ellen MacArthur Foundation (2013) outlines as 'take-make-dispose' pattern. In this linear economy companies extract materials, manufacture a product and sell it to an end-consumer who discards the product without it serving a new purpose. Despite increasing resource efficiency there is still a large loss of resources along the value chain. In a circular economy or closed-loop economy products would be designed for re-use or recycling. The basis for economic growth would then become the reclaiming of material rather than extraction of resources.

An example of an industry that is still largely based on the linear economic model is the construction industry. The construction and the use of buildings in the European Union account for approximately half of the extracted materials and the energy consumption in Europe. Concrete as the most widely used building material in the world is produced by consuming the primary raw resources gravel, sand and limestone. Significant environmental impacts are associated with the production of concrete especially with the cement production from limestone which is responsible for 6-7% of the global CO_2 emissions (Shi et al., 2011). Other environmental impacts are associated with the large amount of transport of bulk materials and the energy use in the concrete production. Moving this patter from a linear model to a circular one could therefore significantly reduce the environmental impact of this industry.

This report will look at the possibilities of shifting the economic model of the concrete industry from a linear economy towards a closed-loop economy. To do so, this report focussed on the Netherlands because it has a unique opportunity for the recycling of concrete. Approximately 40% of the demolition waste in the Netherlands is concrete, making it the main constituent of demolition waste. Almost all End-of-Life (EoL) concrete is being used as road fill because there has been a ban on landfilling of all construction and demolition (C&D) waste since 1997 (Rijksoverheid Nederland, 1997). In 2009 only 1.9% of all concrete was processed using wet processing to become recycled aggregate (Agentschap NL, 2010). According to Lofti et al. (2013) the amount of concrete that can be used in road fill will decline significantly to only 40% of the EoL concrete in the near future. This means that a different means of re-using EoL concrete will need to be found. According to Müller (2006) the amount of concrete used in the second half of the 21st century in the Netherlands is going to be equalled by the amount of EoL concrete, this would make recycling EoL concrete into new concrete the ideal end-of-life waste management option.

Assuming that recycling of EoL concrete in the Netherlands is the best end-of-life waste management option for concrete when road filling is no longer possible, the question arises on how to achieve this. This research will therefore be carried out by using a backcasting technology to answer the question: "How to reach a complete recycling of end-of-life concrete by 2050 in the Netherlands?" Input data needed for the backcasting will be divided into four different analyses; a technology assessment, environmental analysis, economic analysis and a stakeholder and FIS (Function of Innovation System) analysis. The following chapter will describe the exact methodology used.

1 Methodology

Backcasting, a term used first by Robinson (Robinson 1982, 1990; as cited in Quist, 2013) or according to Lovins 'backwards-looking analysis' (Lovins, 1977; as cited in Quist, 2013) can be considered to be the opposite of forecasting. In forecasting, you start with where you are today, and based on observed trends, deduce where those trends will lead you in the future. In backcasting an aspirational vision is set and a development path to reach this vision is constructed by working back from the future to the present. Figure 1 visualizes this approach (Backcasting toolbox, 2014; Natural step, 2014).

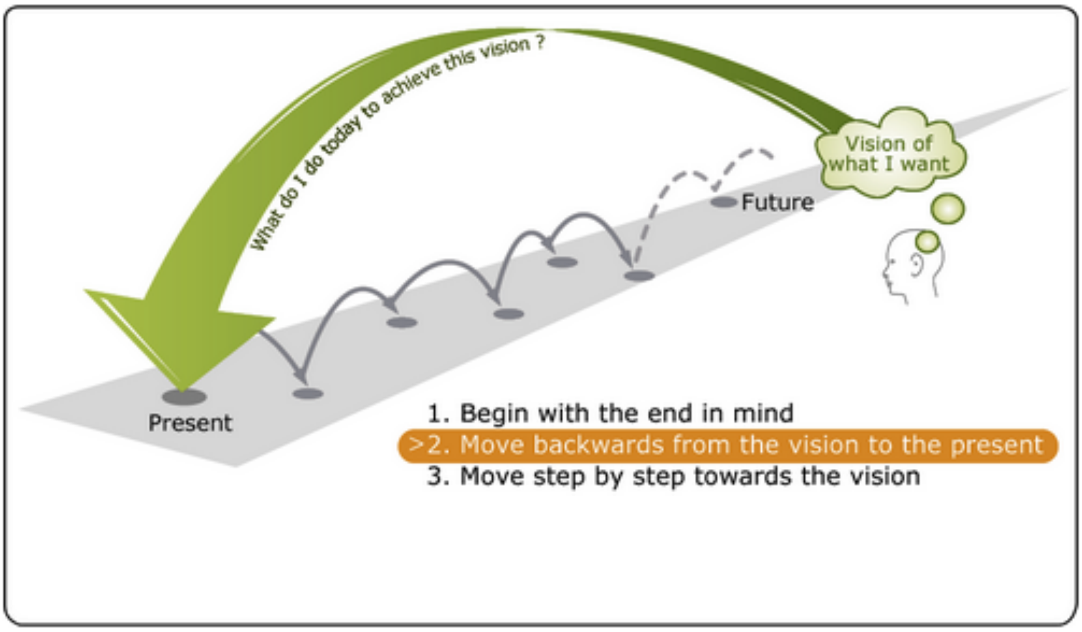


Figure 1: Visualization of backcasting approach (adopted from Natural step, 2014)

The backcasting methodology is in this research used to determine the development path towards complete recycling of end-of-life concrete in the Netherlands by 2050. Because a large part of the end-of-life concrete will no longer be able to be recycled or downcycled into road filling, approximately 60% of the EoL concrete will need to be recycled into new concrete. If possible more could be recycled into new concrete because other wastes could be used for road filling instead.

The backcasting methodology as described by Holmberg (1998) will be used for the backcasting. The described analysis is divided into four parts;

1.1.1.1.1 Define criteria for sustainability and desirability
1.1.1.1.2 Describe the present situation in relation to the desired future
1.1.1.1.3 Envision and assess potential solutions
1.1.1.1.4 Construct a development path

To be able to describe the present situation in relation to the desired future as well as come up with different solutions, four different analyses will be made in the Chapter 2 - 5 preceding Chapter 6, which describes the backcasting. Each of the four analyses is described shortly below but the methodologies for the four different analyses as well as the backcasting methodology are described in more detail in their respective chapters.

Chapter 2 will analyse the extent to which the concrete loop can be closed with current technologies by discussing best available technologies such as C2CA and SmartCrusher (SC) technology. Also this chapter will discuss technologies and innovation that could become feasible in the future or that might have an influence on closing the loop in the concrete industry.

Chapter 3 will analyse the overall reduction of environmental impact that can be achieved by closing the loop of concrete production that could be achieved when the best available technologies are developed further by 2050. A comparison is made between the production of one ton of concrete with recycled input materials based on a hypothetical technology and one ton of conventional concrete used in the Netherlands by means of a Life Cycle Analysis (LCA) methodology.

Chapter 4 will first describe the current economic situation in the Dutch concrete market and developments that are likely to occur in the market before 2050. To determine the implications of closing the loop of concrete a cost comparison will be made between the current recycling method of recycling concrete by means of wet technology, recycling by means of C2CA technology and recycling by means of SC technology. The last part of the chapter describes some practices and policies in the market that might have an impact on the before discussed cost comparison.

Other bottlenecks for closing the concrete loop that are not technological or economical will be discussed in Chapter 5. A stakeholder analysis will define the stakeholders that are important in the recycling of concrete and will be categorized in a power-interest matrix as defined by Mendelow (1991) to define the potential influence of the stakeholder groups. Also existing regulations will be discussed. A Functions of Innovation System (FIS) Analysis will be carried out to analyse the direction in which the concrete industry is moving and the factors that can influence the development of the industry. This analysis can be used to determine how decision making processes can be changed to successfully implement a closed-loop concrete industry.

The report will finish with a conclusion on how to make the transition from the current practices in the concrete industry towards a complete recycling of end-of-life concrete in the Netherlands by 2050. Also suggestions for further research will be made.

2 Technology Assessment

In this chapter we describe the current technologies that seem to be able to completely close the loop for concrete recycling in the future. The chapter is divided into two parts; the first part describes the concept of two contemporary technologies; C2CA and SC and the second part describes technologies or innovations that could become feasible in the future that might have an influence on the possibility of closing the loop.

Two main concrete recycling technologies that are C2CA and SC have been discussed in this and the following chapters since they are the most developed and seem most promising at present. The other technologies discussed in this chapter are not part of environmental analysis, economic analysis, stakeholder analysis and FIS analysis, however they are taken into account while carrying out the back-casting analysis.

To assess the two main technologies used by C2CA and SC we have used the Technology Readiness Level (TRL). TRL is a scale to define the maturity of a technology before it can be implemented. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress (NASA, 2012). There are nine levels of maturity 1 being the lowest and 9 being the highest level of technology readiness. The following levels of technology development definition are applied to rank a technology, unless specified otherwise (NASA, 2012).

TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

This guideline to assess different technologies is proven very helpful while comparing the feasibility of different technologies.

Both the C2CA technology and the SC technology are relatively well developed. The ADR (Advanced Dry Recovery) technology used in C2CA has been developed and used in a niche level project in Groningen. In this experiment, multi-storied office buildings have been demolished in order to test the ADR technology (Di Maio et al., 2012). However, the sensor technology of C2CA is still being under development in the laboratory. Looking at this progress C2CA has been ranked at level 3 of TRL system (INNOVATIONSEEDS, 2012). For C2CA technology to gain a higher TRL ranking it has to integrate different components of the technology, i.e. ADR and sensor technology to prove that they work together. However, this has not been proven at lab scale.

SmartCrusher (SC) technology has been validated in laboratory but is still not being implemented in the business environment. SC has been applied at Veluwse Afval Recycling (VAR) and has worked fine at smallscale pilot project (K. Schenk, personal communication, December 10, 2014). Still the technology has to be refined to eliminate dust production and also an addition of quality check of output needs to be made, either using sensor technology or else. We rank it on TRL 3 level as well.

Though SC achieves the same ranking on TRL scale as C2CA, it still lacks support from actual application, which C2CA can claim, e.g. pilot project in Groningen (Di Maio et al., 2012), demolition of building of University of Utrecht (Universitiet Utrecht, 2014).

2.1 C2CA

C2CA is a European Research project set up by 14 different partners including universities such a TU Delft and companies such as Strukton which runs until the end of 2014. The TU Delft is the coordinator of the project. The FP7 project is largely funded by the European Commission (European Commission, 2011).

The project had five initial goals (European Commission, 2013);

1. "To identify important factors and materials constituents related to the economic value and ecological impact of construction and demolition waste (CDW) concrete streams.
2. To develop sensing technologies and related data interpretation models to characterize feed and product streams;
3. To optimize breaker and separation processes for recycling EoL concrete into fine cement paste and coarse aggregate;
4. To create models of the chemical reactions and mass transport that are necessary to develop the thermal technology for the conversion of the fine cement fraction into a new cementitious binder;
5. To understand the economy and ecology of CDW recycling to such an extent that policies can be developed that facilitate an efficient transition towards a combination of optimal value recovery from CDW and sustainable building."

Di Maio et al. (2012) divide these goals into three parts; innovation with breakthrough technologies of the recycling of concrete, the demonstration of the economic and ecological viability of these technologies and the defining of the transition towards the use of these technologies including policy facilitation (Di Maio et al., 2012). The different steps currently used in C2CA are; smart dismantling and demolition, sorting and size classification, grinding, milling, ADR, sensor for quality control and assurance (Lofti et al., 2013). The separation into fine cement paste and the creation of the models to use this fine cement paste (goal 4) have not been completed. The parts of C2CA that have been developed are described below.

Preliminary C2CA results indicate that aggregates that are produced by means of C2CA technology can lead to the creation of concrete with a higher compressive strength compared to concrete made with virgin aggregates (European Commission, 2013).

Smart dismantling and demolishing

In the Netherlands, most buildings are demolished after dismantling. Within the scope of C2CA project, special efforts had been put on better planning and management of the dismantling and demolishing procedures to improve the purity of the EoL concrete. It shows that by proper dismantling of buildings a better quality recycled aggregate can be produced because the EoL concrete contains less contaminants (European Commission, 2013). In smart dismantling roof felt, gypsum, plastics, wood, ferrous and non-ferrous metals and other materials (CDW mix) are removed before demolishing of a building (Hu, 2012).

A good example of smart dismantling and demolishing as applied at Utrecht University is the full stripping of the interior of a building before demolishing and consequently the separation of different materials on-site (Universiteit Utrecht, 2014).

ADR

In order for the aggregates that are produced from the smart dismantling and demolishing process to be of the same or higher quality than virgin aggregates the fine materials (below 2 mm) need to be removed and cement paste needs to be removed from the surface of aggregates (European Commission, 2013)

With conventional methods this is only possible to separate and re-use material that has a size of 12 mm or larger (Di Maio et al., 2012). Advanced Dry Recovery (ADR) makes it possible to classify and separate moist construction and demolition waste down to 1 mm without drying or addition of water (de Vries et al., 2009). In ADR a 1 mm fraction is separated from a 1-12 mm fraction. From the 1-12 mm coarse fraction a 1-3 mm fine fraction is removed as well as the metal and the wood content. The rest of the coarse fraction can be processed using conventional methods. The ADR technology is able to produce coarse aggregates that can be used in the production of new concrete. Through C2CA (2011-2014) ADR technology is further developed. A semi-mobile pilot plant was installed in Utrecht Theo Pouw facility to recover 0-2mm fraction (Rem, 2014).

Sensors: Ensuring Quality

When working with any recycled materials, striving for purity is often the greatest challenge (Park, 2001). To ensure the quality of recycled aggregates, the level of contamination is analysed, contaminants are identified and removed via a combination of optical and sorting technologies. This sensor analysis is done continually, providing information at the same rate that the aggregates are being produced (Xia and Bakker, 2012). Sensor technology for C2CA has not been applied yet but is still being tested in the laboratory.

The sensors are meant to fulfil three tasks; first, differentiation of different materials in the waste flow, for example, wood, foam, gypsum, polymer and organic matter. This is achieved by a semi-quantitative method, meaning that relative rather than absolute data is obtained. Second, to control the processing unit (ADR), the compositional variation of input and output materials has to be monitored. This can also be achieved by a semi-quantitative method, however the sensor has to detect a wider range of contaminants because we want a cleaner output from ADR separation. Third, using a quantitative method, different contaminants such as high silicon content in cement, chlorine or sulfur must be measured (Xia and Bakker, 2012).

Near-Infrared (NIR) sensor is typically used in combination with mechanical separation to physically take out contaminating materials from material streams. NIR technology to be used in C2CA operates by means of its electromagnetic (EM) principle in identifying the nature of material inputs. Materials are differentiated based on their absorbance, transmittance and reflectance properties using specific wavelength emitting light, in this case the near-infrared region of the EM spectrum (Bakker et al., 2013). The result, for this application is the physical separation of such materials like polymer, semi-homogenous and other non-useful waste from the stream could be achieved effectively.

Laser Induced Breakdown Spectroscopy (LIBS) to analyse the composition of recyclables and to assess the quality of output from the ADR process. Also the further processing of fines to produce clean sand and cement fraction to be used for cement recycling can be achieved by the application of LIBS. The results are based on laboratory analysis (Xia and Bakker, 2012) and the technology still needs to be precisely modelled to integrate in C2CA.

In addition to LIBS and NIR, C2CA also aims to use Hyperspectral Imaging (HSI), another type of sensor technology, used to ensure the quality of output from mechanical separation. HSI is a new laser based quality-inspection technology which works based on imaging camera principle. Hyperspectral camera systems are able to deliver a wide spectrum of information from particulate solids streams and materials so that they can fully characterize the quality of the different flow streams resulting from mechanical separation. For the further development of C2CA, HSI is a new hope for “early-on-site” detection of the concrete, before the demolition, in terms of its composition and contaminants identification (Maio et al., 2012).

2.2 SmartCrusher

SC is a technology that is developed by Koos Schenk who is the owner of the company Schenk Concrete Consultancy. SC is an alternative technology as compared to C2CA that is being developed to recover sand, gravel and cement fraction from EoL concrete. Schenk Concrete Consultancy is an active member of CSR Netherlands and their start-up business is supported by Climate-KIC Accelerator in the Netherlands (SmartCrusher BV, n.d).

SC technology has been patented by Koos Schenk. This technology has been tested in the laboratory and later built on a large scale. The pilot version tested at the plant of VAR functions better than the one in the laboratory. The pilot version uses 10% of the energy of a traditional crusher / breaker (K. Schenk, personal communication, December 10, 2014). The preliminary results show an expected throughput of approximately 20 ton per hour and the energy consumption is expected to be lower than 1 kwh per ton (SmartCrusher, 2013). SC uses a combination of a wind sifter and the smart breaker to separate the hydrated cement fraction from the non-hydrated cement (K. Schenk, personal communication, December 10, 2014). Koos Schenk claims when the recycled sand and aggregate are used together in a new concrete product, about 25% less cement is needed because of the increased quality (K. Schenk, personal communication, December 10, 2014). The concrete that is currently being broken up in the breaker is well treated against drying out, and thus little water is needed.

SmartCrusher vs. Conventional Jaw Crusher

An analysis of recycled concrete was carried out by Florea et al (n.d.) using SC against the conventional jaw crusher. SC provides very fine output materials down to the size of 65 um. Compared to the conventional jaw crusher, SC increased recovery of cement paste by 50% in the same particle size range. Sieving the two outputs from the conventional jaw crusher and SC showed a much higher output of fines from the SC; up to five times in volume for the particles under 1 mm. Therefore, the crushed cement paste particles recovery was 7.5 times the one from the conventional jaw crusher.

Thermal treatment of finer particles under size of 150 um releases the cementitious properties of recycled cement fraction. At 800 ^{o}C calcite from recycled cement fraction is converted to lime. The sand fraction undergoes a phase change at temperatures higher than 500oC.

The room-temperature form of quartz, α-quartz, undergoes a reversible change in crystal structure at 573 °C to form β-quartz. This phenomenon is called an inversion, and for the α to β quartz inversion is accompanied by a linear expansion of 0.45%. β-quartz is more reactive and if the cooling takes place rapidly then this phase change can be preserved. Conventional crushers produce an output with a high α-quartz whereas SC output has a low percentage of α-quartz in the fine particles below the size of 150 um. After heat treatment of the fine particles if a high reactive β-quartz is present in the recycled cement then it will lead to better binding properties and a higher strength of cement paste. However this has not been achieved yet as concluded by Florea et al. (n.d.).

It was demonstrated in this study that untreated RCF and 800 °C treated Recycled Concrete Fines (RCF) can be used in mortar samples up to 20% replacement ratio without causing large detrimental effects to the mechanical properties in hardened state. All the cement substitution materials showed a negative effect at 30% replacement ratio because of the water absorption value and the dilution effect to the cement.

Recycled sand was used to replace 100% sand in new cement paste and mortar strength at different days, 3, 7 and 28 days was tested. It was observed that the 3 days, 7 days and 28 days flexural strength increased by 45.3%, 33.2% and 13.7% respectively. The 3 days and 7 days compressive strength increased by 65.6% and 40.3%, respectively. However, the 28 days compressive strength increased only by 1.1%. These results show that in future new sand can be completely replaced by recycled sand from SC without affecting the mechanical strength of mortar.

One concluding remark for the recycled cement fraction can be made that it has similar chemical compositions as cement and thus can possibly be used as part of the raw material for cement production. However, this is not easy to realize on laboratory scale.

Future developments in SmartCrusher

Addition of laser technology for the assessment of concrete input into the SC can improve the quality of the output and to maintain the working of the machine to optimum. An addition of laser technology for output assessment will also prove beneficial (K. Schenk, personal communication, December 23, 2014). For the future improvement of SC, technology can be developed to take in a variety of waste materials including bricks, wood, glass, metals etc. which can be separated into different waste streams. This will help to avoid any pre-processing of EoL concrete waste. Dust production during EoL concrete processing also needs to be eliminated or brought down to acceptable levels.

2.3 Other technologies and trends for the future

2.3.1 Design for deconstruction

Future buildings could be constructed in such a way that recycling of concrete would be made easier, so that less time will need to be put in smart demolition. Prefabricated slabs in buildings could possibly be used entirely instead of having to be taken apart for recycling. This would lead to a move towards reuse.

2.3.2 Decreased amount of cement used in concrete production

There are several methods with which the amount of cement needed for the production of concrete can be reduced. The first one is to improve the aggregate packaging. This can lead to the reduction of 10% the necessary cement (van Lieshout et al., 2013).

The less cement is used the longer it takes for concrete to reach a required strength, so the more time is allowed the less cement is needed. Therefore another way of reducing the amount of cement is to allow for more time for the concrete. This primarily applies to prefab concrete (van Lieshout et al., 2013).

2.3.3 Decreasing amount of reinforcement needed

The amount of steel that is used for reinforcement could be reduced by replacing it with steel fibres. This could lead to the same properties as conventional reinforced concrete. However in the current demolition methods this steel cannot be completely recycled, this would be the case if smart demolishing is applied (van Lieshout et al., 2013). In conventional recycling only 86% of the fibres can be recovered (BEwerken, 2013).

2.3.4 Using different building materials

By using different materials in construction the demand for concrete could be reduced. Developments are happening in the technology for the production of for example laminated wood and polymer materials that might obtain similar properties to the properties of concrete.

2.3.5 Electric Pulse Technology for separation of aggregates from cement paste:

A promising technology for separation of fines from aggregates is the application of electric pulses to demolition waste of size 150 mm. It produces clean aggregates of high quality. The method is being tested by Japanese researchers in Kumamoto University (Inoue et al., 2008). The dielectric breakdown of gas occurs in concrete by the pulsed electric discharge at first. Ionized gas forms plasma and explosive volumetric change tears concrete matrix. A shock wave is also generated at the same time. The shock wave generates the tensile stress at the boundary and mortar is separated from aggregate. This method is environmentally beneficial as compared to dry or wet methods. However electric pulses will need to be controlled according to properties of demolition material.

In another pilot project called COFRAGE coordinated by BRGM in France the same technique is used to produce clean aggregate and fines with the intention to produce recycled cement. The COFRAGE project also includes the use of microwave heating for cracking and fragmentation of concrete. Results from laboratory produced high quality clean aggregates (BRGM, 2014)

These technologies show immense potential for development in future and by 2050 they can be further improved to use less energy for separating aggregates from cement paste. There is also a possibility that these technologies can be coupled with C2CA or SC in the future.

Other forms of cement

There is whole range of different cements that might come into use in the future. Examples of cements are; calcium sulfoaluminate cements and alkali-activated cements which include slag-based cements, pozzolan cements, lime-pozzolan cements, calcium aluminate blended cements and blended cements which are partly made of Portland and partly made of alkali-activated cement (Shi et al., 2011). The theory behind the pozzolanic reaction is the formation of C-S-H gel from glassy SiO2 and Ca(OH)2.

Both natural and waste pozzolans, which are siliceous materials that bind with CaOH to produce a cementitious material, such as slags, fly ash and glass can replace between 25 and 60% of clinker needed to produce cement (Huntzinger and Eatmon, 2009).

Other technologies for recycling of sand

Recdemo (Germany) was able to separate smaller particles between the size of 1 and 4 mm using a wet separation method and showed that replacing 50% of sand in concrete by recycled fines lead to a 5% reduction of compressive strength of concrete (RECDEMO, 2004). This wet separation method could possibly be used only for the fraction that can currently not be separated using the ADR technology. Thereby minimising some of the downsides of the wet separation process which normally requires large amount of water and produces a large amount of sludge (M. Bakker, personal communication, November 11, 2014). As compared to insight gained from C2CA and use of ADR technology, wet separation does not lead to achieving environmental goals of recycling concrete (Di Maio et.al., 2012). Wet separation process requires large amounts of water, produces sludge and afterwards the separated fractions need to be heat dried.

Since there is no publicly available study result for the percentage used of the sand fraction obtained from the SC method, this technology proves better than SC that it replaces at least 50% of the sand in new concrete.

Other technologies for recycling of cement paste

Some of the calcium oxide that was in the original cement that is used in the production of concrete might not have reacted yet, this unreacted part is often referred to as freelime. This freelime can be used to replace the quicklime that comes from the burning of limestone as an input to the kiln process. The size of cement particle is less than 0.09 mm and these particles are often mixed with different forms of contaminants. Therefore according to the World Business Council for Sustainable Development (WBCSD, 2009) cement cannot be recycled. However there are some promising technologies that might make cement recycling possible.

It must be noted that it is only interesting from an environmental and circular economy perspective to recycle the cement fraction of the fines if it replaces Portland cement. Otherwise the cement fraction is being downcycled. If the cement fines are used as a filler or as a binding agent rather than a replacement of Portland cement it will only replace other waste streams such as fly ash (van Lieshout & Berghout, 2014). Therefore this report only considers the recycling of the cement fraction as replacement of Portland cement. The trend of using different fillers for cement production is discussed in part 3 of this Chapter.

Florea and Brouwers (2012) have conducted a research in which they assess the replaceability of cement paste with fines from the recycling of concrete. By means of crushing, heating and sieving they separate the fines that have a particle size below 0.15 mm. The strength of replacing between 10 and 30% of mass of cement with these fines resulted in a reduction of both the compressive and flexural strength in 7 and 28 days with up to a bit above 30% in the case of 30% replacement. They conclude that only the replacing of 10% cement is beneficial because the strength is reduced with less than the amount of primary cement being replaced. There is a possibility that if fines with a size below 0.1 mm instead of 0.15 mm would be sieved out that it would allow for higher levels of cement replacement.

Ma et al. (2010) did a similar research, by heating the demolition waste to 750 °C and sieving the 0.15 mm fraction. The pulverized dehydrated cement paste can be mixed with portland cement and is shown to have the same strength as low strength cement. The exact amount of portland cement that could be replaced by blending in pulverized dehydrated cement paste is not mentioned in the study.

Because of the heating of the fine fraction in both Florea and Brouwers (2012) and Ma et al. (2010) more water is needed than would be needed for the production of Portland cement from natural raw materials. The higher the heating temperature of hydrated cement paste the more water will be needed (Shui et al., 2009).

3 Environmental Analysis

This chapter will provide insight into the potential environmental impact reduction of producing concrete from recycled input materials compared to the current production of concrete in the Netherlands. So far the technology that seems to be able to recover the largest part of the materials from the EoL concrete is the SC. Both this technology and the C2CA technology are likely to become more mature before 2050.

To be able to make the comparison between the conventional concrete production and concrete production from recycled input materials the method of life cycle assessment (LCA) is used. A quick and dirty LCA will be conducted and the rest of this chapter is structured according to LCA methodology, starting with a goal and scope definition, an inventory analysis, impact assessment and interpretation of the results. The goal and scope definition includes a description of a possible future efficient recovery of the material used in concrete based on data from both the C2CA and SC technology as described in the previous chapter. A description of the conventional concrete production is also included. More information about the current Dutch concrete market can be found in Chapter 4.

3.1 Goal and scope definition

The comparative LCA that will be conducted is an attributional LCA, because the use of a recycled materials in concrete production will reduce the amount of inputs needed per ton of concrete produced and thus will not lead to a large shift in the market of input materials.

3.1.1 Functional unit

The functional unit for the LCA is one ton of concrete. This ton of concrete can be produced by either the conventional production method as is now the case in the Netherlands or by using recycled materials. Both alternative production methods are described below.

Conventional concrete production

Currently EoL buildings are mostly demolished using a conventional dismantling and demolition method in which the building is being dismantled of hazardous materials and the rest of the building is demolished as one item without separating different materials in the process.

As described in the introduction of this report a very small amount of concrete is recycled as aggregate. In 2009 the amount was approximately 1.9% (Agentschap NL, 2010) and is unlikely to have risen above 3% now. However because there is still more concrete being produced than is available as EoL concrete, only 1% of the mass of one ton of concrete originates from recycled concrete (Bijleveld et al. 2013). The conventional recycling method for EoL concrete is by means of wet processing.

The following table described the rest of the composition of one ton of conventional concrete in the Netherlands at the beginning of this century based on a study from Krutwagen and Broekhuizen (2010) and Bijleveld et al. (2013).

Table 1: Composition of one ton of conventional concrete in the Netherlands (source: Krutwagen and Broekhuizen (2010) and Bijleved et al., 2013)

Material	Kg per ton of concrete
Cement	150 kg
Sand	330 kg
Granulate, from EOL concrete	10 kg
Gravel	461 kg
Concrete Iron	40 kg

The cement in the Netherlands according to Krutwagen and Broekhuizen (2010) consists for 50% out of hoogovencement, 40% is Portland cement from the CEM I type and 10% is Portland flyash cement. Hoogovencement uses the waste product of steel production instead of the normal clinker that is used in Portland cement. It is assumed that the Portland flyash cement is of the CEM II-BV type.

Both the sand and gravel according to Bijleveld et al. (2013) are excavated from a river.

Concrete production from recycled materials

Because the technologies for the recycling of EoL concrete are still under development as described in the previous chapter, this alternative relies on a large number of assumptions on the development of these techniques. This alternative must therefore not be seen as an actually existing production technology but as a best estimate for the lowest environmental impact that the production of one ton of concrete could have in the Netherlands by 2050.

EoL buildings will need to be demolished in a different way in order to obtain cleaner EoL concrete that can be recycled. Therefore C2CA proposes smart dismantling and demolition. In this alternative it is assumed that all EoL buildings are demolished using this smart dismantling and demolition method.

According to Müller (2006) in the second half of the 21st century the amount of concrete used is going to be equalled by the amount of EoL concrete from the housing stock. Therefore we will assume that by 2050 the amount of EoL concrete will approximately equal the demand for new concrete. Therefore based on the different technologies described in the technology assessment it will be assumed that 90% of the sand and gravel fraction of the EoL concrete can be recovered and thus 90% of these natural inputs to the new concrete can be replaced by their recycled counterparts. The other 10% of the materials will still need to be supplied by means of conventional production methods as they are described in the previous alternative. If the recycled aggregates and sand will have the same quality as is the case in the laboratory scale SC then approximately 25% less cement will be needed to bind the materials because of their better binding properties (K Schenk, personal communication, December 23, 2014).

Approximately 30-40% of the cement in EoL concrete is unreacted and can be extracted as unhydrated cement. This means that from one ton of conventional EoL concrete in principle 60 kg of unreacted cement can be extracted and from EoL concrete produced from recycled materials 47.6 kg. It is unlikely that 100% of the unhydrated cement can be extracted but there will also remain to be a mix between conventional EoL and EoL concrete made from recycled materials in the coming century. According to Koos Schenk (Personal communication, December 23, 2014) the recovered unhydrated cement can replace 80% of the cement in CEM I cement with recycled cement. Therefore it will be assumed that in 2050 from one ton of EoL concrete 47.6 kg of CEM I can be produced which contains 80% recycled cement. The rest of the cement will be assumed to consist for 83% of Hoogovencement and for 13% out of Portland flyash cement, based on the current ratio of these cements being used in the production of conventional concrete in the Netherlands.

Furthermore because even when the iron in structural concrete will be included as fibre it can be recovered using the SmartCrushing technology it is assumed that 100% of the concrete iron is provided from recycled iron.

The following table represents the composition that will be assumed for the production of one ton of concrete from recycled materials. The total amount of aggregates and sand used per ton of concrete have slightly increased compared to conventional concrete production because less cement is needed per ton of concrete produced.

Table 2: Composition of one ton of concrete from recycled materials

Material	kg per ton of concrete
Cement	71.4 kg
Portland cement with 80% EOL cement fines	47.6 kg
Sand	35 kg
Sand, from EOL concrete	311 kg
Granulate, from EOL concrete	443 kg
Gravel	50 kg
Concrete Iron from recycled iron	42 kg

Quality assessment

Data that will be used for this analysis is described under data collection. If there are multiple data sources available for one variable needed, the most recent number was used that are most applicable to the Dutch case.

3.1.2 System boundaries

The analysis has been conducted for the situation in the Netherlands, from cradle to cradle, meaning that all produced aggregate, cement paste and or sand will be subtracted from the initial amount needed for the production of the concrete in both cases. The production of capital goods is excluded. Most of the processes in the two systems have been defined as is done in a paper by Hu et al. (2013).

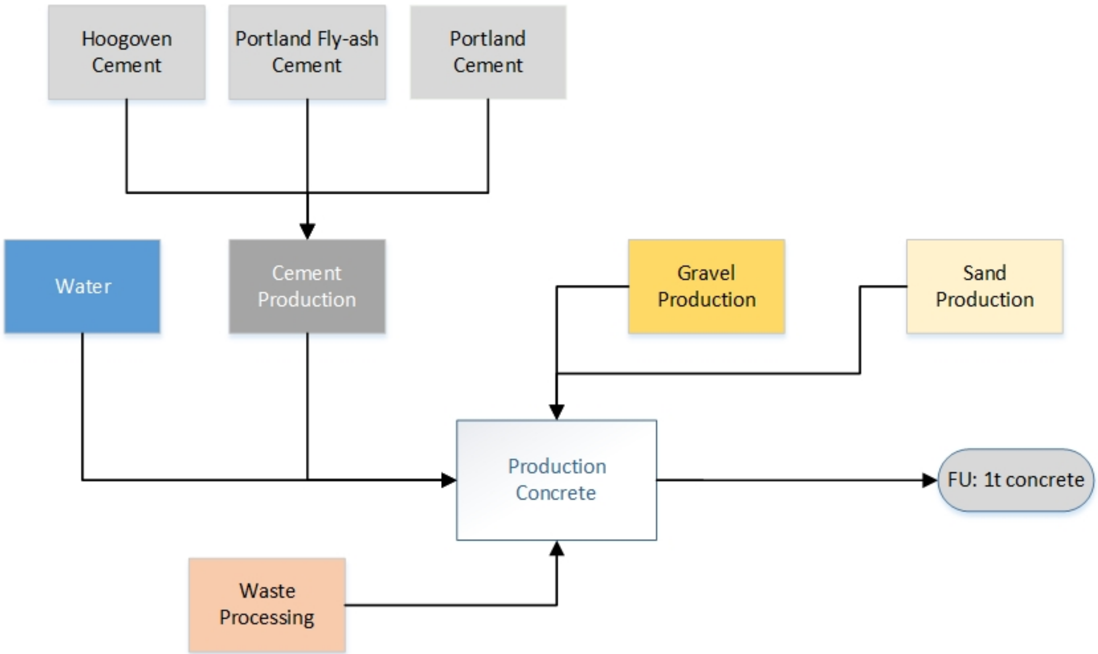


Figure 2: ***Flow diagram for conventional concrete production***

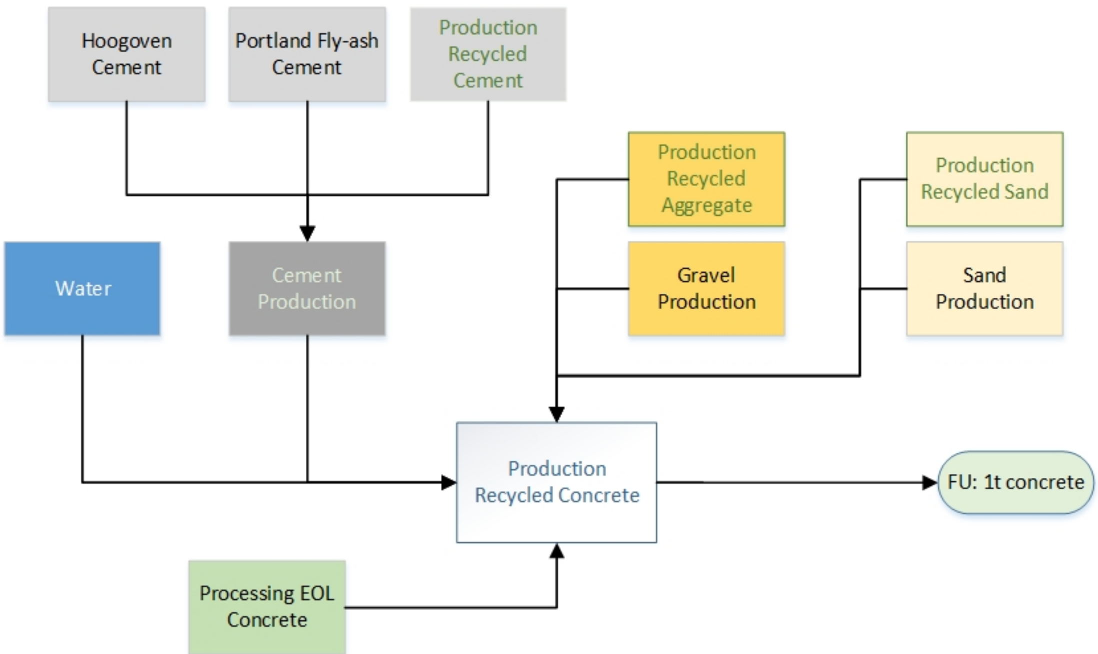


Figure 3: ***Flow diagram for production of concrete from recycled materials***

3.2 Inventory analysis

3.2.1 Data collection

The following tables list the economic inputs, the environmental inputs and the environmental outputs for each of the different materials used in the two alternatives. The same is given for the production of concrete, the demolition of EoL buildings and the transportation of the different materials.

1. Hoogovencement production

The Hoogovencement is assumed to be of the III/B type cement, which contains 30% clinker. Data are based on Josa et al. (2004 and the water used in the cement production originates from a study by v.d. Heede and Belie (2012).

Table 3: Environmental and economic inputs for the production of 1 kg of Hoogovencement

Material	Amount
Clinker	0.300 kg
Slag	0.640 kg
Gypsum	0.060 kg
Energy (heat)	2.16 MJ
Energy (electricity)	0.355 MJ
Water	0.343 litre

For the production of one kilogram of clinker according to Josa et al. (2004) 0.510 kilogram of loam is needed and 0.066 kilogram of other materials. What materials are used to provide the mass for the other half of the one kilogram of clinker is unclear.

Table 4: Environmental emissions for the production of 1 kg of Hoogovencement

Pollutants emitted to air	Amount
SO_2	0.58 g
NOx	1.11 g
CO_2	334.00 g
Dust	0.08 g

2. Conventional portland cement production

The conventional portland cement used in the Netherlands is of the CEM I type. Data are based on Josa et al. (2004 and the water used in the cement production originates from a study by v.d. Heede and Belie (2012).

Table 5: Environmental and economic inputs for the production of 1 kg of conventional portland cement

Material	Amount
Gypsum	0.06 kg
Water	0.343 litre
Energy (electricity)	0.318 MJ
Energy (heat)	3.38 MJ

Because the amount of clinker needed is not mentioned by Josa et al. (2004) it is assumed that one kilogram of clinker is needed for the production of one kilogram of Portland cement. For the production of one kilogram of clinker according to Josa et al. (2004) 1.6 kilogram of limestone is needed and 1.41 kilogram of water.

Table 6: Environmental emissions for the production of 1 kg of conventional Portland cement

Pollutants emitted to air	Amount
Particulate matter	7.50 g
Carbon dioxide from process	853.0 g
SO_2	0.09 g
NOx	2.58 g

3. *Portland ash cement production*

Data are based on Josa et al. (2004 and the water used in the cement production originates from a study by v.d. Heede and Belie (2012).

Table 7: Environmental and economic inputs for the production of 1 kg of Portland flyash cement

Material	Amount
Water	0.34 litre
Clinker	0.70 kg
Slag	0.08 kg
Fly ash	0.31 kg
Gypsum	0.05 kg
Energy (heat)	2.53 MJ
Energy (electricity)	0.29 MJ

For the production of one kilogram of clinker according to Josa et al. (2004) 1.190 kilogram of loam, 0.042 kg of clay, 0.035 kg of chalk and 0.014 kg of iron oxides are needed.

Table 8: Environmental emissions for the production of 1 kg of Portland flyash cement.

Pollutants emitted to air	Amount
SO_2	0.90 g
NOx	2.33 g
CO_2	692.90 g
Dust	0.18 g

4. Production of Portland cement with 80% recycled cement

80% of the mass of the clinker in conventional Portland cement production can be replaced by recycled dehydrated cement. Which when assuming that half of the emissions from the production of Portland cement originate from the production of clinker, leads to a reduction of emissions of 40% compared to the production of conventional Portland cement. The water use, energy use and gypsum use are assumed to remain the same as in conventional Portland cement production. The following table shows the emissions that are assumed for the production of Portland cement with 80% recycled cement.

Table 9: Environmental emissions for the production of 1 kg of Portland cement with 80% recycled cement

Pollutants emitted to air	Amount
Particulate matter	4.5 g
CO_2	511.8 g
SO_2	0.054 g
NOx	1.548 g

5. Production of natural aggregate and natural sand

Data have been found for the production of natural aggregate from a river in a study done by Marinkovic et al. (2010). It is assumed that natural sand production from a river is done in the exact same way and thus needs the same inputs and produces the same environmental emissions.

Table 10: Environmental and economic inputs for the production of 1 kg of natural aggregate / natural sand

Material	Amount
Energy (diesel)	0.014 MJ

Table 11: Environmental emissions for the production of 1 kg of natural aggregate / natural sand

Pollutants emitted to air	Amount
CO	0.0035 g
NOx	0.015 g
SOx	0.005 g
CH_4	0.0013 g
CO_2	1.4 g
N_2O	0.000055 g
NMVOC	0.000039 g
Particulate matter	0.0015 g

6. Production of concrete iron

Data for the production of concrete iron have been obtained from v.d. Heede and Belie (2012). The energy used for the production is assumed to be electricity because recycled steel is mostly produced by means of an electric arc furnace (EAF) which runs on electricity.

Table 12: Environmental and economic inputs for the production of 1 kg of concrete iron

Material	Amount
Energy (electricity)	16.57 MJ

Table 13: Environmental emissions for the production of 1 kg of concrete iron.

Pollutants emitted to air	Amount
CO_2	1.356 kg
SO_2	0.012 kg
NO_2	0.005 kg
Particulate matter	0.003 kg

7. Transport

The transport of each of the imported materials have been largely based on Bijleveld et al. (2013). The transport of cement and recycled cement is based on the average of the transport of CEM I and CEM II cement. The transport or recycled sand has been estimated.

Table 14: Transport distance per ton of commodities

Commodity transported	Distance	Means of transport
Sand	38 km	Transoceanic freight ship
	159 km	Barge
	4 km	Truck
Gravel	51 km	Transoceanic freight ship
	239 km	Barge
	10 km	Truck
Cement	1.5 km	Barge
	146.5 km	Truck
Concrete iron	150 km	Truck

Recycled cement	1.5 km	Barge
	146.5 km	Truck
Recycled sand	150 km	Barge
	15 km	Truck
Recycled aggregate	35 km	Truck

The transport from the demolition site to the conventional crushing process is obtained from Bijleveld et al. (2013). It is assumed that there is no transport from the demolition site to the SC process because both the SC technology and the C2CA technology are currently aiming and a mobile processing unit. The transport of the recycled unhydrated cement is assumed to be 50 kilometres by truck from somewhere in the Netherlands to the only cement producer in the Netherlands (ENCI) in IJmuiden.

Transport	**Distance**	**Means of transport**
EoL concrete from demolition site to conventional crushing	15 km	Truck
Recycled unhydrated cement to cement production	50 km	Truck

8. Concrete production

For each of the two alternatives for concrete different materials are needed as shown in table 1 and table 2. Besides according to v.d. Heede and Belie (2012) 0.248 liter of water is needed per kilogram of concrete produced.

9. Conventional dismantling and demolition

According to Bijleveld et al. (2013) 76.7 MJ of energy in the form of diesel used in machinery are needed for the dismantling and demolition one ton of EoL concrete.

10. Smart dismantling and demolition

Smart dismantling and demolition requires the use of more energy than conventional dismantling and demolition. However exactly how much more energy will be needed is yet unknown. Therefore it is assumed that twice as much energy is needed as is the case for conventional dismantling and demolition.

11. Conventional crushing

The EoL concrete needs to be crushed after having been removed form an EoL building. According to Bijleveld et al. (2013) for crushing one ton of EoL concrete 20.5 kilogram of CO_2 is being emitted to the air. This includes the amount of emissions associated with the energy use of the crushing process. The exact energy use is unknown.

12. SmartCrusher

According to SmartCrusher BV (2013) the crushing of one ton of EoL concrete requires 3.6 MJ. Which is assumed to originate from electricity. It has been observed during a visit to the technology that a substantial amount of dust is created during the crushing process. However it is assumed that by 2050 the dust creation will have been reduced substantially because more of the fines such as the unhydrated cement will be captured and these emissions are therefore disregarded. Besides it can be assumed that there are no other direct emissions from the process.

From this future crushing and separation process iron, recycled aggregates, recycled sand and unhydrated cement is produced. It is assumed that the iron can directly be re-used in the production of new concrete because in the future steel fibres are likely to be used in concrete. The current SC technology extracts these steel fibres completely clean from the EoL concrete, and thus the further development of this or another technology is likely to extract it too.

3.2.2 Omitted data and relating data to unit processes

Wet separation of EOL concrete to produce granulate in alternative one will not be included in this LCA because no data has been obtained on the environmental impacts because of this production. However since only a very small amount of the inputs of concrete is recycled concrete produced by the wet method and the largest part of EoL concrete ends up in road fill it is unlikely that omitting this part has a large impact on the results. The impacts that are thus disregarded would only make the difference between the conventional concrete production and the production of concrete from recycled materials larger.

Despite the fact that some economic and environmental inputs have been found for the production of the different types of cement, some of these inputs are disregarded because no production process has been found in the EcoInvent v2.2 database. The inputs that are disregarded are loam, chalk, clay and iron oxides. However again if these would be included this would make the difference between conventional concrete production and the production of concrete from recycled materials larger. All other economic and environmental inputs have been found in the EcoInvent v2.2 database, and the best geographically and temporal match has been sought.

Besides slag and fly ash are assumed to have no environmental burdens associated with them because they are produced as a waste from different production processes. All particulates and dust are represented as particulate larger than 10um.

3.2.3 Allocation and aggregation

The entire burden of the smart demolition and dismantling and the SC needs to be allocated to the concrete produced from recycled materials. Since recycled iron is the only fraction of concrete that is entirely recycled back into recycled concrete, it was decided to allocate the entire environmental burden of the production of recycled concrete to production of iron. However this is just a technicality, and the allocation could also have been done in a different way.

3.3 Impact Assessment

The following environmental issues are taken into account as midpoint impact categories:

- Climate Change which besides other consequences leads to an increase in average global temperature.

- Ozone Depletion leads to an increased UV-B radiation causing for example skin cancer.
- Acidification leads to a change in the acidity of soil causing a shift in species in the area.
- Eutrophication is the nutrient enrichment of aquatic regions which may lead to algae blooms and drastic changes in ecosystems.
- Toxicity is the exposure and effect of certain chemicals on nature and humans, which may lead to illness and death.
- Human health damage due to PM_{10} and ozone may lead to the shortening of human lives.
- Ionising radiation of radioactive substances may lead to the shortening of human lives.
- Water depletion can lead to water shortages.
- Mineral resource depletion may lead to mineral shortages in the future.
- Fossil fuel depletion may lead to fossil fuel shortages in the future.
- By using potentials from ReCiPe 2008 (Goedkoop et al. 2012) the environmental impact is calculated in CMLCA. The Hierarchist approach is chosen, which mostly uses a 100 years time horizon.

3.4 Results

Category	Recycled Concrete (per ton)	Conventional Concrete (per ton)	Ratio impact recycled concrete to conventional concrete
Marine eutrophication	84.6 kg N-Eq	333 kg N-Eq	25.4%
Marine ecotoxicity	0.0699 kg 1,4-DCB-Eq	0.822 kg 1,4-DCB-Eq	8.5%
Terrestrial acidification	0.649 kg SO2-Eq	1.85 kg SO2-Eq	35.1%
Terrestrial ecotoxicity	0.00135 kg 1,4-DCB-Eq	0.0128 kg 1,4-DCB-Eq	10.5%
Water depletion	-0.42 m3	-1.04 m3	40.4%
Metal depletion	-0.342 kg Fe-Eq	-0.919 kg Fe-Eq	37.2%
Fossil depletion	-10.4 kg oil-Eq	-61.7 kg oil-Eq	16.9%
Photochemical oxidant formation	0.517 kg NMVOC	1.51 kg NMVOC	34.2%
Climate change	83.2 kg CO_2-Eq	326 kg CO_2-Eq	25.5%
Ionising radiation	1.9 kg U235-Eq	23.6 kg U235-Eq	8.05%
Freshwater ecotoxicity	0.0625 kg 1,4-DCB-Eq	0.786 kg 1,4-DCB-Eq	7.95%
Human toxicity	2.75 kg 1,4-DCB-Eq	36.1 kg 1,4-DCB-Eq	7.62%
Ozone depletion	3.42 E-06 kg CFC-11-Eq	1.15 E-05 kg CFC-11-Eq	29.7%

Table 15: Environmental impacts for the production of one ton of conventional concrete vs one ton of recycled concrete in NL

Table 15 shows the environmental impacts for the production of one ton of conventional concrete and one ton of recycled concrete in the Netherlands. For all impact categories the environmental impact of the production on concrete can be reduced with more than 50%. The carbon dioxide equivalence can be reduced with almost 75% by producing recycled concrete.

3.5 Interpretation

3.5.1 Contribution analysis

The large difference between the production of conventional concrete and the possible future production of concrete made from recycled materials is mainly due to the emissions during the production of the Portland cement. The difference can also partially be explained by the decrease in energy demand for the production of input materials for concrete when these materials are recycled. The energy use for recycling is thus lower than the energy use for the extraction of these materials.

3.5.2 Uncertainty analysis

A large part of the environmental impact of concrete production is due to energy use. Therefore if the specific energy mix used in the production would be changes, the environmental burden of concrete production could be reduced significantly. If the Dutch energy system would move towards a more sustainable electricity system the environmental impact of the production of both of the concretes would reduce significantly. However this is unlikely to change the results of the LCA.

3.6 Conclusion

It can be concluded that a large environmental impact reduction can be achieved by recycling concrete and producing new concrete from End of Life materials. This quick and dirty LCA has shown the reduction potential based on assumptions made for the development of current available technologies for the recycling of EoL concrete. However the results must not be seen as definitive because the technologies still need to be developed and may only serve as an indication of the large reduction in environmental burden that can be made.

4 Present & Future Economics for Concrete Recycling

This chapter will describe the current economic situation in the Dutch concrete market and the developments that are likely to occur in this market before 2050 and their respective impacts. In this the supply of materials and the production capacity are described. Secondly to determine the economic implications of closing the loop of concrete a cost comparison is made between the current method of recycling of concrete as aggregates (business-as-usual) with the recycling of EoL concrete by means of C2CA and SC technologies as described in Chapter 2. The last part of the chapter describes practices and policies in the market that might lead to changes in the before discussed cost comparison.

This analysis makes it possible to assess whether or not the recycling of concrete in the Netherlands is economically feasible and which parts of the value chain lead to the largest additional value creation. This data can be used to provide input to the scenarios that will be developed in Chapter 6 as well as serve as a basis on which to come up with potential solutions for closing the loop of concrete by 2050.

4.1 Current Economic Situation

In 2010 approximatly 33.6 Mt of concrete were comsumed in the Netherlands, (Bijleveld et al. 2013) which rounds down to just about 1 cubic meter per inhabitant per year. The market is devided between the mortar and the precast industries with a respective 55% and 45% share (Bonora 2014). New concrete is used for infrastructure (10%), housing (40%) and utilities (50%), the dominant share of infrastucture and utilities does suggest the importance of government and municipal share in demand. The dutch concrete market is also characterized by a strong dependance on imports as it lacks the necessary natural resources.

The raw materials for the production of concrete in the Netherlands are either locally produced or are imported mainly from both neighbouring countries, Germany and Belgium. Figure 4 shows the provision of raw materials for the concrete Industry in the Netherlands in 2003. Filling sand, making up the largest part of the concrete recipe is abundantly excavated within the Netherlands and therefore there is no export. This is not the case for materials used as aggregate in concrete.

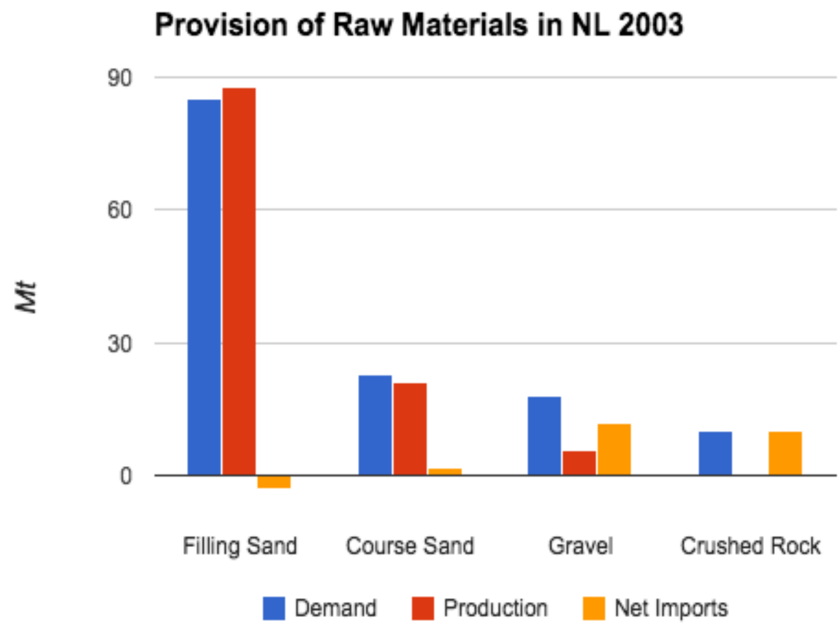
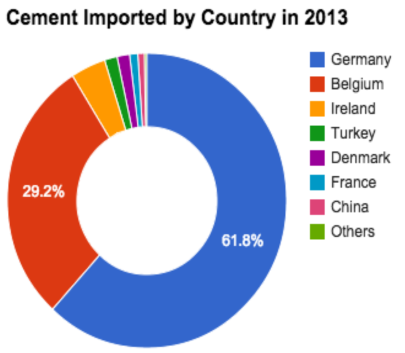


Figure 4: ***Demand, production and net imports of raw materials (van der Meulen et al., 2003)***

Continued dredging projects will also contribute to consolidating the current market for this material (E. van Roekel, personal communication, October 10, 2014). The required aggregates for concrete prodution is partly sourced from the constant dredging of rivers, however the amount excavated in this way does not meet the demand for aggregate. Therefore the Netherlands relies largely on imports. As a result of a ban on landfilling recyclable demolition waste, the concrete industry has been focussing on reducing its waste. Currently the largest part of EoL concrete is being recycled in low value applications such as fill or road sub grade as it presents excellent compaction properties. In 2009 only 1.9% of all concrete was processed to become recycled aggregate (Agentschap NL, 2010). Recycling could however lead to a lower reliance of teh concrete sector on imported aggregates.

Another material for which import is vital to meet the demand of the concrete industry is the cement. Also in this case recycling of EoL concrete could reduce the dependency on imported cement. The production of cement in the Netherlands only accounts for a small fraction of total consumption. Presently there is only one integrated cement plant which also extracts its own gypsum. Planned to terminate production in 2018 (de Volkskrant, 2014), this plant has a capacity of 1.1 Mt per year. By importing foreign clinker, approximately 2.5 Mt of cement is produced per year in addition to this (CemNet, n.d.). Another 4 Mt of cement is being imported mainly from Germany and Belgium (Figure 5) while about 1 Mt is being exported again (International Trade Centre, 2013). The exported cement consists mainly of blast furnace cement due to its specific water resistant properties.



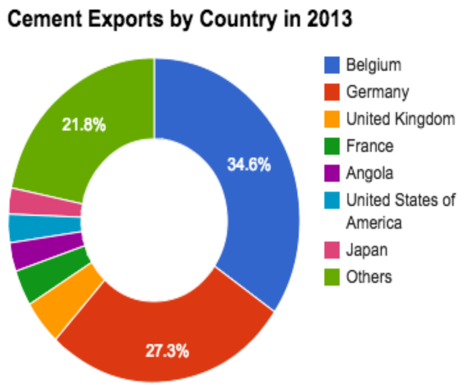


Figure 5: ***Cement imports and exports by country in 2013 (International Trade Centre, 2013)***

The total cement consumption was 4.8 Mt per year in 2010, a figure that has been slowly decreasing since the 1990's (Figure 6). This is due to a slowdown in the construction industry and is expected to have begun to recover in the second part of 2013.

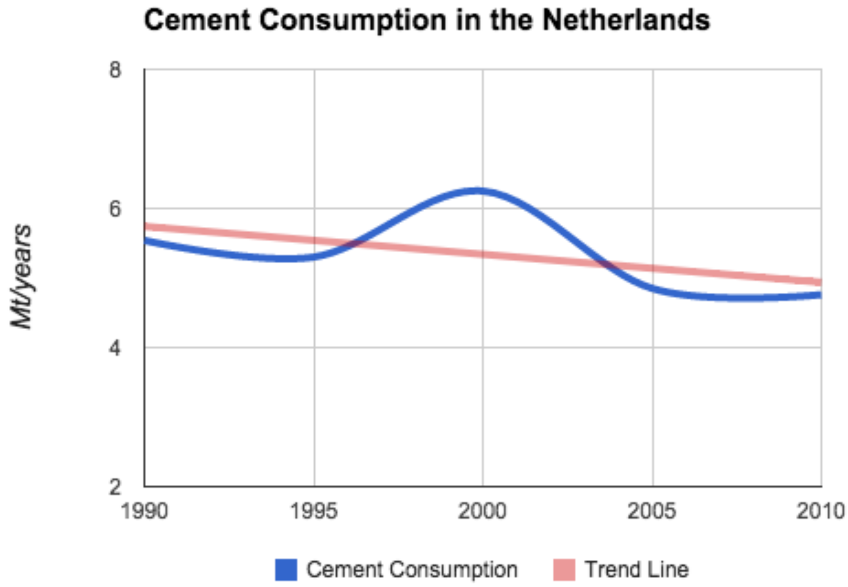


Figure 6: ***Cement consumption in the Netherlands (Edwards, 2012)***

4.2 Future Developments of the Concrete Market

The price of concrete is also expected to change because of different recipes that could be used in the concrete industry. The current trend in the concrete industry is to lower the clinker factor in the concrete (C. Müller, personal communication, December 2, 2014). Currently cement producers have a big influence on the recipe of concrete but it is possible that in the future engineers will be more involved in determining the recipes by explicitly defining strength and temporal requirements of concrete to minimize cement use, since cement is the most expensive ingredient in concrete.

Due to high transportation costs for all of the materials, the recent fluctuation in oil prices may have an impact on added costs (NASDAQ, 2014). How this will affect the market in the long term is difficult to predict. The Netherlands does however have a distinct advantage over other countries as its many coastal and inland waterways enables for large quantities of material to be moved by barge to inland locations. Ultimately this reduces logistical costs (Edwards, 2012). However it can be assumed that the price of sand will remain the same in the foreseeable future because production exceeds demand in the Netherlands.

The closing of the ENCI plant in 2018 will lead to a transformation of the grounds into a grinding site as well as a centre for innovative building materials for which many different companies have already asserted their participation (Edwards, 2012). The Netherlands has been facing strong public opposition to granting new excavation permits. If this continues, it may possibly in part limit the future excavation and supply of sand and gravel (E. Schut, personal communication, December 9, 2014). There is however too much uncertainty involved establishing the likelihood of a subsequent increase in the price of virgin materials.

The amount of recycled aggrates used in the concrete industry is expected to increase to as much as 20% recycled aggregate ratio for exterior facing concrete and 30% for interior facing concrete (C. Müller, personal communication, December 2, 2014). The renewal of the aging building stock in the Netherlands is predicted to double the EoL concrete from 10.5 Mt in 2003 to 22 Mt in 2025 (Poel, 2008). This doubling of supply in contrast to a diminishing road base demand will undoubtedly reduce the price of EoL concrete and could thus provide a basis for providing the recycled aggregates.

4.3 Cost comparison

Many economic barriers to recycling concrete can be identified. To begin with, there is a need for rapid demolition and the clearing of the site. As demolition costs are coupled with the duration of the task, smart demolition and an efficient separation of material providing uncontaminated recycling streams is an additional cost that must be weighed against the expected value of the materials recovered. In the absence of established cost effective recycling technologies and a market for recycled aggregates, such practices are difficult to stimulate.

In terms of investment, the capital costs in equipment to produce recycled aggregates from EoL concrete may be comparable to process aggregates from natural sources. This implies that for C2CA, the competitive advantage of recycled aggregates must emerge from efficient sourcing, processing, transport, storage and sale. For the case of SC it is a different scenario as it seeks to recover more than just the aggregates such as the sand and unhydrated cement fraction. Other materials which if recovered could represent a higher market value than recycled aggregates alone. Either way, these technologies can only be attractive if they can compete with the current market price and quality of virgin materials.

To be able to assess the economic viability of recycling and the severity of the economic barriers to implement recycling a cost comparison is performed. The life cycle costs of conventionally recycling one ton of EoL concrete into aggregates (business-as-usual) is compared with practices employing C2CA and SC technology respectively.

The data for the cost comparison for the dismantling and demolition for the business-as-usual and C2CA method are gathered from the case study done by the C2CA project (European Commission, 2013). Data for the value gained from aggregate production and the direct cost of wet processing, ADR and the sensor technology of C2CA originate from the same source. The cost and revenue for the C2CA technology and the business-as-usual technology can be found in appendix 1.

In the abscence of a documented case study done for the costs and revenues of the SC technology, it is assumed that the same processes and subsequent costs for dismantling and demolition apply as in the other two recycling processes. The quantity and value of the material obtained from the SC technology are based on the research of SC carried out by Florea (2014) with the price chosen from the U. S. GEoLogical Survey (USGS) (Dolley, 2010). The direct costs for the SC technology have been largely gathered through interviews with the inventor of the technology (Koos Schenk, Personal Communication, December 23, 2014). However the market value of the material gained by SC, such as the unhydrated cement fraction recycled, have been valued at market price. They are presented in appendix 2.

As presented in appendix 1, the total life-cycle cost of one ton EoL of concrete treated by business-as-usual method is 30.14 €/ton. Direct cost of dismantling and wet processing contribute to most of the total with 11.61 €/ton and 8.93 €/ton respectively. This is mainly due to the capital cost of demolition and wet processing and the fuel cost of material transported in those phases.

In appendix 2, one ton of EoL of concrete treated by C2CA has a total life-cycle cost of 28.15 €. This is mainly due to demolition cost and direct cost of ADR. But, in total, this is less than life-cycle cost of EoL of concrete treated by conventional method. In addition to that, revenue gained with C2CA method is also higher than conventional method. C2CA has revenue 27.74 €/ton while conventional method has only 26.94 €/ton.

As for EoL of concrete treated by SC, it has much less total life-cycle costs compared to the other two methods, only 24.09 €/ton due to the low direct cost. Appendix 3 shows that concrete treated by SC generates higher revenue compared to the other two methods. This is mainly due to the higher amount of fines and unhydrated cement recovered by this method. With the SC method, revenue of 5.1 €/ton of EoL of concrete can be achieved. This is coming for the most part from 0.06 tons of fines that can be recycled from one ton of EoL of concrete and it can be used for replacement of Portland cement in new concrete which has sale price of 85 €/ton.

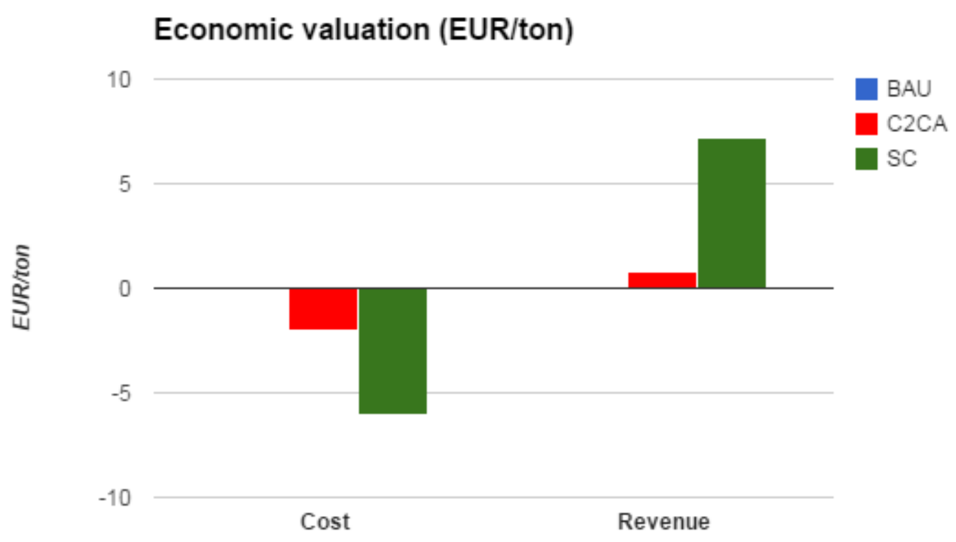


Figure 7: Comparison of the potential costs and revenues of C2CA and SC compared to Business-asusual (BAU)

As a conclusion, compared to BAU, C2CA has the potential to reduce the costs by 1.99 euro per ton of end of life of concrete. This potential is mainly the result of a reduction of capital costs and transport costs due to its mobile attributes. SC has an even higher potential to reduce the capital costs as well as energy and transportation costs. These might lead to a cost reduction of 6 euro per ton of end-of-life of concrete.

C2CA and SC generate higher revenues compared to BAU. The treatment of end-of-life concrete with C2CA generates revenues of 0.8 euro per ton from the sale of sand, aggregates and silica. This is substantially lower than if the SC is used. The treatment of end-of-life concrete by SC can generate revenues of 7.2 euro per ton. This is mainly due to the sale price of the cement fraction.

From the explanations above, if the fines are recycled it is obvious that they are economically beneficial to be used in new concrete production. This cost comparison also shows that it is possible to make concrete recycling economically feasible in the future with both SC and C2CA technologies.

4.4 Practices and Policies

There is a number of practices and policies in the industry that could be implemented or already have partly been implemented that might influence the economic situation for the recycling of concrete in the Netherlands. These would therefore also have an impact on the above-sketched cost comparison.

It is likely that EoL concrete will become cheaper because of the development of the smart dismantling technologies for end-of-life buildings and the increase of EoL buildings. If the current practice of smart dismantling and demolishing would become more prevalent there is a possibility that buildings will start to be constructed with recycling in mind. This would make recycling under all three different technologies more beneficial due to reduced costs for dismantling and demolition.

It is predicted that CO_2 costs will be incorporated in the cost calculations for building design in the future. Currently this is already done in the Dubocalc life cycle assessment (LCA) software of Rijkswaterstraat (E. Schut, personal communication, December 9, 2014). This tool was originally developed for designers in civil engineering but has been re-developed as a green purchasing tool. The software calculates an environmental cost indicator value (Milieu Kosten Indicator). Other software could incorporate a similar concept. This would lead to making especially the recycling of unhydrated cement more profitable.

Not only is there a possibility that the building industry will incorporate the price of CO_2 in their software as a practice, a carbon tax could also be introduced. According to Evert Shut (personal communication, December 9, 2014) a market for recycled materials would be created when a carbon tax of 50 euro per ton of CO_2 would be introduced. Another option is that the current price for carbon under the EU Emissions Trading System will increase significantly above the current price of 5 euro per ton. Such a price on carbon dioxide emissions would have an influence on the cement price and the willingness for cement and concrete makers to incorporate recycled materials.

Conclusion

The important insight acquired through this economic analysis is that there is currently no favorable market that supports the recycling of EoL concrete although it would seem favorable in a country that is not self-sufficient. The influx of EoL concrete to come does indicate a shift in the price of EoL concrete that could create favorable market conditions in the future. For recycled aggregates and others recovered materials, it is currently critical that the processing technologies seek opportunity in reducing costs or the recovery of other more valuable materials. C2CA and SC both generate more value than the BAU scenario in largely two different ways. C2CA reduces transportation costs through its ability to function on site while maintaining a competitive processing rate. While SC focuses on effectively breaking down the EoL concrete into pure flows of reusable and valuable material such as unhydrated cement. These technologies can therefore be considered to operate in the same market while not directly competing. These highlight the importance of creating a market in the backcasting and how both technologies could co-exist within it.

5 Chapter 5: Stakeholder and FIS Analysis

Concrete recycling is a relatively new concept, especially with the focus to acquire concrete to be used in buildings again. The technologies discussed in Chapter 2 are still being tested at lab scale and new businesses like C2CA, SC BV are still evolving. These innovations are in an early stage of development and can be classified as niche level projects under the Multi-level Perspective (MLP) introduced by Rotmans et al. (2001).

The backcasting scenario at the end of this report is built on an analysis of the current situation of the EoL concrete industry, the direction in which it is moving and the factors that can influence its course. In this light the system around concrete recycling can be identified and analysed as an innovation system (IS) as it is defined by Hekkert et al. (2007). Based on this knowledge, it was decided to carry out a FIS analysis of concrete recycling industry in Netherlands following the framework of Hekkert (2007).

To form the basis of FIS analysis a stakeholder and technology analysis of concrete regime in Netherlands was carried out. Results of technology assessment are given in Chapter 2, whereas the stakeholder analysis is presented in this chapter.

5.1 Stakeholder Analysis

In this section, the stakeholders active in the innovation system (IS) for concrete recycling will be identified and described followed by a FIS analysis. For stakeholder analysis every individual actor will be ranked according to their power and interest in the concrete recycling industry. The relative power and interest provides the information needed to make a power-interest matrix of the IS. A good starting point for identifying the stakeholders in the concrete sector is by making a distinction between three different building phases. Bonora (2014) distinguishes the pre-building phase, the building phase and the post-building phase. The following sections will list the stakeholders that operate in each of the phases and will describe their role in the IS.

5.1.1 Pre-building Phase

The pre-building phase consists of concrete production, raw material production (aggregate, sand and cement), design of the building and complying with norms and regulations. The most important actors in this phase are the concrete producers, the aggregate producers, the cement producers, the design team, non-governmental regulators and insurance companies. Table 16 gives a complete overview of the actors in this phase.

Table 16: Stakeholders active in the pre-building phase

Stakeholder	Description
Concrete producers	Theo Pouw, Mebin (part of the Heidelberg Cement group) and Holcim are examples of concrete producers involved in recycling of concrete. All three of them are industry partner in the C2CA project. The concrete production industry can be categorized into the poured and the precast concrete makers. In 2005, 55% of total

	concrete production was poured concrete and 45% was precast concrete (Bonora, 2014). The precast concrete producers express more interest in using recycled concrete, while the on-site pourers are more afraid for the impact it has on their business (M. Bakker, personal communication, September 3, 2014). When recycling of concrete becomes technologically and economically viable and demand increases, the concrete producers have to go along in this movement. Therefore, the concrete producers have only medium power and a high interest, for which the interest from the precast producers is higher than the pouring companies.
Aggregate producers	To the group of aggregate companies belong the primary sand and aggregate producers. The main producers of sand and gravel in the Netherlands are Sagrex (part of the Heidelberg Cement group), Ballast Nedam, Dyckerhoff Basal, L'Ortye and Netterden. The Netherlands is not self-supporting regarding the supply of aggregates, because it has a lack of natural resources. This makes the Netherlands dependent on imports and recycling (Bonora, 2014). The recycled aggregates constitute a threat for the business of the aggregate producers, because they are currently not directly involved in recycling of aggregates. As a result, the aggregate producers have a low power and high interest.
Cement producers	Due to the limited availability of limestone in the Netherlands there is currently only a single production site. ENCI is operated by the German company Heidelberg Cement and is planned to be shut down in 2018, leaving the Dutch concrete industry completely dependent on the import of cement, primarily from Germany. The C2CA research project includes two cement producers, the Swiss company Holcim and the German company Heidelberg Cement. The latter of which is also involved in the German research project, Klimazwei, which is partly initiated by the German Ministry for Education and Research and the German Cement Works Association and also includes the Research Institute for the Cement Industry. The successful recycling of concrete and cement could have an impact on primary cement production which could be a disadvantage for the vested regime. The cement producers try to exert as much control as possible on the niche market of concrete recycling. Hence, the cement industry has a high power and interest in the innovation system.
Design team	The design team is composed of the architect and the structural engineer. They are responsible for the design of the building, which gives them influence on the hardening properties needed for the concrete and the hardening time before the building can be used. Currently however, the interest from the design team in recycled concrete is low, since there is no established market for it as of yet. Thus, the design team has a medium power and low interest.
Non-	The most important non-governmental regulator is the NEN. The

governmental regulators	NEN is an independent organisation that formulates the Dutch norms and standards for quality on a wide variety of products. Concerning concrete, it adopted the European standards for the physical properties, the application and the conduct of using concrete. The alteration of norms is a lengthy and complex process. The actions of non-governmental regulators have a strong influence on the system, but they do not have vested interests themselves. Therefore, they can be characterized as having a high power and low interest.
Insurance companies	The insurance companies provide insurance against mistakes in design, construction and material use during the construction project. With regard to legal issues, the insurance companies want to strictly follow the guidelines set by the non-governmental regulators (such as the NEN) concerning the use of recycled concrete. Hence, they have medium power, albeit a very low interest in recycled concrete.

5.1.2 Building Phase

The building phase consists of construction and use of the building. Here, we can distinguish the contractors, the clients and the users as the most relevant stakeholders. Table 17 provides an overview and description of each of these actors.

Table 17: Stakeholders active in the building phase

Stakeholder	Description
Contractors	The contractors are the construction companies that are responsible for all the construction activities in the project. They are able to hire other construction companies to perform certain jobs in the construction process. Besides that, the contractors also purchase the concrete from concrete makers. Some contractors have already shown to be very interested in using recycled concrete, such as Strukton from the C2CA project. The use of recycled concrete could provide a competitive advantage, as it shows their clients that they care about the environment. Overall, it appears that the contractors currently have a high power and medium interest in realizing a closed-loop concrete economy.
Clients	The clients are the starting point for a new construction project, because they issue the request to construct a building. As the government will be discussed later in this stakeholder analysis, the clients referred to here are only from the private sector, such as project developers. The clients have quite some impact in the design phase of a new building. If they require that sustainable building materials need to be used by the contractor, there is a good chance that recycled concrete is utilized. Nevertheless, at the moment there is still not an established market for recycled concrete, which makes clients unaware of the possibility to use recycled concrete. Therefore, the clients have a medium power and low interest in the concrete recycling niche.

Users	The users of the building do not play an important role in the concrete recycling developments. They might have a strong opinion on recycled concrete and could choose to vent this opinion publicly, but it would probably not have a big impact on the innovation system. Moreover, users are usually not very concerned about the types of material used in the building, as long as it is safe for them to use the building. Hence, users can be classified as having a very low power and interest.

5.1.3 Post-building Phase

The main actors in the post-building phase are the demolition companies and recycling companies. They are responsible for demolishing the building, crushing the demolition waste and recycling it to make new raw materials for construction. This phase is the most interesting one from the perspective of this paper. Therefore, the small companies developing recycling technologies for end-of-life concrete are included as separate stakeholders. Table 18 shows a list and description of all the stakeholders in the post-building phase.

Table 18: Stakeholders active in the post-building phase

Stakeholder	Description
Demolition companies	The demolishers of end-of-life buildings have an important role to provide clean demolition waste that could be separated further and recycled into new concrete. Since currently only 5% of concrete waste is recycled by the industry, there are still many steps to be taken in order to improve this rate (Bonora, 2014). Smart demolition and better pre-sorting could provide great benefits to concrete recyclers, although the demolishers might only be hired to provide this service to the concrete recyclers. Thus, the demolition companies have a medium power and low interest in concrete recycling.
Recycling companies	In the current market, the recycling companies perform the task of crushing and sorting the stony end-of-life concrete material before it goes to roadfill. At the moment, there are 150 crushing companies and 90 sorting companies in the Netherlands. Concrete recycling practices will have a big impact on the business of the recycling companies. If they do not invest in concrete recycling technologies, they might not be part of the value chain of end-of-life concrete any more. In that scenario, recycling companies will only be hired to provide the services of crushing and sorting. The recycling companies therefore have a low power and high interest in the concrete recycling market.
Laser companies	Laser companies are new entrants to the concrete sector. With the development of innovative separation technology there is a need for more quality control, which could be met by laser inspection. C2CA includes two of such companies: Laser2000 and DV s.r.l. Because these laser technologies are still in development, the current power and interest of the laser suppliers is low.

C2CA International BV	C2CA International BV is the spin-off company from the EU-funded C2CA project. Strukton, Inashco and Heidelberg Cement founded it to recycled concrete using ADR and complementary technologies to separate the fines. Because this company is backed-up by multiple established firms in the concrete industry, it has a high power and very high interest.
SmartCrusher BV	SmartCrusher BV is the spin-off company from Schenk Concrete Consultancy in Oss. The company claims to have found a machine that can separate the fines into sand, hydrated cement and unhydrated cement fraction. As opposed to C2CA International, SC currently lacks the strong backing of the concrete industry for its technology. As a result, the company has a very high interest but a substantially lower power than C2CA International.

5.1.4 Other Stakeholders

Finally, there are also stakeholders that transcend the boundaries of the phases, which makes it hard to categorize them. Examples of such stakeholders are the European Commission, the Dutch government, universities and research institutions. Moreover, MVO Nederland that manages the Green Deal Beton is an important actor that operates in all three phases. A complete overview of the stakeholders active in all three phases can be found in Table 19.

Table 19: Other stakeholders active in all three phases

Stakeholder	**Description**
European Commission	The European Commission is one of the biggest funders of research in the field of concrete recycling. The C2CA project has received substantial financing from the FP7 programme. In addition, the European Commission has made European standards for the use of concrete, which have a direct effect on the guidelines set by the non-governmental regulators in the Netherlands. Because of these two ways of exerting influence, the European Commission has both a high power and interest.
Dutch government	The Dutch Government has the intention to reduce greenhouse gas emissions according to the European objectives set in the “20-20-20” targets (European Commission, 2014). In addition, it has put the closed-loop economy high on the agenda. In this light it has put several programs and incentives schemes into place to stimulate innovation in sustainable technologies. One of these is the Green Deal Beton that has been set up as an industry-wide initiative. Even more importantly perhaps is that the national government and municipalities are one of the biggest clients of construction projects. Their role as a client gives them significant control over the type of concrete used in construction projects. Therefore, the Dutch government has a high interest and an even higher power.
MVO Nederland	The Green Deal Beton is an initiative from the Dutch Government

(Green Deal Beton)	that intends to remove regulatory and jurisdictional hurdles for companies that contribute to the government's objectives on sustainability. Evert Schut from Rijkswaterstaat is currently posted at MVO Nederland as the program manager for the Green Deal Beton. This initiative aims to make the value chain of concrete more sustainable. A large part of the actors in the concrete sector are involved in the Green Deal Beton. Unfortunately though, their influence is limited because it cannot force participants to implement sustainable practices. Thus, MVO Nederland has a medium power and high interest.
Universities	In the Netherlands, the universities involved in the C2CA project are Leiden University and Delft University of Technology. In addition, the Eindhoven University of Technology has conducted research on the results of the SC. Because of the scale and impact of the end-of-life concrete problem, research groups within universities express much interest in the field. Especially in the Netherlands concrete recycling will yield enormous benefits, as the Dutch have a ban on landfilling. Given the limited influence of universities on the implementation of new technologies, the universities have a medium power and high interest in the innovation system.
Research institutions	Examples of research institutions involved in C2CA are the Foundation for Research and Technology Hellas (FORTH) and the Barcelona Supercomputing Centre. The economic and environmental potential of closing the loop on concrete makes this an interesting research topic for which funding could relatively easy be realized. This in turn provides opportunities for new research positions in addition to a potential to develop high impact solutions for a global problem, on which can be capitalized through patents and/or spin-offs. Since research institutes have only a limited influence on technology implementation, they have a medium power and high interest.

5.2 Power-Interest Grid

Mendelow (1991) has proposed a power-interest matrix to define the potential influence of the stakeholder groups. The stakeholders described in the previous sections can be plotted in a power-interest grid to show their importance and responsibility in the development of the concrete recycling niche. First, the stakeholders are ranked according to their relative power and interest in the innovation system. Based on this information, a power-interest matrix is made to visualize the influence of each actor.

Figure 8 shows the power-interest grid. The grid provides useful information regarding the policies that need to be implemented to reach the goal of a circular concrete economy in the Netherlands by the year 2050. The backcasting analysis later on in this report will elaborate further on this.

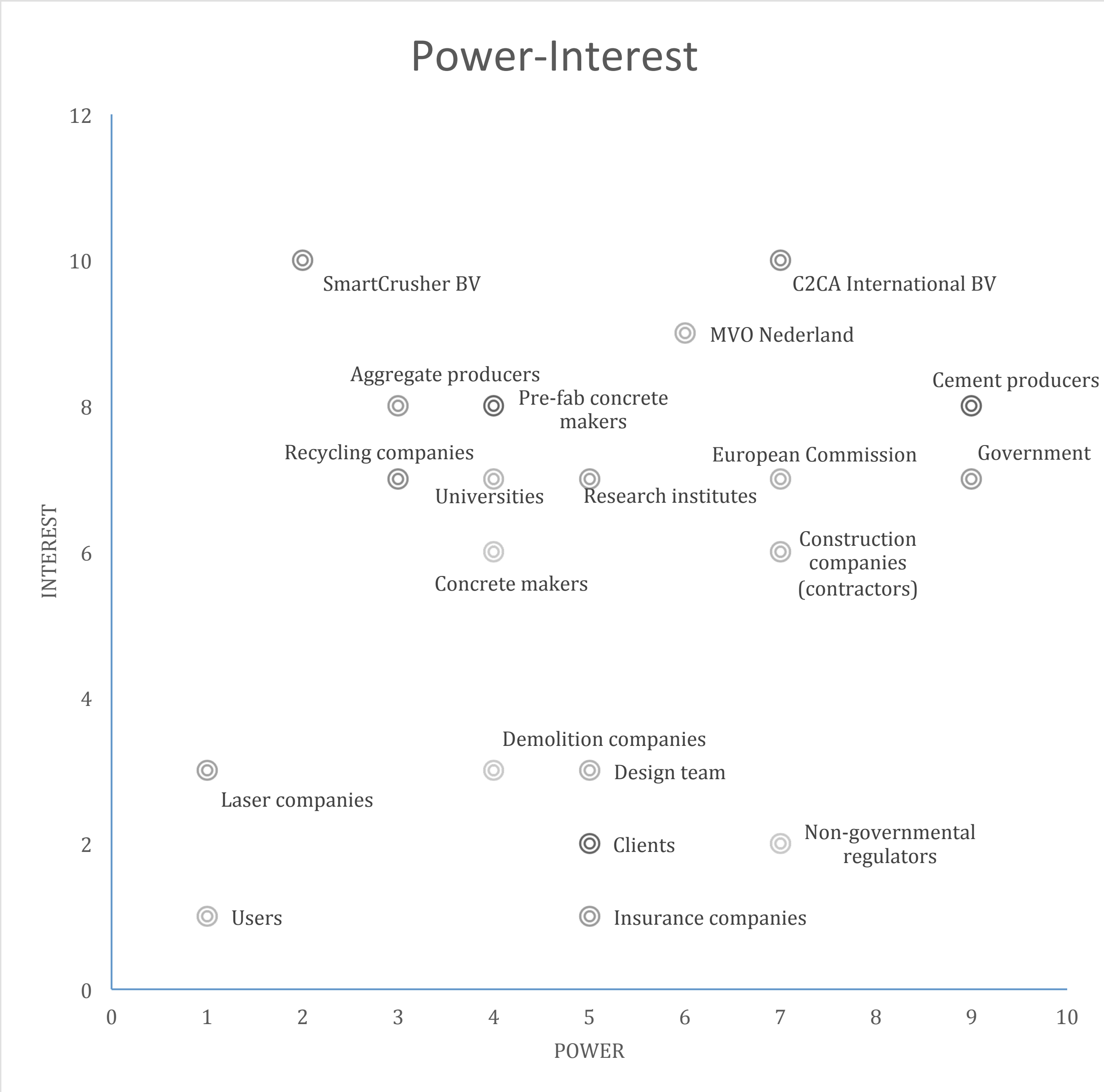


Figure 8: ***The Power-Interest grid of the concrete recycling innovation system***

FIS Analysis

Innovations do not emerge from isolation but from a system of private and public parties, it builds on knowledge structures and relations (Vasseur, Kamp, & Negro, 2013). This system is called an innovation system, and the attributes of this system are often determinants for its effectiveness.

Hekkert (2007) identifies seven key attributes of innovation systems, which he calls functions; the entrepreneurial activities; knowledge development; knowledge diffusion; guidance of the search; market formation; mobilization of resources and creation of legitimacy. Together these functions form the basis of a methodology to analyse innovation systems called functions of innovations systems (FIS). The result of such an analysis gives the researcher insight in a system's strengths and weaknesses and provides handles on what prevents or stimulates innovations in the system under inspection to reach maturity, these are so-called motors of change.

The functions

The seven functions of the FIS framework briefly explained.

- **Entrepreneurial activities** constitute the activities displayed by commercial on the aggregate level. Which include the initiation of pilot project, start-ups and other new market entrants but also market exits.
- **Knowledge development** includes all mechanisms of learning: learning by searching, learning by doing and learning by using. In practice this boils down to scientific research and internal research and development. Which are measured through published articles, available patents and research projects.
- **Knowledge diffusion** is the extent to which knowledge is shared among system members and is a strong indicator for the existence of common interests. The amount of seminars, conferences and joint research projects are an indicator of the level of knowledge diffusion.
- **Guidance of the search** relates to the activities within the innovation system that can positively affect the visibility and clarity of specific needs among the system's members. It specifically refers to the ability of steering the system towards a preceded goal. Often through policy programmes or subsidies.
- **Market formation** does not always occur naturally because it is difficult for innovations to compete with established powers within a system. This function therefore refers to the system's ability to create a (niche) market in which novel products and services can develop.
- **Mobilization of resources** includes material and financial resources and human capital. It refers to the availability and to what end resources are mobilized.
- **Creation of legitimacy** refers to the system's ability to create support for its innovation. This is expressed by the public opinion the presence of a lobby or other advocate groups either pro or contra.

Table 20 depicts an overview of the functions and these indicators.

Table 20: ***Functions and indicators of the FIS framework***

Function	Indicators
Entrepreneurial activities	Entrepreneurial Climate Entries/Exits Pilots Initiatives
Knowledge development	Scientific papers Research projects Experience gained Patents
Knowledge diffusion through network	Conferences & exhibitions Joint ventures

	Quality of interactions between actors
Guidance of search & implementation	Subsidies Tax regime Government Targets Public-Private Cooperation's
Market formation	Installed Capacity Subsidies Tax regime
Mobilization of resources	Humans resources Physical resources
Support from advocacy groups	Public Opinion Environmental Activist Activities

5.3 Analysis of Innovation in Concrete Recycling in the Netherlands

Hekkert (2007) argues that technological change can only be understood through the analysis of the key dynamics in its overarching IS. Which in turn are most efficiently analysed with a functions of innovation system analysis (FIS). This method comprises of seven specific functions that map and identify the key factors that influence the direction and rate of innovation within a certain system. Below these functions are explained and applied for the innovation system around concrete recycling. This IS of concrete recycling is a subsystem of the larger system which comprises the whole of the concrete industry.

5.3.1 Entrepreneurial activities

The innovation system as a whole is structured in such a way that the interaction of actors gives rise to new knowledge, networks and markets. Business opportunities arise out of these developments. Entrepreneurs can take the risk of invest in these opportunities driven by the possibility of financial gain, which is the process of innovation. There would be no concrete innovation without entrepreneurs' role is vital for the system to function. To map out the entrepreneurial activities of a specific IS, the number of new entrants, the amount of incumbent actors and the experimental or niche projects, function as indicators.

Within the IS of concrete recycling there are several branches of companies that are directly or indirectly involved in the innovation system. From the first report coming from the green deal beton it can be concluded that basically all branches present in the overall concrete industry have representatives in concrete recycling in one way or the other (MVO, 2013). The branches are subdivided in two categories. The category of end-users, which includes architects, design agencies and clients. Within the second category of production & maintenance the following branches are distinguished: Cement producers, concrete producers, contractors, breakers, recyclers & demolition companies and transport.

However although this report suggests that, with the exception of the transport sector, a large part (80% to 100%) of the companies in the mentioned branches is committed to the use of second-generation resources (MVO, 2013), the practice is slightly different. In fact a company is already counted as committed when it uses second-generation aggregates in one of its projects (E. Schut, personal communication, December 9, 2014). So it should be restated that a large part of the companies is open to the use of second-generation concrete but it is only a small group that is actively involved in innovative activities like the development of novel technologies.

This group of actively involved companies is represented in a couple of different research initiatives. The first of which is the C2CA research project that includes seven private companies from four different countries and from five different branches. Strukton, a Dutch contractor; Theo Pouw, a supplier of building materials; Heidelberg Cement and Holcim, respectively German and Swiss cement producers; DV s.r.l and Laser2000 are two laser companies from Italy and the Netherlands respectively and Inashco R&D which is a Dutch R&D company specialised in the physical separation of bottom-ash from municipal waste incinerators. It is clear that this project includes diverse mix of entrepreneurs. Entrepreneurs that have already established their presence within the concrete sector, like the cement producers, and new entrants who have virtually no experience with concrete e.g. the laser companies and Inashco R&D.

Another party that is actively involved in closing the loop on concrete is Struyk Verwo Infra. The supplier of infrastructural building materials has developed a method to replace 75% of first generation gravel used in pavement materials by EoL concrete.

In addition to these already more established projects there is the SC of Koos Schenk. This is a start-up with a patented technology that claims to have the potential to separate the fines coming from EoL concrete and prepare it for re-use in cement production. This offers an additional value to the technology involved in the above-mentioned projects.

In conclusion it can be stated that cement and cement industry is a conservative sector since it is still a limited amount of companies who are involved in active development of concrete recycling.

5.3.2 Knowledge development

According to Hekkert et al. (2007), mechanisms of learning are at the heart of any innovation process. R&D and knowledge development are crucial aspects of the innovation system. The function of knowledge development distinguishes between three types of learning, which are learning by searching, learning by doing and learning by using. Specific indicators for each of these types of learning will be analysed for the case of concrete recycling in the Netherlands.

One of the indicators related to learning by searching is the number of patents. A quick scan on Espacenet shows that worldwide there are 265 patents with ‘concrete recycling’ in the title. However, the majority of these patents have been issued in Asian countries like China, Japan, Korea and Taiwan and therefore have only a limited influence on the innovation system in the Netherlands (Espacenet, 2014). In C2CA project, the breaker-sorting technology Advanced Dry Recovery (ADR) has been patented by Inashco, the spin-off company from Delft University of Technology. Although initially developed for recycling of bottom ash from municipal waste incinerators, ADR is now being applied to concrete recycling (INNOVATIONSEEDS, 2014). The Laser Induced Breakdown Spectroscopy (LIBS) sensor technology that is also part of the C2CA project has not been patented yet. LIBS can be used to analyse the composition of recyclables and to assess the quality of output from the ADR process, but it is still in development (Xia and Bakker, 2012). Another type of sensor technology for C2CA, Hyperspectral Imaging (HSI), is also still in development and has not been patented. The aim of HSI is to have “early-on-site” detection of concrete to identify composition and contaminants before the demolition phase (Di Maio et al., 2012). SC technology developed by Schenk Concrete Consultancy aims to recover sand, gravel and cement. This alternative to ADR has been patented (SmartCrusher, 2013).

In addition to the number of patents, the number of research projects in the Netherlands is also an important indicator. C2CA is one of the largest research projects on concrete recycling and has been funded by the EU (INNOVATIONSEEDS, 2014). The C2CA project will end in 2014, but the follow-up project Hiser has been started recently. With Hiser the ADR technology will be developed further, but research will also focus on technologies that can separate the fines (0-4 mm) (E. van Roekel, personal communication, October 10, 2014). Schenk Concrete Consultancy that developed the SC is a smaller research project, but has gained a lot of attention and has recently been asked to participate in the C2CA project (SmartCrusher BV, n.d.).

In the concrete recycling innovation system, learning by doing and learning by using is essentially the same, because the developers of recycling technologies are also the ones who use them. Therefore, the indicators for this category of learning are the ones from learning by doing, which are the number of products produced and the number of niche projects.

The number of recycling technologies developed and niche projects executed is still quite small. In the C2CA project, the ADR technology has been developed and used in a niche project in Groningen. In this experiment, multi-storied office buildings have been demolished in order to test the ADR technology (Di Maio et al., 2012). In contrast with ADR, the sensor technologies have been produced, but are not mature enough yet to test them in niche projects. The SC technique has been scaled up to a larger size recently and is being tested (Van Eijndhoven, 2014). However, experiments in a niche project, such as the one by C2CA in Groningen, have not been executed yet. Finally, Struyk Verwo Infra has initiated some pilot projects in the Netherlands with a technology that recycles the gravel in concrete pavements. Examples of these projects are those in the municipalities of Lingewaard and Castricum (Gemeente Lingewaard, n.d.; Twisk & Bosman Aannemingsmaatschappij, n.d.).

5.3.3 Knowledge diffusion

In many innovation systems, as with concrete recycling, a multitude of public and private parties are involved. These parties have either contradicting or aligning interests when it comes to the direction in which the innovation system moves. Interests of companies might not be motivated by the same reasons even when their interests are aligned. The level of knowledge diffusion is a strong determinant for the way in which common interests are strived for. The manner in which an IS is structured tells a lot about the way in which knowledge is shared. As well as the amount of seminars, conferences and joint research projects which aim to share knowledge across the full scope of actors contained within the Innovation System.

Within certain branches seminars are organised to inform members about the challenges and opportunities of recycled concrete (BRBS, 2010)*. This is important but true knowledge diffusion happens primarily in sharing of knowledge which transcends the different branches within a sector. This is contemplated by the efforts of the green deal initiative from the Dutch government. A green deal is a contract between government and one or more private parties that commit the private stakeholders to invest in sustainable practices while government tries to remove as much regulatory hurdles as possible. The green deal concerning concrete recycling is a deal which aims to make the full chain from cement production to construction and demolition of concrete structures and thus involves a large number of private parties all across the different branches. Not only are these parties informed about sector broad developments through seminars and conferences but they are also actively encouraged to share knowledge with other members within the concrete sector. In practice it seems however that the cement and concrete industry is still dominated by a conservative and non-transparent communication culture (M. van Lieshout, personal communication, January 20, 2015) in which parties rather keep gained insights to themselves for personal benefit. The green deal has opened up new relation and modes of communication so, in a sense, are paving the way for a more open culture. But there is still a long way to go.

Knowledge diffusion occurs in joint research projects. C2CA is currently the only joint research project in the Netherlands that is focussed on concrete recycling. It involves seven international research institutions and a variety of private companies. All members contribute knowledge from their respective expertise. This also assures that any innovations or developments following from this project have chain broad support. In December 2014 a kick-off meeting was scheduled for a similar joint project in Germany focused towards a more sustainable way of cement production specifically (C. Müller, personal communication, December 2, 2014).

5.3.4 Guidance of the search

Guidance of the search relates to the activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users. Whereas the second function, knowledge creation, is defined as the creation of technological variety, guidance of the search represents the process of selection. It shows that technological change is not autonomous, but that the direction can be influenced by changing preferences in society (Hekkert et al., 2007). Indicators for this function are specific goals, policy programs and technological best practices and examples.

In the Netherlands, the Green Deal Beton formulates the most important future goal for the concrete industry. This program, set up as a joint initiative between the government and the concrete industry, aims to have a 100% sustainable concrete industry by the year 2050. Because 100% sustainable is a definition that is hard to grasp, the Green Deal has subdivided the end goal into 10 long-term and non-binding agreements. The first one of these is to strive for closing the loop of concrete and to make use of secondary resources to produce concrete (MVO Nederland, 2013). The past year, the Green Deal has focused on seven different perspectives that can realize reduction of environmental impact in the mid-term. Only the last two of these programs have the objective to close the loop of concrete, as they are called ‘innovative concrete recycling technology’ and ‘circular economy’. The latter one of these is still in the concept phase and needs further development, but in the field of innovative concrete recycling technology there are various ongoing research projects, such as C2CA and SC. The five other programs in the Green Deal are focused on finding low-emission cements and lowering the amount of cement in concrete (Van Lieshout, 2014).

On a higher level, the EU has initiated several Framework Programs under the FP7 name, including C2CA and 'SUStainable, innovative and energy-efficient CONcrete, based on the integration of all-waste materials' (SUS-CON) in Italy (CORDIS, 2013). However, the EU has not communicated future goals or expectations with regard to the sustainability of the concrete and cement industries. Policy programs in Europe also exist outside of the governmental institutions. The European branch associations representing the concrete industry have united in the European Concrete Platform (ECP). This organization has launched The Concrete Initiative in order to tackle the challenges of sustainable construction (European Concrete Platform, 2014). With respect to recycling, The Concrete Initiative calls for recognition of the concrete industry's contribution to a resource-efficient and circular economy. They also argue that targets for recycling of construction and demolition waste need to be differentiated by material type or by environmental impact and not simply by mass (The Concrete Initiative, 2014).

5.3.5 Market formation

Novel technologies often come with high prices due to research and development costs. In addition to these R&D costs are the dominant products within a regime often efficiently attuned to the market due to the shaping force of free-market interactions. It is sometimes necessary to create a safe space in which these technologies can develop so innovations are able to compete with the establishment (Hekkert, 2007). This can be accomplished by setting up temporary niche markets or by putting innovation favoring regulations or tax regimes in place.

The concrete recycling innovation system does not intend to reinvent the end product i.e. concrete. It focuses on the way in which concrete is produced and thus does not offer any direct added value to the end-user. It might cause dissatisfaction if the quality or drying time of second generation concrete is not yet up to par with regular concrete. For this reason it is hard to set up a niche market for second generation concrete since there is no niche that would settle for an inferior product for the same or higher price. Tax regimes could be put in place to incentivize both clients and contractors to favor second generation concrete over regular concrete. No such regimes are in place since the quality of second-generation concrete has not been tested sufficiently to guarantee the needed quality to compete with regular concrete.

The demand for concrete in the Netherlands is growing. So there is an opportunity to provide some of this market growth with second generation concrete. Simultaneously it is predicted that the current market for end-of-life concrete will be saturated within the coming decade. Currently 95% concrete from demolition waste is used as road fill (Ingenieursbureau Amsterdam, 2011). It is inevitable that there will be a surplus of EOL concrete once there the need of new roads will decline. It is not allowed to landfill demolition waste by law in the Netherlands and thus there is a need for an alternative in which this surplus of end of life concrete is dealt with. This creates a strong position for organizations involved in closing the concrete loop.

Within this innovation system the government has a unique position when it comes to market creation. For the ministry of infrastructure and environment is by far the largest client concerning construction jobs involving the use of concrete. The ministry of infrastructure alone represent 30% of the Dutch concrete demand so all governmental organization including municipalities combined amount up to a substantial fraction of the total concrete demand in the Netherlands. Adopting a nation-wide policy for all construction jobs commissioned by governmental organizations to favour second generation concrete would set the odds in favor of second generation concrete needed market. The green deal for the greening of the concrete value chain already involves such an intention calling it sustainable procurement ('duurzaam inkopen' in Dutch) (E. Schut, personal communication, December 9, 2014). It could however take several years before this principle is widely adopted and correctly applied by all governmental organizations (van Lieshout, personal communication, January 20, 2015).

5.3.6 Mobilization of resources

Resources are of crucial importance to make knowledge production possible. They can therefore be considered as a prerequisite for all the activities in the innovation system. The indicators for this function are the different types of resources needed to produce knowledge. These are financial capital, human capital and physical capital (Hekkert et al., 2007). Furthermore, Bergek et al. (2008) propose that possible complementary assets, such as complementary products, services and a network infrastructure, can also be viewed as an indicator for mobilization of resources.

Financial resources for recycling of concrete are mainly made available by the European Union's Framework Programs operating under the name FP7. The funding programs have financed the C2CA project in the Netherlands, but also the SUS-CON project in Italy (CORDIS, 2013). The Dutch Green Deal Beton, that obtains funds from the participating companies, is not established as an organization that funds technology development, but is mainly focused on creating awareness and doing research. Until now, the private sector has not contributed as much financial resources as governmental institutions. Companies like Strukton and Heidelberg Cement have allocated financial capital to develop the technology from C2CA. Moreover, they also provide the financial means to establish the subsidiary company C2CA International BV, which is a spin-off from the C2CA project (E. van Roekel, personal communication, October 10, 2014). On the other hand, external investors, such as seed and venture capital funds, have been absent in financing the concrete recycling technologies. Final small sources of financing are the competitions that award prize money to innovative technologies. For example, Schenk Concrete Consultancy has won 10,000 euro in prize money from the ASN Bank Wereldprijs competition (Trommelen, 2014).

Universities and research institutions in European collaborations mainly provide human capital, consisting of scientific and technological knowledge. In the C2CA project, 7 universities and research centers from various countries joined forces to develop the ADR and sensor technologies (C2CA, n.d.). Each of them have their own specialization, but in this joint project the partners need to share knowledge and experiences with each other. In the Netherlands, Delft University of Technology and Leiden University are the participating universities. Delft University of Technology is leading the research and has a great amount of knowledge in the physics of recycling. Leiden University's Institute of Environmental Sciences (CML) has great expertise in calculating the environmental impact of producing concrete. Schenk Concrete Consultancy obtains human capital from Eindhoven University of Technology (Florea et al., n.d.). The researchers from this university have performed external tests of the SC lab installation and have reported the results.

The C2CA project has quite some physical resources. A complete plant of the ADR technology has been built and tested in a niche project in Groningen (Di Maio et al., 2012). Furthermore, the technology is currently being scaled up in order to be used commercially by the company C2CA International BV, which is a subsidiary of Heidelberg Cement, Inashco and Strukton. A facility has been built in Hoorn next to a mortar factory and the company is planning to set up four other plants as well (E. van Roekel, personal communication, October 10, 2014). The SC does not yet have that much physical resources. In addition to a lab installation, it has recently built a pilot plant where larger amounts of concrete can be crushed and analysed (Van Eijndhoven, 2014).

5.3.7 Creation of legitimacy

Innovation is by definition legitimate. However the extent to which this legitimacy is supported is for a large part determinant for its ability to reach and influence the current regime. Parties involved in the development of new technology have obvious interests for the technology to succeed. Just as parties with vested interest will take an opposing standpoint. The formation of lobby groups by actors with common interests can function as an accelerator for the creation of legitimacy. The rise, growth and actions of these advocacy coalitions function as an indicator for the creation of change.

Concrete is the second most used resource in the world after water. Cement alone contributes approximately 8% of global CO_2 emissions (Shi et al., 2007). The political and societal attention for climate-change rises increasingly. So from a political and environmental perspective will any innovation improving the environmental performance of concrete use and production legitimate. For the Dutch case it becomes even more interesting. Netherlands is almost completely dependent on the import of cement for the production of concrete in contrast to most other countries. In addition, it is only a matter of time before there will be a surplus of EoL concrete in the Netherlands in the coming decades. Without the possibility to landfill, new ways of dealing with this increase will need to be developed. Due to the abundance of the natural resources used for cement and concrete is this pressure less felt outside of the Netherlands. However there does not yet seem to be an anti movement from vested parties. Both parties with vested interests and new organizations across all links of the concrete chain seem open to the possibilities of concrete recycling (C. Müller, personal communication, December, 2, 2014).

Most of the parties that are involved in concrete recycling in the Netherlands are represented in the C2CA research program. This coalition also lobbies for policy and regulation favouring second generation concrete. They actively try to grow in number and power by approaching new parties with common interests, like the SmartCrusher to join their network. On the other hand has the inventor of the SmartCrusher, Koos Schenk, according to his own reporting experienced reluctance and even counteraction to the use of his technology (K. Schenk, personal communication, December 23, 2014).

Motors of Change

From this analysis some relations between the different functions can be identified. These so called motors of change indicate where the system can be influenced. Figure

9 depicts the different relations within the system. Relationships that are not self-explanatory are further explained.

Entrepreneurial activities and knowledge development are mutually beneficial. More knowledge is generated through the joined research programs and newly generated knowledge stimulates more entrepreneurial activities as can be seen in the C2CA research project.

The relationship with the state of knowledge diffusion and entrepreneurial has two sides. On one hand these joint research projects improve communications and knowledge diffusion amongst different disciplines in the sector. While on the other, conservative and closed culture of the concrete industry still has a strong hold on success of upcoming parties like the SmartCrusher.

Mobilization of resources has no direct positive influence on the entrepreneurial activities due to the division of focus to which resources are displaced. A substantial part is still aimed at finding alternatives for cement instead of reusing concrete and cement from end-of-life concrete.

The lack of market formation negatively influences the amount of entrepreneurial activity, which in turn affects the mobilization of resources. This is a determining factor in the whole system on which the government can exert direct influence through a more aggressive adoption of their own policy of sustainable supply.

The guidance of search is effective through other channels for example in the mobilization of financial resources in the form of subsidies for C2CA and the green deal has initiated a possible transition towards a more open culture for knowledge diffusion.

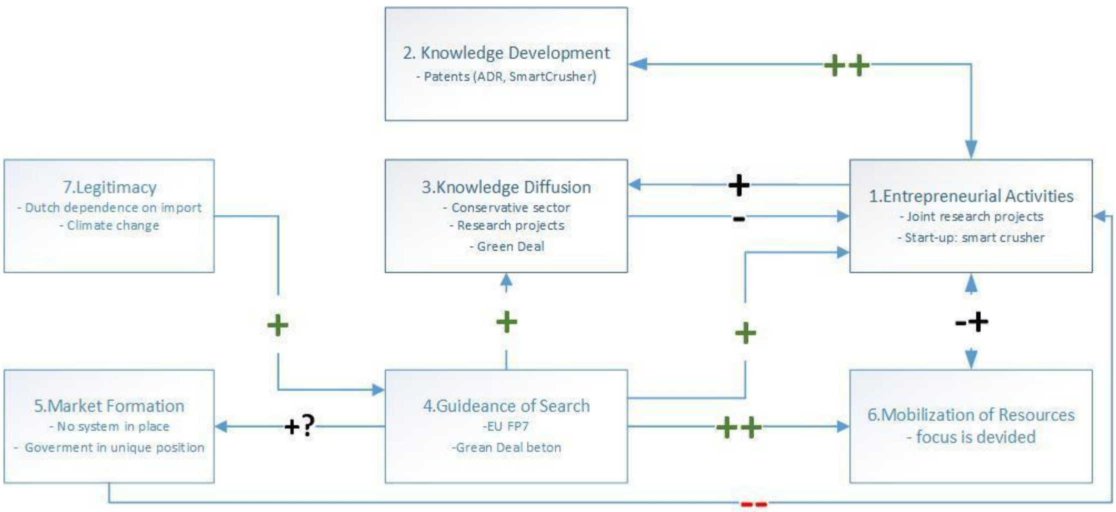


Figure 9: ***Relationships within the system***

6 Backcasting

In this section a pathway for closing the loop on EoL concrete by the year 2050 is constructed with a backcasting analysis using the framework described by Holmberg (1998). As described in Chapter 1 this analysis consists of four steps;

1. Define criteria for sustainability and desirability
2. Describe the present situation in relation to the desired future
3. Envision and assess potential solutions
4. Construct a development path

The methodology used in each of these steps will be desribed below as well as the results obtained.

6.1 Define criteria for sustainability and desirability

In this first step the criteria on the basis of which possible solutions are evaluated are formulated. These criteria are not necessarily specific to the problem at hand but they refer to the broader context of sustainability and desirability to avoid overlooking undesired spill-over or rebound effects of any of the proposed solutions that will be developed in step 3 of the backcasting.

The following criteria have been defined that include sustainability adressing both the socal and the environmental aspect of sustainability.

- No greenhouse gas emissions
- No creation of waste
- No depletion of natural resources
- People have access to and can afford the concrete they need
- Quality of life is maintained or improved
- Structures made of concrete are safe
- Ecosystem services are maintained and biodiversity is conserved
- The concrete industry is resilient and efficient

6.2 Describe the present situation in relation to the desired future

In this second step the current situation is defined and evaluated to the criteria developed in step 1, Holmberg (1998). The current situation is described based on the results obtained in the analysis done the previous four chapters.

6.2.1 Current technological situation

To diminish the environmental impact of the production of concrete several technologies are being studied and developed. Including research in different types of cement, that can possibly replace Portland cement. Some of these options are already being applied. This is however not the case for concrete recycling. None of the technologies discussed in this report have operational large-scale facilities. One of the challenges to be overcome is formed by the fact that EoL concrete consists of mixed waste which makes it difficult to recycle it back into clean valuable product streams. So most of the concrete used is made from regular cement that is produced under high emissions of carbon dioxide.

6.2.2 Current economic situation

The vast majority of EoL concrete in the Netherlands is downcycled as roadfill. In addition there is virtually no market for recycled concrete. This is partly due to an abundance of virgin materials namely sand and aggregates. Together, these circumstances add up to only 1.7% of EoL concrete that is recycled (wet processing) for reuse as concrete or aggregate. The lack of market applies to both recycled cement and aggregates. The formation of a market is currently not demanded by contractors, clients, end-users nor legislation. Today primary concrete remains the main building material in the Netherlands and it is prospected that the demand for building materials will increase as well as the supply of EoL concrete. The latter will rise relatively faster that the need for its application in road filling leaving a surplus of EoL concrete which has to be dealt with. Landfilling of EoL concrete is not an option since that has been banned in the Netherlands, a policy that is now adopted among the other EU member states as well.

Furthermore, currently there is one cement production facility in the Netherlands, which is not able to meet domestic demand. On top of that, they are planned to shut down excavation of limestone in Maastricht by 2018 (ENCI, 2009). Netherlands will be dependent on imported cement to fulfill its demand.

6.2.3 Current impacts on environment

The concrete industry accounts for approximately 8% of the global greenhouse gas emissions. This means that the current situation does definitely not align with the sustainability criteria of no greenhouse gas emissions. In the current situation there is a depletion of natural resources that also does not align with the sustainability criteria.

The environmental impact of the concrete industry can be decreased significantly by recycling EoL concrete. The carbon dioxide equivalence could be reduced as much as 75% by producing concrete from recycled materials. This reduction can be mainly achieved by reducing the emissions during the production of Portland cement by replacing clinker with recycled cement and by reducing the energy use during the production of raw materials by replacing them with recycled materials.

6.2.4 Existing FIS & Stakeholder situation

From the stakeholder an FIS analysis it followed that the industry as a whole has a very rigid, closed and non-transparent character. This gives little room for new innovative market-entrants and does not allow for smooth knowledge diffusion through the sector. Both direct contact with members of industry and indirect narratives reveal that the efforts made to green the industry are not motivated by the will to reduce environmental impact but by the will to gain a competitive advantage by market repositioning.

As with many other sectors is it the organizations that have direct control over the primary resources, which hold the most power, in the case of concrete these are the cement makers. In addition to the lack of power balance there is strict regulation in place to ensure the quality of concrete that leaves only very limited room for recycles or innovative alternatives. These alternatives run into all sorts of troubles when they search for possible applications ranging from quality standards that cannot be met on the basis of definition and difficulties with insurance possibilities.

The government is reluctant to influence the market through regulation, something that in this case might not even be needed. For in this case it has a unique position for all governmental organizations combined represents close to 50% of the concrete market on the demand side. Although intentions to improve procurement policy have been made official through the green deal 'sustainable procurement' is the enforcement of this policy completely lacking.

In conclusion it can be stated that the current situation does not do well on most of the predefined sustainability criteria. The concrete industry is responsible for a large part of greenhouse gas emissions; it is still primarily produced with virgin materials and thus depleting natural resources and damaging ecosystems. Due to the possible application as road fill the EoL concrete is currently not defined as a waste but will be as soon as there is a surplus and since this surplus seems inevitable could the current system be evaluated as inefficient and unstable. It does provide readily available concrete for everyone that is in need of it; a strong point that should be taken into account when reviewing the solutions emerging from the next step.

6.3 Envision and assess potential solutions

The third step of the backcasting methodology can be divided into three sub-steps. The first sub-step includes the envisioning of a wide range of different solutions that can individually or together lead to complete recycling of EoL concrete by 2050. These proposed solutions are not limited to the theory previously discussed in this report. For this report only states the current situation and trends. While this range of solutions strives to complement these trends with creative possibilities out side of the scope of the current paradigm. Delving into more general trends like moving towards a service based economy. In the second sub-step four different scenarios are developed of different futures that could occur in the Netherlands which may lead to different possibilities of implementation of the envisioned solutions. In the third sub-step the solutions are weighted both on there possibility of being implemented in the four different scenarios as well as against the sustainability and desirability criteria developed in the first step of the backcasting.

6.3.1 Envision potential solutions

The following solutions have been developed and are categorized into solutions aimed at market creation, technology development, policy & regulations, mobilization of resources and other.

1. Market Creation

- Solution 1: Carbon tax of 50 euro per ton. As discussed in Chapter 4, according to Evert Schut (personal communication, December 9, 2014) an introduction of a carbon tax of 50 euro would increase the market for recycled materials from EoL concrete. A carbon tax is a different policy instrument than a cap and trade emissions system as is currently in place for certain industries in the European Union. Since it is important that the environmental emissions are reduced in the concrete industry and not in a different industry to achieve the recycling of EoL concrete, a cap and trade emissions system is not viable. Such a system makes it possible to buy permits for the emission of greenhouse gasses from different industries that have reduced their emissions. The introduction of carbon tax would provide an incentive for the concrete industry to change its behavior because the tax increases the price of virgin materials creating an alternative market for recycled materials.

- Solution 2: Sustainable procurement of concrete by the Dutch government. As discussed in Chapter 5 the Dutch government represents a significant part of the demand for building materials in the Dutch concrete market. If the Dutch governmental organizations would critically assess their supply chains and select the product that are least harmful to the environment a demand for recycled materials from EoL concrete would be created.
- Solution 3: Subsidize recycled concrete. By artificially reducing the price of recycled concrete through subsidies it can compete with regular concrete and attain market share.
- Solution 4: Prefab concrete producers adopt recycled concrete. The prefab concrete producers have a unique position for adopting recycled materials due to the controlled environment in which their products can harden. Accelerated adoption of recycled concrete materials within this industry creates a market opportunity.

2. *Technology Development*

- Solution 5: Reducing cement use by improving aggregate packaging. As discussed in Chapter 2 improved aggregate packaging can reduce the demand for cement which is responsible for the majority of emissions from the concrete industry.
- Solution 6: Introduction of new types of cements. As discussed in Chapter 2 new types of cement such as self-healing cements, pozzolan cements and organic derived cements could decrease the need for Portland cement and thus reduce the environmental impact of concrete production.
- Solution 7: Maturation of C2CA. The current C2CA technology as discussed in Chapter 2 will need to be developed further to recycle the cement from EoL concrete. Also the laser technology will need to be developed to assess the quality of the input and output materials. If the technology were mature the recycling of EoL concrete on-site would significantly reduce the need for virgin materials.
- Solution 8: Changing to different building materials. As discussed in Chapter 2 different materials such as laminated wood and polymers could mirror the properties of concrete in the future. Thus could reduce the need for concrete and the associated environmental impacts during production of concrete.

3. *Policy & regulations*

- Solution 9: Flexibility in strength and hardening standards. As discussed in Chapter 5 the flexibility of strength and hardening standards would allow for different concrete recipes containing more recycled materials. This is especially feasible because most projects can be executed with lower hardening standards.
- Solution 10: Redefining recycled aggregates and recycled cement. The fact that second life cement and aggregates are labeled as 'recycled' makes the fall into a different category of building materials. For materials in this category stricter regulation is in place than for virgin materials. However the physical properties do not have to differ from their virgin counterparts. Relabeling could overcome some of these difficulties.

- Solution 11: Label for building recyclability. A label for the quantities and extractability of material in buildings. Such a label is very similar to the European energy label and could make recyclability of a building a marketable feature of a house.

4. *Mobilization of resources*

- Solution 12: Support the development of SC. Currently the SC technology has less support from the industry and less funds than the C2CA technology. Financial and organizational support coming from either public or private funds is necessary to continue and extend the research and development of the SC.

5. *Others*

- Solution 13: Design for recycling, smart demolition and dismantling. As described in Chapter 3 buildings could in the future be constructed with recycling in mind. Buildings are designed in such a way that the valuable materials within it can easily be recovered and re-used at the end of a building's lifetime

- Solution 14: Change the culture in the concrete industry. As discussed in Chapter 5 the current culture in the concrete industry is closed and not prone to change. Moving the concrete industry towards a more open and transparent business culture by incorporating all the actors across the value chain could lead towards a climate of knowledge sharing. Such a climate could make it easier to implement changes in the industry.

- Solution 15: Integrate carbon costs into structural design software. As described in Chapter 4 the Dubocalc software includes carbon costs. By implementing this, designers could become more aware of the materials they use and the environmental impacts these materials have by implementing this software.

- Solution 16: Concrete producer owns concrete in use**.** Many industries are shifting their business model from a product-based model to a service-based model. Something similar could occur in the building industry where the concrete in buildings remain in the ownership of the concrete producer which will receive a fee for it across the life-time of a building. At the time of demolition the concrete producer will be incentivized to retrieve as much of the materials in the building, which still have worth.

- Solution 17: Building owner owns EoL concrete. At this moment the owner of the building owns the concrete however they hand over the ownership at demolition to a breaker company. This solution makes sure that building owners will become more aware of what they actually own besides the function the building represents and will play an active role in retrieving as much of its value at the end of a buildings utilization phase.

- Solution 18: Standardized buildings. Standardized buildings can substantially increase the use of prefab concrete. This would allow for the use of more recycled materials in the production of concrete because of the hardening of the concrete under controlled circumstances.

6.3.2 Scenario development of different possible futures

In order to develop different scenarios it is necessary to determine the external factors that influence the course of concrete industry and the efforts towards 100% recycling of EoL concrete. These factors are categorized on a matrix with probability on one axis and impact on the other axis. The factors that are categorized as having a high probability and a high impact are called trends. From the factors that have a high impact but a lower probability two factors are chosen that are called critical uncertainties. All other factors are not used in further analysis because their impact is deemed too small. The extremes of the critical uncertainties are the basis for four scenarios.

The following factors are identified as having an influence on the pathway of attaining the envisioned goal of 100% recycling of EoL concrete by the year 2050.

- Carbon tax
- Climate change
- Sustainability awareness
- Age structure, changing demographics, population
- Economic performance
- Technology development (not SC and C2CA)
- Resource scarcity / depletion
- RoHs directive
- International political stability (only looking at Germany, Belgium, Netherlands)
- Import tariffs
- Fuel prices
- EU regulation
- Natural disasters: flooding, earthquakes Groningen
- Urbanization

From this list the sustainability awareness and the economic performance have been categorized as critical uncertainties because their development in the future is unsure. The carbon tax, the age structure and changing demographics, technology development besides SC and C2CA, EU regulation and urbanization have been determined as trends because their direction of development is more clear. The trends are described in more detail below. The other factors are deemed to have a low impact on the development path towards reaching the foal of 100% recycling of EoL by 2050.

Trends

The EU policy seems to follow a steady trend towards more environmentally conscious regulations. In addition to the EU 20-20-20 ambitions there is a clear focus on reducing waste and increasing recycling activities. The carbon tax seems to be an inevitable measure when the above ambitions are intended to be reached. The current system of a carbon market does not seem to have the desired effect and thus it seems plausible to assume that this will be replaced by a carbon tax within the coming decades.

As has been extensively discussed in this report there is no lack of ideas and technologies in development for a cleaner concrete production. Also an increase of end of life concrete is a direct result of a disproportional increase of demolition waste relative to the demand of the current application as road fill.

Scenarios

From the two identified critical uncertainties four possible scenarios are constructed. One, in which the economic performance is high and the awareness about sustainability is also high the so called *sustainable future*. The scenario where the economic performance is low but a high awareness about sustainability remains is called *the way of the environmentalist*. When there is a high economic performance but low to no awareness of sustainability the situation is comparable to the *conservative growth* that preceded the current situation. In the final scenario there is little economic performance and little attention for environmental problems and thus takes the world *a step backward*. The scenarios are further explained below.

1. Sustainable Future

In the sustainable future scenario there is a high sustainability awareness with a good performing economy. When the economy thrives there is a strong investment climate which in combination with the strong environmental awareness this will result in a mobilization of financial resources towards sustainable and innovative solutions. There is also a higher tolerance for sustainable and climate change averting regulations. he building sector has a strong correlation with the state of the economy and thus will a period of economic growth be coupled with an increase for construction jobs and thus the demand for building materials.

2. The Way of the Environmentalist

With a high sustainability awareness and low economic performance there will be little resources for investments however investments done will be preferred to be in sustainable activities. Companies will be compelled to comply with environmental regulations to maintain or regain market share. The building sector suffers under economic pressure and will be forced to green their activities.

3. Conservative Growth

Low awareness and attention for environmental issues and a focus on economic growth has led the world to the current situation in which a threat of depleting resources rises. In such a climate there will be resources for investment but there is no necessary preference for sustainable investment opportunities. The construction industry thrives in such a scenario not needing to comply for sustainable regulations.

4. A Step backward

In this scenario there is a low awareness for sustainability problems and a bad performing economic climate. A low economic performance or recession will lead to a decline or arrest of building activities. Decreasing demand for building materials and making it hard for recycled materials to compete. There are little resources for investment and without a lack of sustainability awareness these little resources are most likely not mobilized to aid in sustainable practices unless they present a very good business case.

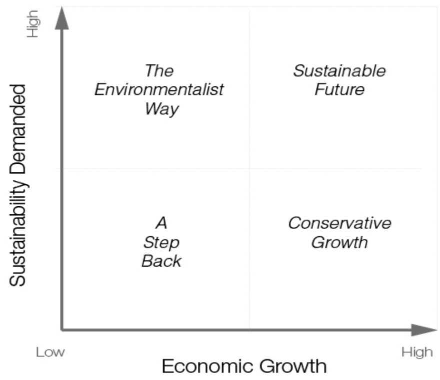


Figure 10: Different scenerios formulated under the effect of sustainability demanded and economic growth

6.3.3 Evaluation of solutions

In the third and final sub-step of step 3 the solutions are evaluated. Herein solutions are judged on their performance on the previously defined sustainability criteria and there their fit within each of the four scenarios is assessed. For the weighing the sustainability criteria have received a multiplication factor for their relevance to reaching the goal of 100% recycling of concrete by 2050.

Table 21: Solutions weighing and rated against Sustainability criteria

	Solutions / Sustainability Criteria	> Ecosystem services are maintained and biodiversity is conserved	> Zero greenhouse gas emissions	> No waste creation	> People have access to and can afford the concrete they need	> The system is resilient and efficient	> Maintains the quality of life or improve it	> Constructed structures made of concrete are safe	No depletion of natural resources	SUM	Verdict
1	Carbon tax increased to 50-60€/ton	3	3	3	-1	-1	1	1	3	84	**Risky**
2	Sustainable procurement of concrete by government	2	2	3	2	2	1	1	2	109	**Viable**
3	Subsidize recycled concrete	2	2	3	2	2	2	1	3	122	**Viable**
4	Prefab concrete producers adopt recycled concrete	1	2	3	1	2	1	1	2	100	**Adjust/Combine**
5	Reducing cement use by improving aggregate packaging	1	3	2	2	2	1	1	2	103	**Adjust/Combine**
6	New type of cements; self-healing cements, organic derived cement	1	3	1	-1	1	1	1	2	66	**Not Viable**
7	Maturation of C2CA : Fine recycling, development of laser technology	1	3	3	2	2	1	1	2	113	**Viable**
8	Changing to different building materials such as wood , polymers etc.	3	3	2	1	2	1	1	1	93	**Risky**
9	Strength and hardening standards should be made more flexible	1	2	1	1	2	1	1	1	70	**Not Viable**
10	Redefine 'recycled aggregates' and 'recycled cement'	1	1	3	2	1	1	-1	2	78	**Not Viable**
11	Label for Building Recyclability	2	3	3	2	1	2	3	2	122	**Viable**
12	Support the development of smart crusher	1	3	3	2	2	1	1	2	113	**Viable**
13	Design for recycling, smart remolition and dismantling	1	2	3	1	2	1	2	2	106	**Adjust/Combine**
14	Change culture in concrete industry	1	2	1	1	1	1	1	1	61	**Not Viable**
15	Carbon cost integrated into structural design software	1	3	1	-3	3	3	1	1	68	**Not Viable**
16	Concrete producer owns concrete in use	1	-1	2	2	3	1	3	2	96	**Risky**
17	Building owner owns EoL concrete	1	2	2	1	2	1	3	2	102	**Adjust/Combine**
18	Standardized building	1	2	2	1	2	1	3	1	92	**Risky**
Importance		**3**	**7**	**10**	**6**	**9**	**3**	**6**	**10**		

The solutions that have scored highest on the sustainability and desirability criteria as can be seen in table 21 and can thus be considered viable are:

- Solution 2: Sustainable procurement of concrete by the Dutch government
- Solution 3: Subsidize recycled concrete
- Solution 7: Maturation of C2CA
- Solution 11: Label for Building Recyclability
- Solution 12: Support the development of SC
- Solution 17: Building owner owns EoL concrete

The solutions that performed relatively well on the criteria but not outstanding are still taken into account as possible additions to, or as a partial solution in combination with, other solutions. These are:

- Solution 4: Prefab concrete producers adopt recycled concrete
- Solution 5: Reducing cement use by improving aggregate packaging

- Solution 13: Design for recycling, smart demolition and dismantling
- Solution 16: Concrete producer owns concrete in use
- Solution 17: Building owner owns EoL concrete

Similarly, all solutions are rated on their fit, or likeness within each of the defined scenarios as can be seen in table 22. Since the likeliness of each of the scenarios is unpredictable, the solutions rated on their overall performance. This means that seemingly promising solutions that perform really bad in one of the four scenarios could be excluded from the proposed pathway.

The solutions that had an overall good performance in the scenarios and can thus be considered viable are:

- Solution 2: Sustainable procurement of concrete by the Dutch government
- Solution 4: Prefab concrete producers adopt recycled concrete
- Solution 5: Reducing cement use by improving aggregate packaging
- Solution 7: Maturation of C2CA
- Solution 10: Redefining recycled aggregates and recycled cement

As was the case for the criteria, there are several solutions that performed relatively well in the scenarios and which will also be taken into account as possible contributors to a more comprehensive solution.

- Solution 10: Carbon tax of 50 euro per ton
- Solution 11: Label for Building Recyclability

Table 22: Solutions implementation in all four scenarios

		HsusHeco	LsusHeco	HsusLeco	LsusLeco		
	Solutions / Scenario	S1	S2	S3	S4	Sum	Verdict
1	Carbon tax increased to 50-60€/ton	3	1	2	-1	5	Adjust/Combine
2	Sustainable procurement of concrete by government	3	1	2	1	7	Feasible
3	Subsidize recycled concrete	1	-1	3	1	4	Not Feasible
4	Prefab concrete producers adopt recycled concrete	3	1	2	1	7	Feasible
5	Reducing cement use by improving aggregate packaging	3	1	3	1	8	Feasible
6	New type of cements; self-healing cements, organic derived cement	3	-1	-1	-3	-2	Impossible
7	Maturation of C2CA : Fine recycling, development of laser technology	3	2	2	1	8	Feasible
8	Changing to different building materials such as wood , polymers etc.	2	1	1	-1	3	Not Feasible
9	Strength and hardening standards should be made more flexible	3	-1	2	-1	3	Not Feasible
10	Redefine 'recycled aggregates' and 'recycled cement'	3	2	3	1	9	Feasible
11	Label for Building Recyclability	3	1	3	-1	6	Adjust/Combine
12	Support the development of smart crusher	2	1	1	-2	2	Not Feasible
13	Design for recycling, smart remolition and dismantling	1	-1	2	1	3	Not Feasible
14	Change culture in concrete industry	1	-1	1	-1	0	Not Feasible
15	Carbon cost integrated into structural design software	3	-1	2	-2	2	Not Feasible
16	Concrete producer owns concrete in use	1	1	2	1	5	Adjust/Combine
17	Building owner owns EoL concrete	1	1	2	1	5	Adjust/Combine
18	Standardized building	-1	-2	2	-2	-3	Impossible

From these solutions two possible sets of solutions are distilled for which a development path is constructed in step 4 of the backcasting. The first solution consists of two sub-scenarios one based on the C2CA and one on the SC technology.

1. Solution: Gradual market creation and the maturation concrete recycling technologies

This set of solutions constitutes of two subsets (i.e. 1A and 1B) in which the main difference is the failure of the C2CA project to separate the fines successfully into value streams. They are similar in the fact that there is a gradual creation of market for recycled concrete through an adoption of recycled materials by the prefab concrete industry. In addition will improved aggregate packaging be applied be widely applied reducing the need for cement per ton of concrete. A construction label will be introduced detailing the specific materials within a building and rating the possibility of their extraction for recycling and the end of a building's life. This will increase awareness of the value of building materials and should induce a shift of responsibility for the material streams coming from building demolition.

In the 1A sub-scenario will these proceedings be complemented with the further development of the C2CA technology in which it will proof a successful separation of the fines into differentiated value streams.

In the 1B sub-scenario will the C2CA project, in spite of heavy funding from the European Union, not succeed in the separation of the fines leaving 50% of the problem of surplus EoL concrete unaddressed. This will create an opportunity for smaller parties to attract financial resources. The SC will benefit from this by extending their research on the quality of its output and successful scaling of the technology.

Although the analysis of the solutions presented slim odds for the SC to succeed in several scenarios namely the ones with a ill performing economy we decided to incorporate a sub-scenario in which it does. The fact of the matter is that although the ADR technology of C2CA is very well capable of producing aggregates that can be reused the production of concrete it currently has very limited accomplishments on the account of the fines. Which constitutes about 50% of the volume of EoL concrete (van Lieshout, 2014). The SC on the other hand has been designed to do exactly that. And the limited research that has been done on the quality of its outputs looks very promising. So since this separating of the fines is such an essential part of closing the loop on concrete we decided to incorporate a sub-scenario in which the C2CA project fails to successfully separate the fines into different value streams giving opportunity for the SC to attain market share and eventually even mature to the main way in which concrete is recycled.

2. Solution: Carbon tax of 50 euro per ton

An alternative to the complex package of solutions as proposed above, a carbon tax could be introduced. We see the introduction of a carbon tax as a trend in the backcasting scenario and thus believe that this is likely to happen before 2050. However, the question is how high this carbon tax needs to be to achieve complete recycling of EoL concrete by 2050. According to Evert Schut (personal communication, December 9, 2014) an implementation of a carbon tax of at least 50 euro per ton would be the most effective way of reducing greenhouse gas emissions in the concrete industry. Also in the Dubocalc software used in the building industry, a carbon tax of 50 euro can be taken into account in the analysis for most cost effective option.

A carbon tax is a different policy instrument than a cap and trade emissions system as is currently in place for certain industries in the European Union. Since it is important that the environmental emissions are reduced in the concrete industry and not in a different industry to achieve the recycling of EoL concrete, a cap and trade emissions system is not viable. Such a system makes it possible to buy permits for the emission of greenhouse gasses from different industries that have reduced their emissions. The introduction of carbon tax would provide more incentive for the concrete industry to change its behavior.

In general a carbon tax can be seen as an environmental fee which in the ideal case would be set at the same level as the marginal environmental damage that you want to see mitigated as a policy maker. This means that business in the market would have the incentive to reduce its environmental damage (or more easily to define environmental emissions) to the level at which it would be cheaper to pay the tax than to abate the environmental emissions by changing its technology. This of course means that it is possible to know the exact price of abating a certain amount of emissions. The abatement costs could have geographical and temporal variations and could change when environmental, social and economic conditions change.

However, it should be possible to determine such a price for the carbon dioxide emissions of the concrete industry in a limited geographical and temporal scope. Specifically, the Netherlands and a temporal scope until 2050. Of course some of the environmental, social and economic conditions may change as has been described in the previous four chapters, but this is likely to lead to cheaper recycling technologies than currently available and possibly even more willingness to implement these because of an increasing environmental awareness. Because the recycling of cement is the most challenging part of the recycling of concrete at this moment, the carbon tax needed for cement will be higher than the carbon tax needed for the recycling of sand and aggregate. It is assumed that both the aggregate and the sand that will be produced by means of the same technology as is used for the recycling of cement will be recycled as by-products.

According to a recent report published by the Carbon War Room (Gupta, 2011) the cement industry sells cement at approximately 100 USD per metric ton and has a profit margin of approximately 33%. This means that the production cost of one metric ton of cement is approximately 55 euro. In 2009 there was approximately 3 billion metric tons of cement produced leading to a bit more than 2.4 Gt of CO_2 emissions (Gupta, 2011). Therefore on average the production of one ton of cement leads to the emission of 0.8 ton of CO_2, or 0.82 more precisely according to the Carbon War Room report (Gupta, 2011). This emission originates for about 50% from calcination of limestone, and the rest of the emissions originate from the fuel and electricity emissions.

Reductions of carbon dioxide emissions can be achieved by means of switching to alternative fuels, reducing the amount of clinker needed and increasing the thermal energy and electricity efficiencies (Gupta, 2011). In order to reduce the carbon dioxide emissions by 19%, approximately 5 euro per ton of concrete is needed to finance these changes (Worldwide 150 billion needs to be invested over ten years for the production of 3 billion ton of cement per year). Thus when a carbon tax of 6 euro per ton would be set, it would be more profitable for the cement industry to implement these changes than to pay the tax.

A similar argument can be made for the mitigation of carbon dioxide by implementing recycling technology for EoL concrete. The cost of recycling one ton of concrete after conventional dismantling and demolition is currently 5 euro for the SC technology as was discussed in chapter 4. From 1 ton of conventional concrete a maximum of 60 kilogram of unhydrated cement can be extracted. This unhydrated cement can be used to replace 80% of the clinker in Portland cement as described in chapter 3. When assuming that half of the CO_2 in the production of Portland cement produced in the Netherlands, emitting 850 kilogram of CO_2 per kilogram originates from the calcination of limestone for clinker production, 340 kilograms of CO_2 per ton of Portland cement produced can be mitigated. Since only 40% of the cement market destined for concrete in the Netherlands originates from Portland cement, recycling unhydrated cement can abate only approximately 135 kilograms of CO2 per ton of cement. This means that for 5 euro approximately 135 kilograms of CO_2 can be abated. Therefore the costs for abating a ton of CO_2 an investment of 37 euro is needed.

This analysis is relatively rudimentary and based on a large number of assumptions. Some changes in the production of cement could occur such as the previously mentioned reduction in the amount of clinker used. This could lead to a lower CO_2 reduction because of the replacement of clinker by unhydrated cement. Also the current recycling technologies still require investment money to be developed further and to be scaled up. Therefore a carbon tax of at least 50 euro will need to be implemented to make sure that the cement industry will start promoting recycling of EoL concrete to extract unhydrated cement. Evert Schut has also suggested this level of carbon tax (personal communication, December 9, 2014).

Critical notes on the proposed pathways

Some of the solutions proposed in the beginning of this chapter seem intuitive and maybe even obvious. Yet they are not incorporated in the set of solutions proposed for the pathway. This has to do with the fact that they either performed low on some of the sustainability and desirability criteria or that they seemed unlikely to be implemented in one or more of the scenarios. Some of these solutions that did not get incorporated into one of the pathways are discussed below.

A redefinition of recycled materials is not included in the package of solutions because currently, there is not enough evidence that they actually act the same way as virgin materials and thus a rushed redefinition of these materials could be a threatening safety procedure.

Subsidising recycled materials so as to compete with virgin materials does not fit well in the scenarios with a high economic performance, where there is much demand for building materials driving their price up making the need for subsidies less relevant. In addition when there is a lack of sustainable awareness it becomes even less likely that any such subsidies would be implemented.

6.4 Development path

This fourth and final step of the backcasting describes the pathway in which the desired future is attained through the proposed set solutions of solutions in the previous step. As there are two sets of solutions this step also includes two different pathways. Both pathways will be set out over the course 35 years, from 2015 to 2050 in equal steps of seven years. Each of these steps including the current situation are only defined according to the state at which the proposed solutions is implemented at that stage.

1. Market creation and maturing of concrete recycling technologies

2015

Knowledge and technology of aggregate packaging to reduce the need for cement is already available but its application is not yet widely spread. The little recycled concrete there is now supplies a small percentage of the concrete demand for prefab concrete producers. And although the government has a program in place to stimulate sustainable procurement for all governmental organizations there is still little enforcement. C2CA has developed a way to separate aggregates from a wet feed of end of life concrete but has not developed a way to separate the fines in reusable streams of sand and cement. The SC of the independent inventor Koos Schenk is currently operational at lab scale in his garage. Here he crushes dry chunks of EoL concrete back to its original ingredients, with the inactivated cement as the finest particles. The claims on the purity and quality of these outputs are only backed by limited literature. A scaled up version of the machine is in hands of the demolition company VAR, which is excluded from usage of the technology due to legal issues with Schenk.

2022

- Aggregate packaging is now applied in 20% of its possible applications. The C2CA research project finalizes its laser technology allowing them to closely monitor pollutants and the quality of the stream of recycled concrete. The governmental policy for sustainable procurement has reached the municipality level, 20% of their building materials are sourced sustainably.
- Koos Schenk managed to acquire funding for the research needed to back up his claims on the quality and purity of the outflows of his technologies.

2029

Aggregate packaging is implemented at 50% reducing the amount of cement needed for concrete production. The governmental program for sustainable procurement is now adopted by half of all the governmental organizations 50%. A RBM (recyclability building materials) label is introduced that gives insight in the building materials contained within a building and their possibility of clean extraction for re-use.

- The C2CA research project still backed by funding from the European Union and from industry has realized a way to separate the fines into reusable streams of sand, hydrated cement and unhydrated cement. The SC is struggling to compete due to the fact that the C2CA technology allows for a wet feed stream.
- The C2CA research project did not succeed in separating the fines in an economic feasible way and funding from the EU was cut. In the meanwhile

has the SC proven that the concept works and required further funding to scale up the technology.

2036

Procurement of sustainably sourced building materials by the government and municipalities is increased to 65%. The previously introduced label is now mandatory for all new buildings this off sets a shift in responsibility for the owner of the building will now want to capitalize on the materials within it. Aggregate packaging has become a mainstream practice and implemented in 75% of cases.

- The technology produced by the C2CA research project is now scaled up and prepared for commercial application for on-site concrete recycling. The SC was not able to compete and fails to attain a substantial market share.
- After the funding for C2CA was cut the project was terminated. The laser technology is sold to the SC, which is scaled up to stationary facility where it can control the wet content of the feed stream.

2043

The prefab concrete industry was the first to move on recycled concrete and is now supplied by a majority by recycled concrete. All of the governmental organizations will have adopted the sustainable procurement intention, which is now strongly enforced by MVO Nederland.

- To match this demand the technology from C2CA should have been sufficiently scaled up.
- This demand is matched by the maximum capacity of the large scale facility of the SC. However with a growing demand and supply of EoL concrete the plans for a second facility are in the making.

2050

The entire prefab industry and all governmental organizations have moved to the use of recycled concrete materials. Current levels of demand support the continued processing of EoL concrete.

- Large-scale implementation of C2CA technology allows for 100% EoL concrete to be recycled.
- A second SC facility is able to meet the supply of EoL concrete.

2. Implementation of carbon tax of 50 euro per ton

Even though the introduction of carbon tax can be seen as a trend, we do not see the introduction of a carbon tax as high as 50 as a given. When rating this tax according to the different scenarios, it seemed unlikely that such a high tax will be implemented in the Step backward scenario. We therefore believe it is only possible to introduce such a carbon tax if it is gradually introduced and the worst side-effects are mitigated. Gradual implementation allows for the concrete and cement industry to adjust to the high impact of the regulation. The following development path for the carbon tax can therefore be envisioned to work.

2015

Currently there is no carbon tax in place in the Netherlands.

2022

In 2020 the framework for the carbon tax will have been developed and the first relatively low carbon tax of 10 euro has been put in place. With this level of carbon tax the cement industry will start to switch towards the use of alternative fuels, will start reducing the amount of clinker needed in the production of concrete and increase its thermal energy and electricity efficiencies.

2029

By 2029 the changes instigated in 2022 are likely to have been put in place and alternative methods for reducing carbon emissions are being explored by the concrete and cement industries because of an increase of the carbon tax towards 20 euro per ton of CO_2 emitted. Investment is made into the development of recycling technologies for EoL concrete to be able to extract unhydrated cement. Technologies that are invested in are among others the SC technology and C2CA.

2036

In 2036 the carbon tax is increased to 30 euro per ton of CO_2 emitted. Even more money is invested into recycling technologies because the concrete and cement industries realize that this is the most cost effective way of reducing their CO_2 emissions if the carbon tax will increase further. The money is invested in the large scale pilot testing of the now mature technologies.

2043

Large amounts of EoL concrete are being recycled by 2043 because concrete and cement manufacturers start buying recycled materials. The carbon tax is in the meanwhile increased to a level of 40 euro per ton of CO_2.

2050

All EoL concrete is being recycled in 2050 when the carbon tax is increased until 50 euro. This makes it economically feasible for cement and concrete producers to use recycled materials rather than raw materials in their production, so as to avoid having to pay the higher carbon tax.

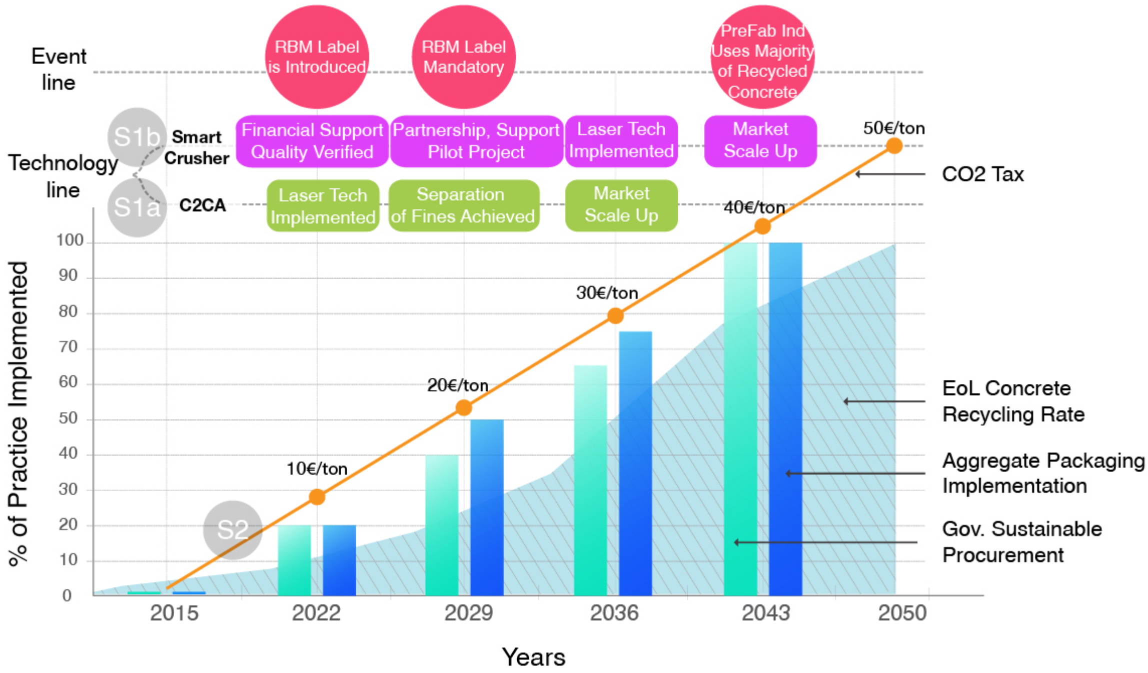


Figure 11: Development path to closing the loop on Concrete in Netherlands by 2050

Conclusion

Now we can provide an answer to the research question of this report. The introduction formulated the research question as follows:

How to reach a complete recycling of end-of-life concrete by 2050 in the Netherlands?

The backcasting analysis has indicated that there are three solutions that could realize a circular concrete economy in the Netherlands by 2050. The first option is a solution combination of maturation of the C2CA technology, market creation by the government and the pre-fab industry, and the introduction of recyclability building materials (RBM) labelling. The alternative to the first solution is essentially the same as the second one, only differing in the fact that C2CA will not develop as expected and SC will be the dominant recycling technology in the future. The third option is a single solution option that describes how a carbon tax is established in the EU, which is gradually increased to 50 euro per tonne of carbon dioxide emissions. The following paragraphs explain for each of the solutions what kind of barriers and threats there will be and recommendations are given about how to overcome these.

The main idea of the first solution combination is to create a market for recycled concrete by governmental procurement and adoption of recycled concrete by the pre-fab industry, in combination with maturation of the C2CA technology, recyclability building materials (RBM) labelling and implementation of aggregate packaging. The most critical factor of this combination is the maturation of the C2CA technology from a technological perspective. The success of market creation and implementation of RBM labelling are contingent on the technology being developed successfully. In order to do this, the C2CA research group needs to take some large steps to improve the technology, so that it will be able to separate the fine fraction of EoL concrete into cement and sand. Since C2CA already managed to receive industry-wide support and funding, the only recommendation that can be given for this pathway is therefore to focus all the attention on research and development regarding fines separation. In this respect, it is not only relevant to refine the ADR technology further to make this possible, but also search for complementary technologies that were initially created for other purposes, like the ADR technology itself.

The alternative pathway for the first solution is based on a situation where the C2CA technology fails to separate the fines and SC becomes the main technology for concrete recycling. SC seems to be a more sophisticated technology compared to C2CA, because it is already capable of separating the fines. Although SC also has some technological issues that need to be resolved and it has not been tested in a business environment yet, the technology development does not appear to be the most critical factor in this pathway. The current lack of support by the concrete sector is what poses the greatest threat to successful implementation of this pathway. It is of vital importance that SC is able to attract support from the sector, similar to how C2CA has done this, otherwise it will not be able to grow into a mature technology. Funds, for example from the Dutch government and the EU, need to be made available for SC to make research and development possible. The company also needs on going collaborations with research institutions and universities to support research and exchange knowledge, like it has done already with Eindhoven University of Technology. However, the highest priority for SC is to find some key players in the concrete and cement industry that are willing to cooperate by testing the machine in pilot projects. The company is dependent on the concrete and cement makers to adopt recycled aggregates and cement. If the industry partners are involved in the process of producing recycled concrete constituents, they have more confidence in the quality of the recycled materials and will be more inclined to buy it from SC. In order to receive support and legitimize the use of the SC, it is recommended that the company seeks partnerships with sustainable initiatives like the Green Deal Beton. The Green Deal is a useful platform that brings parties together and creates a more open and transparent culture in the concrete sector. This will be needed if SC is to become the dominant recycling technology on the road to 2050.

The carbon tax pathway is an effective top-down solution that forces the cement industry to implement recycling practices and develop cements with low emissions. It is however solely relying on the EU to take action and impose the tax of 50 euro per tonne. Consequently, there are many potential obstacles for this solution to actually be implemented. In worst case scenario, awareness for global warming becomes less over time and the EU does not see the need to enforce the carbon tax. Nonetheless, even in the case when environmental awareness is high, there are still barriers to overcome. There is going to be a strong lobby from the cement industry and other polluting sectors to persuade the EU not to impose the carbon tax. It remains to be seen if the EU can withstand this lobby. Moreover, the tax will initially have a negative economic impact, even when it is implemented gradually over the years. There could be strong opposition from some of the EU member states, especially from those with large clinker and cement industries. Thus, whereas at first sight the carbon tax looks like the simplest and at the same time highly effective solution, the realization of this pathway is highly uncertain. It is therefore recommended that the players in the Dutch concrete industry who are in favour of concrete recycling should not count on this to happen, but keep up their efforts to close the loop in 2050.

Despite their drawbacks, the three solutions described above present according to this report's findings the best and most feasible course of actions leading up to 100% end-of-life concrete recycling in the Netherlands by 2050. The pathways should be considered as a guideline for the industry as well as policy makers to plan ahead. They anticipate and elicit the changes that will result in the major transition to a closed-loop economy in the concrete industry.

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Appendix

Appendix 1: Cost and revenue of recycling of end-of-life of concrete (Business-as-usual)

	Process		Business as usual (BAU)*	
			cost (€/ton)	revenue (€/ton)
1	Clean EoL concrete production			
		conventional method		
	a	**economic value of material**	**2.7**	**11.3**
		roof	0.1	
		waste wood	0.1	
		gypsum	0.6	
		CDW mix	1.8	
		sale of non-ferrous metal		1.9
		sale of steel scraps		7.9
		sale of EoL concrete-brick mix		1.6
	b	**direct cost of dismantling**	**6.9**	
	c	**direct cost of demolition**	**11.6**	
		capital cost	8.2	
		fuel cost	2.2	
		personnel cost	1.1	
		transportation worker	0.1	
		Value added		**9.9**
2	Clean aggregates production			
		wet processing		
	a	**value of material**		**15.6**
		sale of non-ferrous metals		0.1
		sale of steel scraps		8.7
		sale of 4-22 clean aggregate		5.7
		sale of 0-4 sieve sand		1.0
		sale of 0-4 clean sand		0.2
	b	**direct cost of wet processing**	**8.9**	
		capital cost - capital reservation (10% depreciation)	3.2	

		capital cost - maintenance	1.0	
		capital cost - certification	0.0	
		capital cost - site rental (1% investment)	0.3	
		capital cost - investment	0.2	
		energy - diesel	0.4	
		energy - electricity	0.4	
		personnel	0.7	
		transport (EoL concrete)	2.5	
		auxiliary material	0.0	
		waste disposal	0.3	
3	Use of the recycled CA for new concrete production			
	TOTAL		**30.1**	**26.9**

Appendix 2: Cost and revenue of recycling of end-of-life of concrete (C2CA)

No	Process		C2CA scenario	
			cost (€/ton)	revenue (€/ton)
1	Clean EoL concrete production			
		smart dismantling and demolition		
	a	**economic value of material**	**2.7**	**11.3**
		roof	0.1	
		waste wood	0.2	
		gypsum	0.6	
		CDW mix	1.8	
		sale of non-ferrous metal		1.9
		sale of steel scraps		7.9
		sale of EoL concrete-brick mix		1.6
	b	**direct cost of dismantling**	**7.3**	
	c	**direct cost of demolition**	**11.1**	
		capital cost	6.5	
		fuel cost	1.5	
		personnel cost	2.7	
		transportation worker	0.4	
				9.7

2	Clean aggregates production			
		mobile ADR + sensor technology		
	a	**value of material**		**15.4**
		sale of non-ferrous metals		0.1
		sale of steel scraps		8.7
		sale of 16-32 clean aggregate		2.8
		sale of 4-16 clean aggregate		3.2
		sale of 1-4 clean aggregate		0.6
		sale of ADR fines		0.0
	b	**direct cost of ADR**	**5.5**	
		capital cost - capital reservation (10% depreciation)	2.2	
		capital cost - maintenance	1.0	
		capital cost - certification	0.0	
		capital cost - site rental (1% investment)	0.0	
		capital cost - investment	0.1	
		energy - diesel	1.3	
		energy - electricity	0.0	
		personnel	0.9	
		transport (EoL concrete)	0.0	
		auxiliary material	0.0	
		waste disposal	0.0	
3	Use of the recycled CA for new concrete production			
		recycled concrete		
	a	**value of material**		**1.0**
		Sale of >100μm silica		1.0
	b	**direct cost of recycled concrete**	**1.6**	
		material transport (ADR fines)	1.5	
		capital cost	0.4	
		energy cost	0.2	
		saving of limestone	-0.3	
		saving of CO_2	-0.4	
	TOTAL		**28.2**	**27.7**

Appendix 3: Cost and revenue of recycling of end-of-life of concrete (SmartCrusher)

No		**Process**	**SmartCrusher scenario**	
			cost (€/ton-)	revenue

				(€/ton)
1	Clean EoL concrete production			
	conventional method			
	a	**economic value of material**	**2.7**	**11.3**
		roof	0.1	
		waste wood	0.1	
		gypsum	0.6	
		CDW mix	1.8	
		sale of non-ferrous metal		1.9
		sale of steel scraps		7.9
		sale of EoL concrete-brick mix		1.6
	b	**direct cost of dismantling**	**6.9**	
	c	**direct cost of demolition**	**11.6**	
		capital cost	8.2	
		fuel cost	2.2	
		personnel cost	1.1	
		transportation worker	0.1	
				9.9
2	Clean aggregates production			
	SmartCrusher			
	a	**value of material**		**17.7**
		sale of non-ferrous metals		0.1
		sale of steel scraps		8.7
		sale of 16-32 clean aggregate		3.0
		sale of 4-16 clean aggregate		4.0
		sale of 1-4 clean aggregate		1.5
		sale of 0-1 clean aggregate		0.3
	b	**direct cost of SmartCrusher**	**2.9**	
		capital cost - capital reservation (10% depreciation)	1.0	
		capital cost - maintenance	1.0	
		capital cost - certification	0.0	
		capital cost - site	0.0	

		rental (1% investment)		
		capital cost - investment	0.0	
		energy - diesel	0.0	
		energy - electricity	0.4	
		personnel	0.5	
		transport (EoL concrete)	0.0	
		auxiliary material	0.0	
		waste disposal	0.0	
3	Use of the recycled CA for new concrete production			
		recycled concrete		
	a	**value of material**		5.1
		Sale of >100μm silica		5.1
	b	**direct cost of recycled concrete**		
		material transport (fines)	1.5	
		capital cost	0.4	
		energy cost	0.2	
		saving of limestone	-0.3	
		saving of CO_2	-0.4	
	TOTAL		**24.1**	**34.1**