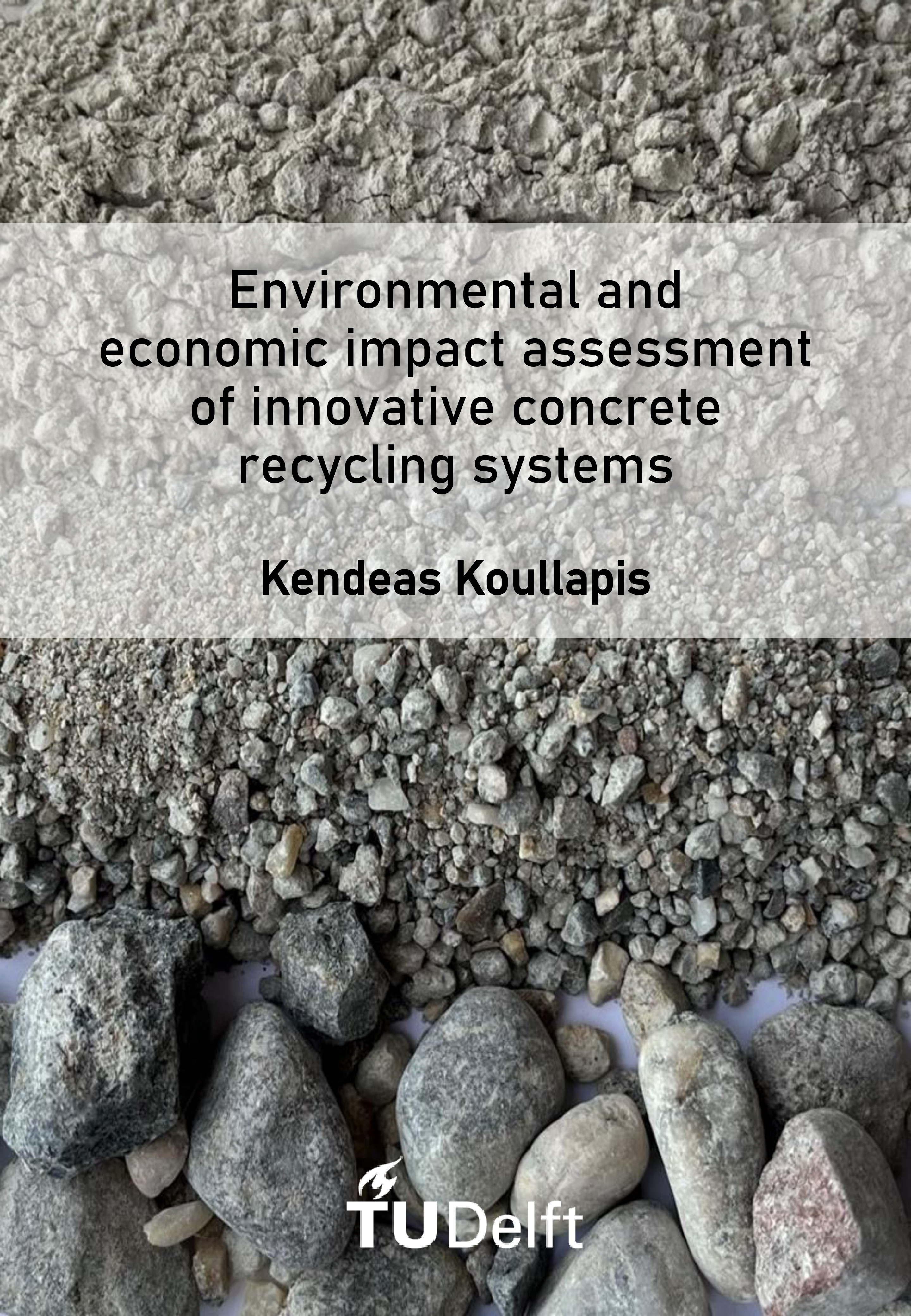

Environmental and economic impact assessment of innovative concrete recycling systems

Kendeas Koullapis

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by

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Preface

This research work is the conclusion of my master's thesis and it fulfils the requirements to graduate at the MSc. Building Engineering program with a specialization in Structural Design, at the Delft University of Technology, Faculty of Civil Engineering and Geosciences.

The motivation behind this research was the need to see my father's earthworks and demolition waste management company grow in the field of sustainability. The discussions with my supervisors Prof. dr. Henk Jonkers and dr. ir. Marc Ottele, helped me to realise the importance of expanding our knowledge on new innovative concrete recycling technologies. This research was a great nine-month journey where I had the opportunity to dive into the environmental and financial aspects of this field. Of course, this thesis project could not be accomplished without the guidance of Henk and Marc but also the other members of the committee, ir. Sander Pasterkamp and ir. Anna Alberda van Ekenstein.

I would also like to express my gratitude to Vincent Jansen and Sven Hiskemuller van der Zijden and John Smit for providing confidential data for the Smart crushing recycling system. All of them were available to answer my questions and give me a tour of the facilities of Rutte Groep, where I had the opportunity to see the innovative technology in operation. Their inputs were essential for the execution of this thesis.

Last but not least, I would like to thank my family, my friends and my girlfriend for all the support and believe in me throughout this process.

Kendeas Koullapis
Delft, October 2022

Abstract

Over the last few years, the construction sector has experienced increasing demand for raw materials due to the rapid growth of the urban population. At the same time, most of the post-war buildings in Europe have reached the end of their service life. As a consequence, a period of intense demolition activities with significant waste generation is expected in the upcoming years. Both situations are eventually translated into significant environmental pressure. Concrete is the main component in construction and demolition waste (C&DW). Due to the high environmental footprint of this material, it is crucial to eliminate its consumption through recycling and re-use. Currently, concrete rubbles are crushed with regular crushers and used mainly for low-grade applications (down-cycling) such as road foundations. Despite the environmental and financial benefits, this practice is still not at a sustainable level since raw materials are still needed for new structures, while the demand for low-quality secondary materials in the construction sector has already declined.

Two innovative recycling technologies called C2CA and Smart crushing (SC) developed recently in the Netherlands, aiming to close the material loop in the construction sector. These technologies recover most of the original concrete materials at high-quality, which can be use in the production of new concrete at higher rates than traditionally. This research focuses on the environmental and financial implications of the novel C2CA and SC recycling systems as alternative solutions to the Traditional crushing (TC) method. The evaluation was conducted based on an integrated LCA&LCC analysis framework in which the monetised environmental impacts (shadow costs) were internalised in the actual costs occurred within the supply chain of recycled concrete (production of primary materials, recycling, transports). On this basis, the recycling systems were compared from two different perspectives. First, the recycled materials produced were used for concrete production according to the current European standards. In this case, the traditional recycled coarse aggregates (TRCAs) were used to replace 50% of the primary gravel, while the innovative coarse (IRCAs) and fine (IRFAs) aggregates from the innovative systems replaced 100% of primary gravel and 60% of primary sand respectively. The maximum potentials of the innovative systems were investigated in a second scenario in which IRCAs and IRFAs completely replaced the primary concrete aggregates. In addition to that, the produced recycled concrete powder (RCP) was used as supplementary cementitious material (SCM) to replace 20% of the primary cement. In this study, the innovative recycling systems were considered as mobile units located at the demolition site. In contrast, the TC recycling was executed off-site at a stationary plant to secure the sufficient quality of TRCAs.

The results of the integrated LCA&LCC study revealed that both C2CA and SC systems were financially better options than the traditional recycling route. Especially when the SC system was used to replace higher quantities of primary materials, the total cost was reduced by up to 19% relatively to the TC method. On the other hand, the C2CA technology showed better performance when following the current standards, where about 8% cost reduction was achieved. However, environmental improvements were reported only for maximum utilisation of the SC products, resulting in about 17% lower shadow cost than the traditional method. In the case of the C2CA system, the environmental impact was found 5% increased for both scenarios. Both innovative systems displayed overall benefits over the TC method regarding social cost (internalised environmental impacts), with the SC system exhibiting the best overall performance for maximum use of its products. In this case, the overall benefits reached almost 19%, while the rest scenarios were not higher than 5%.

The sensitivity analysis emerged that the innovative recycling systems presented benefits only when they were located close to the demolition site due to increased transportation of EoL concrete. For the same locations and up to 23 km away from the demolition site, only the SC2 scenario (maximum use of SC products) was more efficient than the traditional recycling route. The rest scenarios became more effective as the traditional plant was placed away from the demolition site. On the other hand, changes in the recycling phase, such as energy consumption and equipment operating costs, had a negligible impact on the results. Even if renewable energy sources would power the recycling plants, the environmental and cost benefits throughout the supply chain were not higher than 5% and 2.5%, respectively.

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Abbreviations

ADR	Advanced Dry Recovery
C&DW	Construction and demolition waste
C2CA	Concrete to Cement and Aggregates
C_P	Primary materials cost
C_R	Recycling cost
C_T	Transport cost
d	Transport distance
EC	Energy consumption
ECI	Environmental Cost Indicator
EF	Electrical fragmentation
EoL	End-of-Life
HAS	Heating Air Classification System
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
m	Mass of the material
MH	Microwave heating
IRCA	Innovative recycled coarse aggregates
IRFA	Innovative recycled fine aggregates
L-RCA	Low-quality recycled coarse aggregates
L-RFA	Low-quality recycled fine aggregates
P_{unit}	Average unit productivity
RCP	Recycled concrete powder
SC	Smart Crushing
TC	Traditional crushing
T	Operating duration
TRCA	Traditional recycled coarse aggregates
TW	Transported weight
WA	Water absorption
WCF	Water-cement factor
WE	Effective water
WP	Wet Process

1

Introduction

1.1. Background

Construction and demolition waste (C&DW) is widely acknowledged as one of the major challenges the current construction sector has to deal with in the near future. Due to the rapid growth of the urban population, there is an increasing demand for raw materials to construct new infrastructure and buildings (Di Maio et al., 2020). In the meantime, most of the European constructions built after World War II must be renewed or demolished, resulting in enormous amounts of C&W, which eventually translated to environmental pressure. The EU has set a long-term goal to reach a fully circular economy with net-zero greenhouse gas emissions by 2050 (European Commission, 2018). Reducing raw material extraction and minimizing C&DW generation is the main focus of this strategy. Concrete plays an important role in this attempt as the main material contained in the C&DW. It is estimated that about 60-70% of the total C&DW volume is end-of-life (EoL) concrete (Lotfi, 2016) whose production is responsible for no less than 6-7% of the global CO_2 emissions (Shi et al., 2011). Due to the large volumes and environmental impact of concrete, new opportunities to recover valuable building materials from C&DW are generated. Therefore, it is of major importance to promote concrete recycling as a solution to close the material loop of the construction sector.

Figure 1.1: Demolition of a reinforced concrete building (EPA,2021, 2021)

1.2. Challenges in concrete recycling

Currently, the most common practice of recycling concrete rubble is through regular crushing. The resulting material called recycled coarse aggregates (RCAs) can be used as a virgin gravel replacement in various applications (Zhang et al., 2020b). Nevertheless, due to the lack of quality standards, most countries have invested more in low-grade recycling applications, particularly in road foundations and backfilling (Di Maria et al., 2020). Such applications are labelled as down-cycling. In practice, down-cycling is the re-use of a material for applications of lower value than its original purpose Allwood (2014). However, road construction in Europe experiences have declined and at some point is expected to be stabilised (Lotfi et al., 2017). As a consequence, there is already a problem of saturation of low-quality secondary materials, which this sector cannot absorb. Higher-value applications must be promoted to overcome this issue and make the best use of EoL concrete. The most effective way is to use the RCAs in the production of concrete (up-cycling). This way, the environmental impact and cost of concrete production can be reduced.

Despite the up-cycling potential of EoL concrete, certain technical and economic barriers must be overcome. The use of RCAs produced traditionally (TRCAs) in the production of concrete is only allowed up for partial replacement of virgin gravel (Kurda et al., 2017). The main reason for this restriction is the presence of impurities and particularly adhered mortar on the surface of the recycled aggregates, which results in lower quality compared to the natural material (McNeil et al., 2013). The porous structure of the adhered mortar increases the water absorption of TRCAs with detrimental consequences on the mechanical, durability and workability properties of the new concrete (Evangelista and de Brito, 2010). Over the past years, many researchers have investigated the effect of TRCAs on the performance of concrete, concluding that they can replace up to 20-30% of virgin gravel without major consequences on concrete's performance (Oksri-Nelfia et al., 2016). CROW-CUR Recommendation 112 (2014) suggests that a replacement of up to 50% can be achieved for sufficiently clean TRCAs.

Beyond that, a greater challenge in concrete recycling is recovering the finer fraction (0-4 mm) generated as a by-product of the crushing process. This fraction consists of about 30% of the initial EoL concrete volume and contains most of the old sand and cementitious material (Ottele and Schenk, 2020). Due to its highly contaminated and moisturised nature, this material has low value in the concrete industry, and thus, it is often used as low-quality material for backfilling. Under these conditions, neither down-cycling nor partial up-cycling of TRCAs are sustainable solutions since extraction of raw materials is still required. The optimal goal is to achieve 100% up-cycling of all concrete components without hindering the quality of the new concrete. To do so, more advanced recycling technologies are required to produce cleaner products of higher quality.

1.3. Recycling technologies

Efforts have been made to improve the quality of TRCAs through alternative recycling techniques. The wet process (WP) is a common method used for this purpose, aiming to remove the fine material (0-4 mm) employing washing. As a result, clean secondary gravel of high quality is produced, ready to be up-cycled in the concrete industry. However, this method requires large washing plants and consumes an enormous amount of water, making the whole process expensive and time-consuming (Lotfi et al., 2014). Furthermore, the fine washed-out material is a mixture of dirt, sand and hydrated cement, which is eventually discarded as waste or used for backfilling (Zhang et al., 2019). Recovery of the hydrated cement and sand is currently only possible through thermal treatment (Shui et al., 2008), however, at the expense of high cost and production of a considerable amount of CO_2 emissions (Jaroslav and Zdenek, 2017). A certain amount of sludge is also produced during the WP, which usually ends up in landfills (Zhang et al., 2019).

Finally, additional recycling methods such as electrical fragmentation (EF) and microwave heating (MH) were also developed to produce cleaner recycled materials. Both technologies use non-mechanical techniques to separate the cement paste from the original aggregates. Nevertheless, their development is still at an experimental stage, and a lot of research is required before they can be used in the industry.

Over the past few years, two innovative recycling technologies called C2CA (Concrete to Cement and Aggregates) and Smart crushing (SC) have been developed in the Netherlands to solve the above challenges.

The former involves a combination of mechanical sorting and thermal treatment, while the latter uses more efficient crushing and separation techniques. Both technologies aim to produce clean secondary aggregates of high quality by removing the adhered cement paste. The produced recycled aggregates can potentially be up-cycled up to 100% (Di Maio et al., 2020), whereas various applications can be employed to reduce cement consumption by utilising the recovered cement paste (Ottele and Schenk, 2020). Using these materials in concrete production can bring significant environmental and financial improvements by saving natural resources. To this end, the present thesis aims to investigate the viability of the C2CA and Smart crushing technologies as alternative solutions to the traditional crushing recycling.

2

Literature review

This chapter provides a literature review on common and innovative concrete recycling systems. The working principle and the products of each system are briefly discussed, along with their advantages and limitations. Then, the maximum utilisation rates of the different recycled materials are elaborated in the next part. The last part of this chapter provides a brief description of the LCA (life cycle assessment) and LCC (life cycle costing) methods used in this thesis.

2.1. Concrete recycling methods

2.1.1. Traditional crushing recycling

As mentioned in the Introduction, the traditional crushing (TC) method uses regular crushers to break through the material (Hansen, 1992). Using a series of crushing - sieving - cleaning steps, the input EoL concrete is crushed into coarse concrete granules called traditional recycled coarse aggregates (TRCAs). The more crushing steps are involved in the recycling process, the better the quality of the final product will be (Hansen, 1992). Typically, this method uses two types of crushers: the primary and the secondary ones. The primary crushers are mainly used to reduce the size of EoL concrete as it arrives from the demolition site. Initially, the size of concrete rubbles ranges between 0.5 - 1 m, which must be reduced to 40 - 50 mm to fit in the secondary crusher. The secondary crushers are responsible for crushing the material further until it reaches the desired particle size.

2.1.1.1. Crushers

A combination of different crushers is typically used in TC recycling, with the jaw crusher, the cone crusher and the impact crusher being the most commonly used. The main working principle of all crushers is based on a moving part of the machine working against a stationary part or another moving part. This differential movement induces high pressure on the material until it reaches its elastic limit and causes its breakage (Ning, 2012). All three crushers are available in the market as mobile and stationary units. A brief description of the crushers mentioned above is following provided.

Jaw crusher

Jaw crushers have a relatively large opening size, receiving large chunks of stony materials, making them suitable for primary crushing (Noguchi et al., 2011). They consist of two rigid plates called jaws, where one is fixed in a vertical configuration on the crusher's frame serving as a crushing surface. The other jaw is placed in an inclined position so that the opening is reduced gradually (see Figure 2.1 (a)). As the material flows in the crusher, the inclined jaw moves alternately against the fixed one, crushing the material into smaller fragments. The material stays in the crusher until it reaches a size smaller than the bottom opening size. The width of the bottom opening can be adjusted to produce aggregates of different sizes according to the application. Usually, the output product size ranges between 40 - 50 mm (Noguchi et al., 2011).

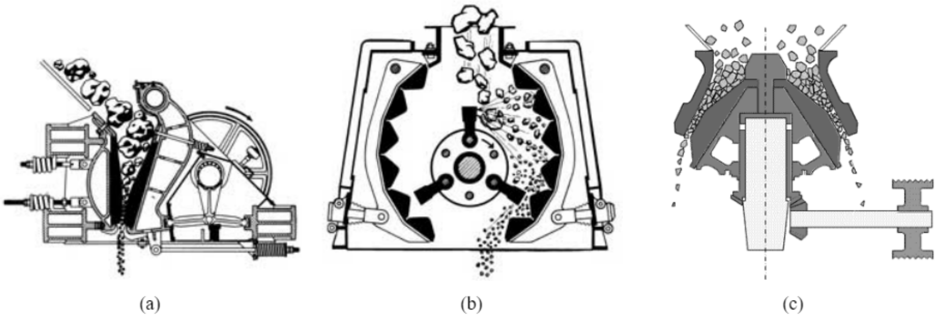

Figure 2.1: Schematic representation of (a) jaw crusher, (b) impact crusher and (c) cone crusher (Silva et al., 2016)

Impact crusher

Impact crushers can be used for both primary and secondary crushing (Hansen, 1992). In this case, the material is fed from the top, and a spinning rotor throws it on impact plates (see Figure 2.1 (b)). The very high speed of the rotor causes high impact force and, thus, breakage of the material. A drawback of this crusher type is that it produces a large amount of fines as a by-product (Hansen, 1992).

Cone crusher

Cone crushers are suitable for secondary crushing having a maximum feeding size of 200 mm (Hansen, 1992). The working principle of a cone crusher is demonstrated in Figure 2.1 (c), where two conical shells crush the material. The outer shell is stationary, and the inner (cone) rotates around the eccentric axis. As the material moves down to the crushing chamber, it breaks due to the reduced space. The material stays in the chamber until it reaches the desired particle size.

2.1.1.2. Recycling procedure

Figure 2.2 illustrates a simplified flow process diagram of the TC recycling procedure. Typically there are two crushing phases, where each phase includes a crusher supported by screening and cleaning devices. Including a preliminary manual separation of large contaminants might be necessary before the primary crushing if selective demolition is not used. In the case of selective demolition, this step is less necessary since the C&DW mainly consist of EoL concrete and minor light contaminants. Furthermore, the different steps within each phase (primary and secondary crushing) operate in a closed loop until the material reaches the required size for the next phase. As mentioned above, jaw crushers are typically used for primary crushing, while impact or cone crushers are proffered for secondary crushing. After the secondary crushing phase, the material is separated into two size fractions, 4 - 32 mm and 0 - 4mm. The former fraction is the target material (TRCAs) of this recycling method, while the latter is regarded as as a by-product of the demolition and crushing activities. A more detailed explanation of a typical TC recycling plant is provided in Appendix A.

2.1.1.3. Products

The produced TRCAs (4 - 32 mm) from the TC recycling process consist of natural coarse aggregates (NCAs) covered by a layer of cement paste (see Figure 2.3). TRCAs can be used as secondary gravel in earthworks, road construction and concrete production. Their use in concrete production is limited due to their lower-quality compared to the NCAs (Oksri-Nelfia et al., 2016). The quality of the TRCAs is typically determined by the amount of adhered cement paste on their surface, which causes an increase in their water absorption capacity and creates a rougher surface. This issue has been studied extensively in the last decades, with several authors reporting lower workability properties of the fresh concrete when high percentages of TRCAs are used (Fraj and Idir, 2017). The rough surface, the increased water absorption and angularity of TRCAs due to cement paste are the main reasons for this issue (Pellegrino and Faleschini, 2016). However, the loss of workability can be balanced with additional water or chemical admixtures (superplasticizer) (Florea and Brouwers, 2013).

Reduction of the mechanical properties of the hardened concrete was also observed when TRCAs were used (Oksri-Nelfia et al., 2016). In particular, the water absorption of TRCAs alters the water balance in the

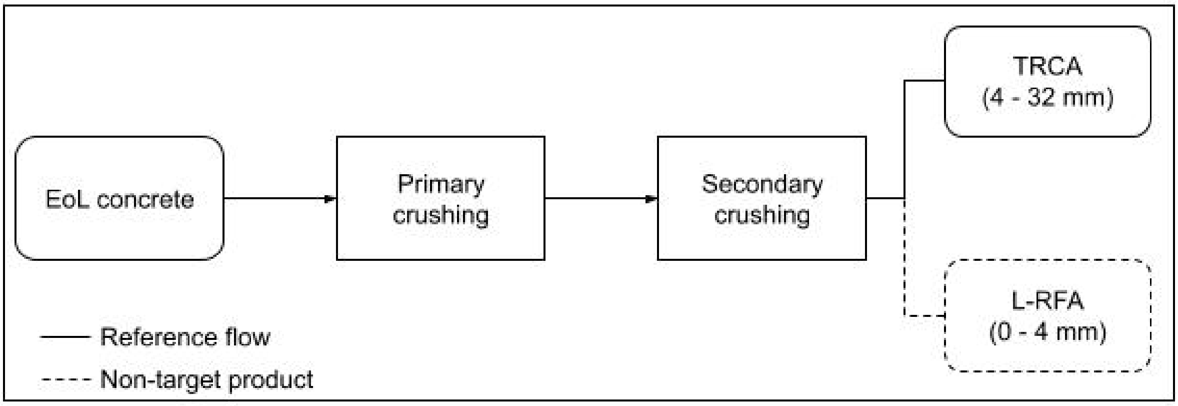

Figure 2.2: Simplified flow process diagram of the Traditional crushing recycling procedure

Figure 2.3: Sample of traditional recycled coarse aggregate (TRCAs) (Pellegrino and Faleschini, 2016)

mix resulting in a lower water-cement factor (WCF). At low WCF (less available water), the strength of the concrete also reduces due to incomplete cement hydration (Pellegrino and Faleschini, 2016). According to Fraj and Idir (2017), the 28days compressive strength of concrete can be reduced by up to 40% if the full amount of primary gravel is replaced by TRCAs. A possible solution to compensate for the loss of strength is to increase the cement content in the mix; however, this practice is regarded as costly and environmental unfriendly (Pellegrino and Faleschini, 2016). Apart from strength, the durability properties of concrete are also affected at lower WCF (Fraj and Idir, 2017). The porous structure of TRCAs increases the risk of chemical attack (carbonation, chloride penetration, etc.) and freezing. In this case, using mineral additions such as fly ash at low WCF can enhance the durability properties of concrete (Pellegrino and Faleschini, 2016). Based on the above, it was concluded that TRCAs are allowed to be used in concrete mixture up to 50% as primary gravel replacement. More information regarding the maximum replacement rates of recycled materials is provided in Section 2.2.

The low-quality fines from the TC recycling process (< 4 mm) contain sand and hydrated cement particles as well as other light pollutants (wood, plastics, paper, etc.). The contamination level of this material makes it unsuitable for up-cycling; however, it can be used as back-filling material in road construction by replacing primary sand. According to Hansen (1992), the quality of TRCAs increases as more fines (< 4mm) are removed by introducing additional crushing and sieving steps.

2.1.1.4. Recycling plants

Depending on the quality requirements of TRCAs and economic parameters, the TC recycling process may be executed in a stationary plant (off-site) or at the demolition site with a mobile unit (Ulubeyli et al., 2017)

Stationary plants

Stationary plants (see Figure 2.4) are set up in enclosed areas authorized to receive C&DW, which are usually located far from the demolition site (Pellegrino and Faleschini, 2016). Typically, a stationary plant can process 100-350 tons of C&DW per hour and produce low to high-quality TRCAs (Ulubeyli et al., 2017). Coelho and Brito (2013) further distinguishes the stationary plants in three levels. Stationary plants of level 1 have a similar configuration to mobile units. They are not provided with cleaning devices to remove fine materials and pollutants; thus, the quality of the produced TRCAs is regarded as low for concrete production. Level 2 stationary plants produce medium-quality TRCAs which are suitable for foundation material. Level 3 plants are equipped with more sophisticated technologies and produce high-quality TRCAs.

Figure 2.4: Stationary C&DW recycling plant (BEZNER©)

The main drawback of stationary plants is the need to transport C&DW from the demolition site to the recycling plant, which increases the total cost and environmental impact. In addition, stationary plants require a high initial investment to set up the facility in a large space and to purchase advanced recycling equipment (Pellegrino and Faleschini, 2016).

Mobile plants

Mobile recycling plants (see Figure 2.5) are installed temporarily at the demolition site having a capacity of up to 100 ton/hr (Ulubeyli et al., 2017). Due to relatively low capacity, mobile plants are economically viable for C&DW quantities of approximately 5000-6000 tons/site Ulubeyli et al. (2017). In addition, they are equipped with only one primary crusher (sometimes two crushers) and sorting devices which are less effective in cleaning the material (Silva et al., 2016). As a result, the produced TRCAs are classified as low-quality Pellegrino and Faleschini (2016). Furthermore, dust and noise control must be considered when mobile units operate close to residential areas. The main advantage of mobile plants is the reduced transport of materials and the low initial investment required for the equipment compared to stationary plants.

2.1.1.5. Environmental and economic impact

Several authors have already proved the environmental and financial viability of the TC recycling over traditional concrete production. In the research of Coelho and de Brito (2013), the carbon footprint of TC recycling was evaluated, showing a significant reduction of CO_2 emissions (90% less) compared to conventional concrete production with natural materials. From a financial point of view Ulubeyli et al. (2017) revealed that although stationary plants involve a high initial investment, they are more profitable than mobile units due o higher productivity and quality of recycled materials. However, the financial viability of TC plants (both stationary and mobile) is highly regional dependent. Government incentives such as taxing for extracting natural materials and landfill disposal of demolition waste are significant parameters that influence the concrete recycling market (Silva et al., 2016). Further investigation of the environmental and financial consequences of using the TC recycling method is outside the scope of this thesis.

2.1.1.6. Limitations

Despite the environmental and financial benefits mentioned above, the TC recycling also has some limitations that must be considered. First, the produced TRCAs can only replace half of the primary gravel

Figure 2.5: Mobile C&DW recycling plant (ROCKSTER$^{©}$)

in concrete. At the same time, the fine material (0 - 4 mm) cannot be used in concrete due to its high-contamination levels. This material contains most of the original sand and cementitious materials, which are "lost" in low-grade applications. Therefore, the production of all materials used in concrete is still necessary, resulting in significant environmental pressure, especially for cement. On top of that, a considerable amount of the original gravel and sand is lost during the crushing due to the high pressure imposed by the traditional crushers. Moreover, the high initial investment might also be a limiting factor, especially for stationary plants. Thus, new, more advanced recycling technologies must be considered to recover more materials from EoL concrete at sufficient quality for concrete production.

2.1.2. Other concrete recycling technologies

2.1.2.1. Wet process

Until today, the wet process (WP) is the most common method for producing high-quality clean gravel from EoL concrete. This method involves multiple crushing and washing steps to clean the coarse aggregates from the cement paste (Zhang et al., 2019). Together with cement paste, sand and other contaminants are also washed out. The clean coarse material can be used directly for concrete production. A significant disadvantage of this method is that the washed-out materials (sand and cement paste) require additional treatment to be recovered, with similar challenges to the low-quality fines obtained from the TC recycling method. On top of that, a considerable amount of sludge is also generated during the WP, which can be treated at a high cost or sent to a landfill, a practice which is not desired (Zhang et al., 2019). The high cost also results from the enormous amounts of water needed for washing (Lotfi et al., 2014). Finally, WP recycling plants are only available in stationary configuration (see Figure 2.6); therefore, additional environmental and financial implications occur due to transportation.

2.1.2.2. Electric fragmentation

Electrical fragmentation (EF) or high-voltage pulse fragmentation is an alternative recycling technology for producing clean concrete aggregates of high quality. In this method, a high-voltage electrical pulse is discharged underwater on EoL concrete granules generating a shock wave between the constitutive materials (Touzé et al., 2017). The shock wave causes locally thermal expansion and thus tensile stresses at the interface of aggregates. With a sufficiently intense pulse, this mechanism can separate the original sand and gravel from the adhered cement paste (Touzé et al., 2017). The electric pulse density and the fracture location are determined based on the electric properties and particle size of each material (IPG report, 2015). Although this method has the potential to be more efficient and environmentally friendly than the TC and WP recycling systems, it demonstrates two main disadvantages. First, the electric pulse must be controlled according to the electric properties of the materials, which are different for each EoL concrete (IPG report,

Figure 2.6: Example of a wet concrete recycling plant (CDE©, 2022)

2015). In addition, this method restricts the recovery of cement paste since it is applied underwater (Di Maio et al., 2020). As a result, the total amount of cement paste will be fully hydrated without reactivity. Finally, EF is still at an experimental level and according to Di Maio et al. (2020), upgrading it at an industrial scale is a great challenge.

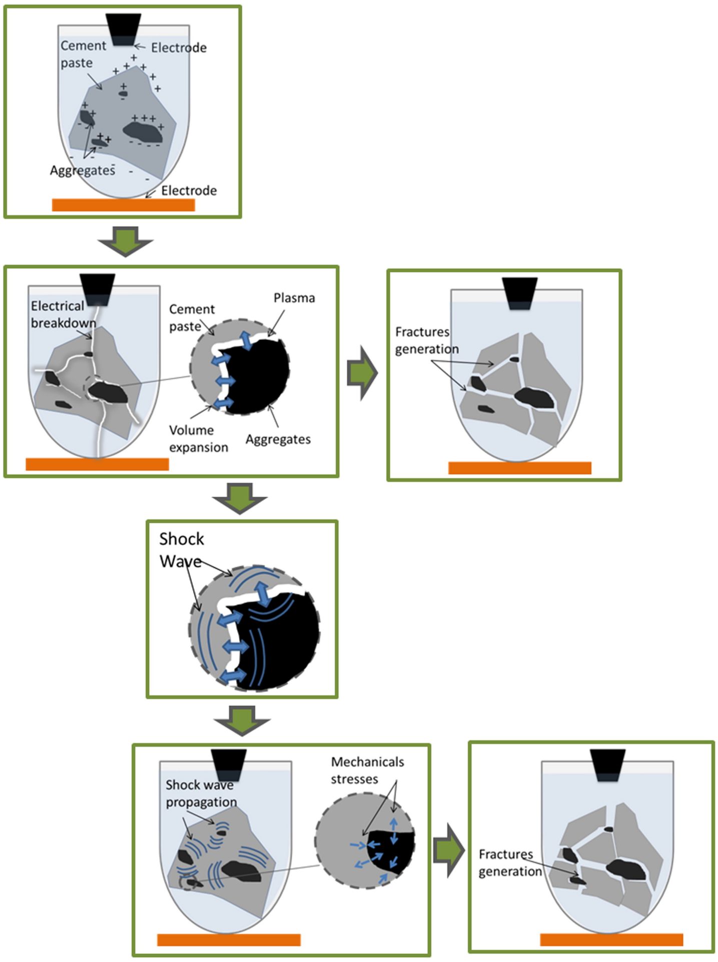

Figure 2.7: Schematic representation of the electrical fragmentation principle (Touzé et al., 2017)

2.1.2.3. Microwave heating

Another method to remove the adhered cement paste from the aggregate's surface is microwave heating (MH). Similarly to the previous method (EF), microwaves cause thermal expansion (tensile stresses) and eventually interface fragmentation (Lippiatt and Bourgeois, 2012). The development of this method is also at an early stage, and further research is required until it can be scaled up (Moreno-Juez et al., 2020).

The following sections provide information regarding the innovative C2CA and SC recycling systems as a solution to the limitations of the technologies mentioned above.

2.1.3. C2CA recycling

A new recycling system called C2CA (Concrete to Cement and Aggregates) technology has been developed in the context of the C2CA project. It consists of two innovative systems, the Advanced Dry Recovery (ADR) and Heating Air Classification System (HAS), working in a complementary way. This combined system aims for cost-effective and high-grade recovery of all components from EoL concrete streams (Lotfi et al., 2015). It is designed as a sensor-based and mobile unit to reduce transportation and human intervention (Lotfi and Rem, 2016). A brief description of the constitutive technologies is following presented.

2.1.3.1. Advanced Dry Recovery (ADR)

The quality issues of TRCAs associated with the adhered cement paste (see Section 2.1.1) led to the development of the novel ADR technology (see Figure 2.8). The ADR is a mechanical sorting system that receives pre-crushed concrete with a maximum size of 16 mm. Its working principle is based on ballistic separation using kinetic energy to detach the cement paste from the surface of the original aggregates. Eventually, this technology delivers two materials, ADR coarse (4 - 16 mm) and ADR fines (0 - 4 mm). The former fraction is the target product of this technology, whereas the latter proceeds for further treatment by the coupled HAS system (see Section 2.1.3.2).

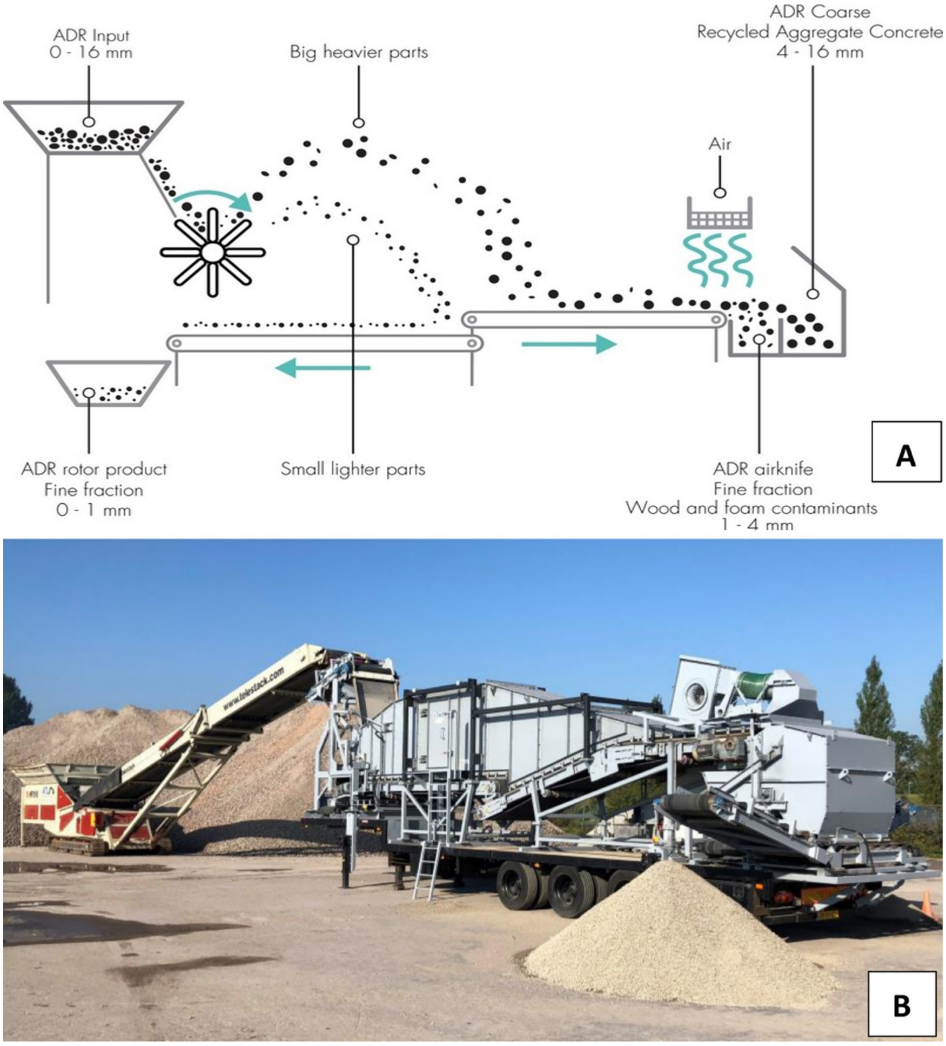

Figure 2.8: (A) Schematic representation of the ADR principle,(B) On-site ADR installation (Di Maio et al., 2020)

Furthermore, the ADR system can only receive "clean" material with low contamination levels. Therefore, it is necessary to remove most of the large unwanted materials such as metals, plastics and wood beforehand with selective demolition (Lotfi et al., 2015). Online sensors attached to the ADR systems handle light contaminants that possibly remain in the material. This way, the quality control is performed automatically with minimum human intervention (Lotfi and Rem, 2018). Finally, the ADR system is available in both mobile and stationary configurations, whose capacity ranges between 50 - 100 t/hr (Rem and de Vries, 2012).

2.1.3.2. Heating Air Classification System (HAS)

HAS technology was developed as a supplementary technology for the ADR system to treat further the ADR fines. ADR fines generally are highly moisturized, containing light contaminants, sand and hydrated cement. Thus, the HAS system aims to separate and recover the sand and the cementitious material by applying simultaneous heating and air flow (Moreno-Juez et al., 2020). At high temperatures (around 600^{o}C), the moisture in the material is vaporized, causing weakening of the bonds (formed by moisture) between sand and hydrated cement particles (Lotfi and Rem, 2016). The two materials are eventually separated with the additional force provided by airflow, and the light contaminants are burnt during exposure to heating. In the existing literature, information for the HAS system is only available for a semi-industrial model with a capacity of 3 t/hr (Moreno-Juez et al., 2020).

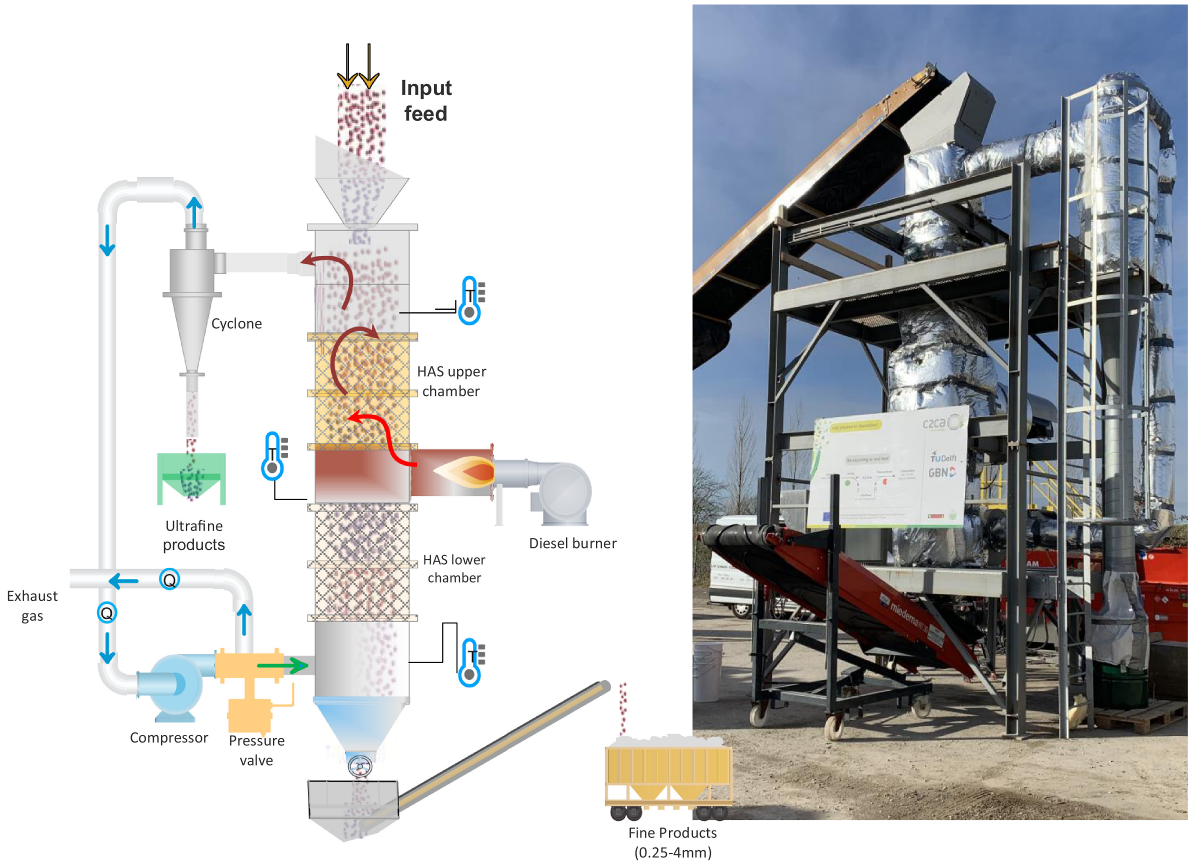

Figure 2.9: Schematic representation (left) and a pre-industrial HAS prototype (3 t/hr) installation (right) (Di Maio et al., 2020)

2.1.3.3. Recycling procedure

The main steps of the C2CA recycling procedure are illustrated in Figure 2.10. At the beginning of the process, the material received from the demolition site is pre-crushed in two steps using traditional crushers (CROW-CUR Recommendation 127, 2021). First, a jaw crusher (primary crusher) breaks the EoL concrete chunks into smaller fragments of about 40 - 50 mm. Then, with an impact crusher, the material is crushed further until it reaches a maximum size of 22 mm. Using a vibrating screen, the pre-crushed material is then separated into 0 - 16 mm and 16 - 22 mm fractions. The cut-off size of 16 mm was determined based on the maximum material size the ADR system can process. Therefore, the coarser 16 - 22 mm is discarded as low-quality RCAs (L-RCA), whereas the 0 - 16 mm material is fed into the ADR system for further processing.

As demonstrated in Figure 2.8 A, the ADR uses a spinning rotor to detach the ultrafine material (0 - 1 mm) called "ADR rotor" employing ballistic separation Di Maio et al. (2020). The heavier material (1 - 16 mm) moves in the opposite direction for further separation using an air-sifter device (airknife). This separation results in two materials, the "ADR coarse" (4 - 16 mm) and the "ADR airknife" (1 - 4 mm). As mentioned in Section 2.1.3.1, both ADR rotor and ADR airknife are further treated as one material (ADR fines) by the HAS system.

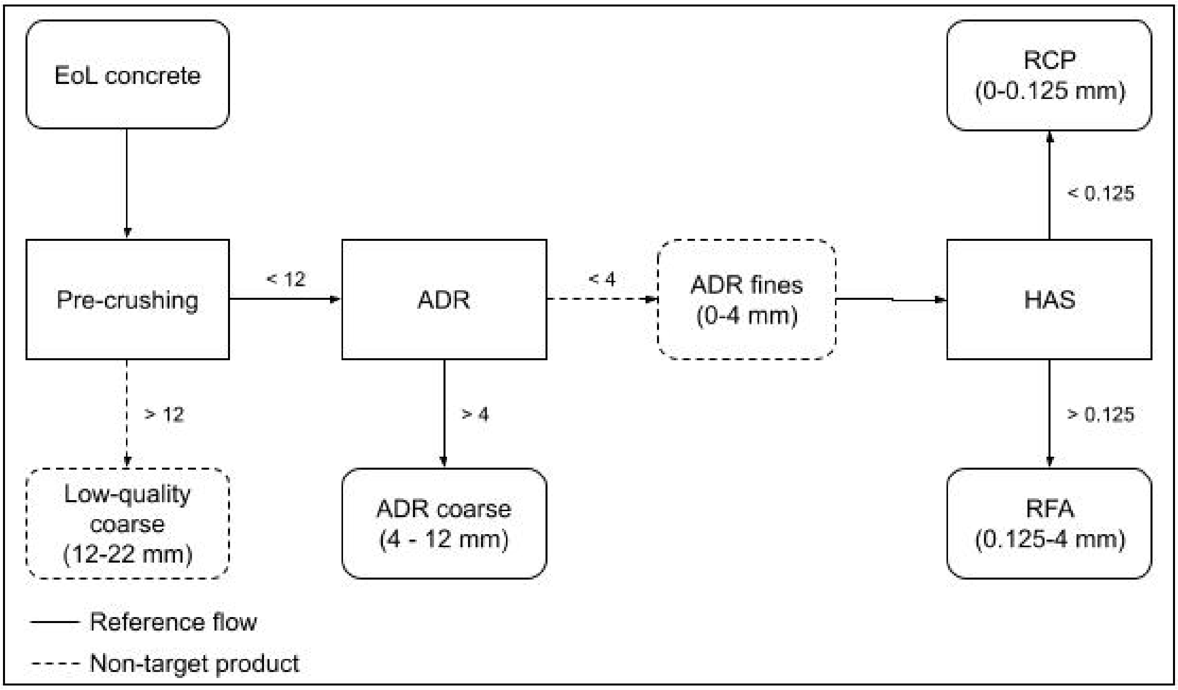

Figure 2.10: Simplified process flow diagram of the C2CA recycling procedure

In the last step of the C2CA recycling procedure, the HAS system starts flowing hot air (at a regulated temperature of 600^{o}C) within a vertical bed-like chamber using a diesel burner (Di Maio et al., 2020). As soon as the top part of the chamber (see Figure 2.9) reaches around 250^{o}C, the ADR fines are fed from the top and left exposed to heating for about 25 - 40s. The horizontal elements in the chamber increase the exposure duration of the material. At this stage, the moisture in the material evaporates and based on the density difference, the sand and hydrated cement particles are separated through airflow. At the same time, the organic contaminants are burnt. The heavier sand particles (0.125 - 4 mm) fall, while the cementitious material (0 - 0.125 mm) is driven upwards in the cyclone (see Figure 2.9). The resulting materials are called "recycled fine aggregates (RFA)" and "recycled concrete powder (RCP)". Finally, the exhaust gases from the cyclone are partially recirculated with a compressor to avoid heat loss in the chamber and thus save energy. The input and output materials of the HAS technology are illustrated in Figure 2.11.

2.1.3.4. Products

In general, the C2CA recycling system results in three main products, the ADR coarse (4 - 16 mm), the RFA (0.125 - 4 mm) and the RCP (0 - 0.125 mm). The ADR coarse (see left Figure 2.11) mainly consists of high-quality secondary gravel with very low-content cement paste. In the study of Moreno-Juez et al. (2020), it is suggested that this material can be effectively used in concrete production by replacing up to 100% of primary gravel. The RFAs (see right Figure 2.11) from the HAS system also have high value in the concrete industry as a primary sand replacement. According to Lotfi and Rem (2018), this product can also be used up to 100% without significant loss of concrete's properties. The RCP (see right Figure 2.11) contains mostly hydrated cement particles and a small amount of silica generated during the pre-crushing phase. This material can be reused in various ways, for instance, as a low-CO_2 raw meal for clinker production (for saving limestone extraction), as a filler in concrete (to improve packing properties) or as a supplementary cementitious material (SCM) (Di Maio et al., 2020). Finally, the coarse material from the pre-crushing phase (12 - 22 mm) is discarded as low-quality material suitable for road construction. More information regarding the up-cycling possibilities of these materials can be found in Section 2.2.

Figure 2.11: Left: ADR coarse (Lotfi and Rem, 2018), Right: HAS input (ADR fines) and output products (RCP and RFA) (TU Delta, 2017)

2.1.3.5. Environmental and economic impact

A few authors have already studied the environmental and economic performance of the C2CA technology. Moreno-Juez et al. (2020) assessed the environmental impact of employing RCP from the HAS system in producing new cement through a life cycle assessment (LCA) analysis. This study produced a commercial cement CEMII 42.5R using 5% of RCP. In addition, the option of biomass as fuel (instead of diesel) for the HAS system was also explored in this study. The results showed that a 5% clinker replacement by RCP brings about a 5% reduction in most impact categories, especially in the Global Warming Potential (GWP) category. Furthermore, it was also shown that the environmental impact when using biomass was half for the impact categories depletion of fossil fuel resources (ADP-F) and photochemical ozone creation (POCP).

In similar research, Zhang et al. (2019) assessed the environmental performance of the C2CA technology as an alternative to the common wet recycling process (WP). Different scenarios, including stationary ADR, mobile ADR and the combined mobile ADR & HAS system, were considered to investigate various parameters that affect the overall environmental performance. The boundary conditions of the study considered three stages of the supply chain of concrete: I) Transportation from demolition site; II) Recycling process; III) Virgin material production. This study did not consider the potential benefits of utilising the RCP from HAS system. The results indicated that the C2CA technology generally demonstrates better environmental performance than the WP. The lowest impact was reported in the case of the combined C2CA system (ADR & HAS), although the impact of the recycling phase was the highest among the rest scenarios. The increased impact in the recycling phase is attributed to the diesel consumption of HAS system, which was eventually compensated by saving raw materials. Furthermore, in the case of mobile units (ADR and combined ADR & HAS system), the total impact was reduced by around 25%, highlighting the significant contribution of transports in the supply chain. Apart from the environmental performance, Zhang et al. (2019) also studied the financial improvements from using the C2CA technology compared to WP through an LCC study. The analysis considered the costs for the recycling process, the transportation and virgin material supply. The results were similar to those obtained from the previous LCA, where the combined ADR & HAS presented the lowest cost among the rest scenarios. Significant savings were realised in the transportation and virgin material supply phases, while the cost of the operating cost was the highest due to diesel consumption by HAS technology. The main conclusion of this research is that the combined C2CA system (ADR & HAS) can reduce the environmental impact and cost of concrete recycling by around 50% compared to the WP.

2.1.4. Smart Crushing recycling

Another innovative system called Smart crushing (SC) has been developed and patented by Koos Schenk in collaboration with Rutte Groep (2022) for high-grade concrete recycling. It is an alternative technology to the C2CA aiming to recover the original gravel, sand and cement paste from EoL concrete. The SC system comprises two innovative technologies, the SmartLiberator and the SmartRefiner (as called by Rutte Groep (2022)).

2.1.4.1. SmartLiberator

The SmartLiberator (see Figure 2.12) is an innovative low-pressure crusher used to detach the cement paste from the surface of original aggregates. Specifically, with low-pressure crushing, the SmartLiberator crushes only the weaker cement paste with a compressive strength of about 15 Mpa, while maintaining the original gravel intact (Ottele and Schenk, 2020). Damage to the latter is cause for stresses beyond 100 Mpa. This "gentle" crushing results in clean secondary gravel of 4 - 32 mm (target product). The crushed cement paste results in a 0 - 4 mm fine fraction, including sand particles which proceeds to the SmartRefiner for further processing.

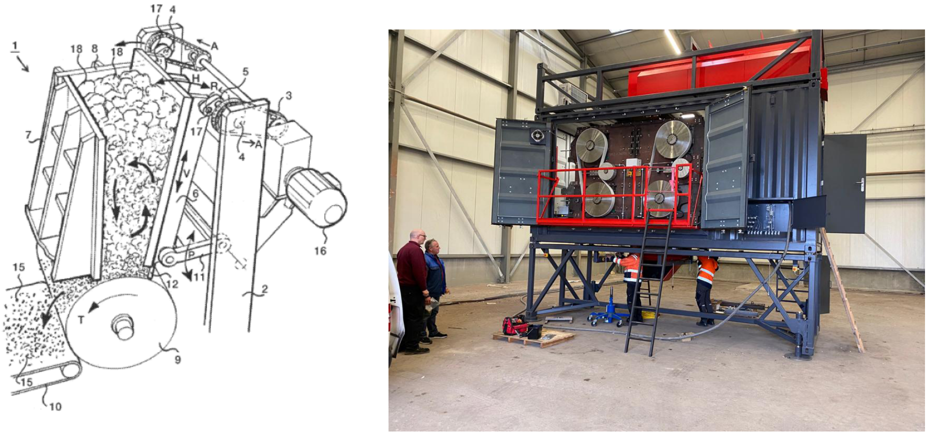

Figure 2.12: Left: The SmartLiberator patent sketch (WO2011/142663), Right: industrial scale SmartLiberator (SmartCrusher B.V.)

To verify the efficiency of the SmartLiberator, Florea et al. (2014) compared the particle size distribution (PSD) curves of the output material from the SmartLiberator and the primary aggregates used for concrete production. It was shown that the PSD of the smartly crushed material was very close to the curve of the initial mix, especially for particle sizes larger than 0.5 mm (see Figure 2.13). This observation verifies that the cement paste is indeed separated from the original gravel when using the SmartLiberator. Furthermore, the deviation of the two curves at smaller sizes (< 0.5 mm) is attributed to the generation of silica during the pre-crushing phase.

2.1.4.2. SmartRefiner

The SmartRefiner (see Figure 2.14) is a density separation device used to process the fine material (0 - 4 mm) produced from the SmartLiberator. Its ultimate goal is to recover the sand, the hydrated and unhydrated cement particles from EoL concrete. Therefore, it separates the input material into three fractions, 4 mm - 125 μm, 125 - 65 μm and 0 - 65μm. The choice of cut-off sizes is based on the actual size of the original materials used in concrete. It is expected that the ultrafine 0 - 65 μm fraction will be enriched with unhydrated (reactive) cement, and the larger hydrated cement will be captured in the 65 - 125 μm fraction, while the sand particles will be included in the coarser material 4 - 0.125 mm. The three fractions are alternatively called as "Freesand", "Freefiller", and "Freement". A minor portion of silica is also expected to be found in the Freement. Although the liberation of unhydrated from hydrated cement is not completely achieved yet, significant steps towards this goal were already made.

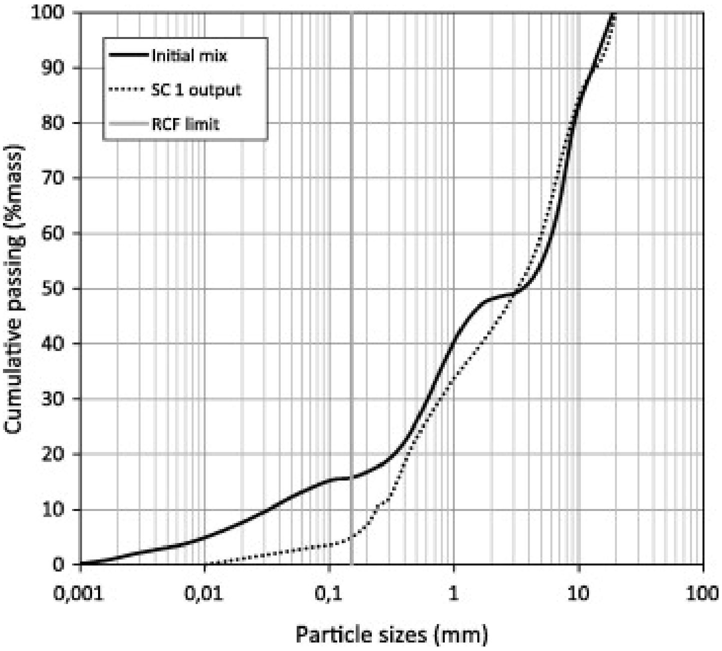

Figure 2.13: Particle size distributions of crushed material from the SmartLiberator (SC 1 output), compared to the original aggregates of the initial concrete mix (Florea et al., 2014)

Figure 2.14: Industrial scale installation of the SmartRefiner (40 t/hr)

2.1.4.3. Recycling procedure

A general flow process diagram of the SC recycling is presented in Figure 2.15. The process starts with pre-crushing the EoL concrete at segments of a maximum of 50 mm. The pre-crushing phase involves a traditional impact crusher supported by multiple cleaning and screening devices to remove light contaminants (metals, wood, plastics). The pre-crushing phase results in coarse (> 4 mm) and fine (< 4 mm) fractions. The former material proceeds to the next step, while the latter is collected as low-quality fine material due to its high contamination and moisture content. Subsequently, the coarser material (4 - 50 mm) is further processed by the SmartLiberator to remove the adhered cement paste. With a vibrating screen, the Freegravel (4 - 32 mm) is separated from the fine material (0 - 4 mm) that is generated during smart crushing. Then, moves to the SmartRefiner for further separation into Freesand (0.125 - 4 mm), Freefiller (65 - 125 μm) and Freement (0 - 65 μm).

2.1.4.4. Products

The Freegravel (see Figure2.16 A) and Freesand products are regarded as high-quality secondary materials for concrete production. They are comparable materials with ADR coarse and RFA from the C2CA technology, and as elaborated in Section 2.2, they can replace up to 100% primary gravel and sand in concrete

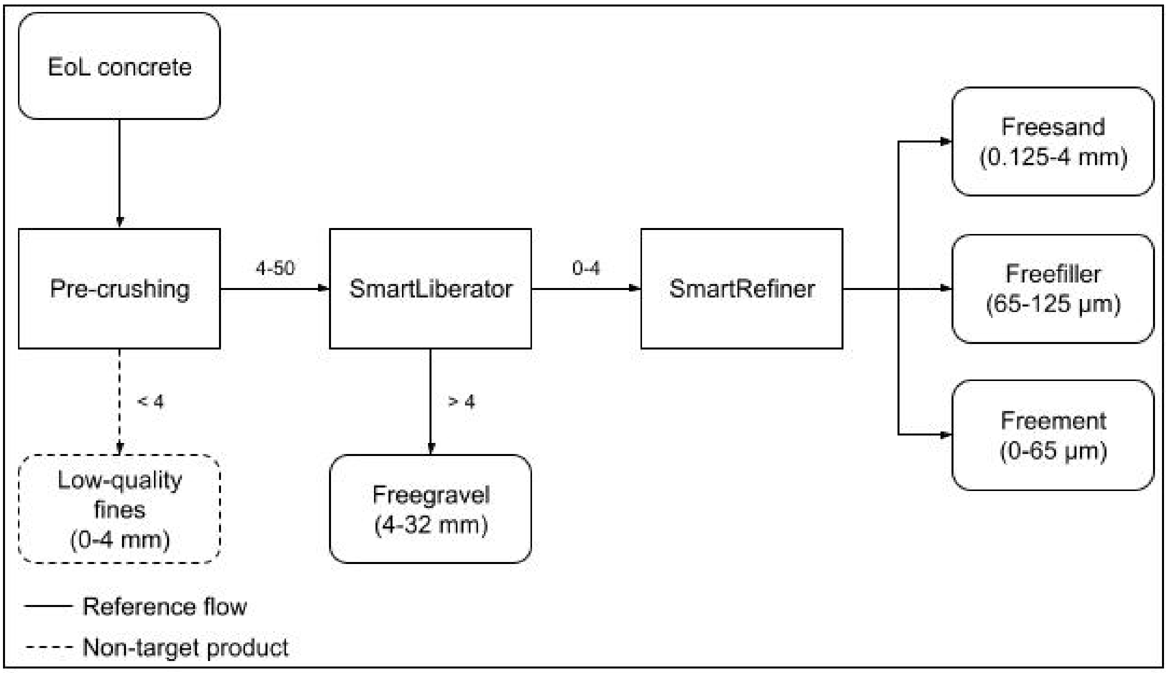

Figure 2.15: Simplified process flow diagram of the Smart Crushing recycling procedure

respectively. Furthermore, the fines (0 - 4 mm) produced during the pre-crushing have similar composition and quality to the low-quality fines of the TC recycling. Thus, a suitable application for this material is as foundation material.

The Freefiller (Figure 2.16 C) contains most of the hydrated cement of EoL concrete. Partially hydrated cement with an unhydrated inner core can also be found. However, liberating the reactive core requires further treatment. Therefore, the Freefiller can be used in similar applications with RCP from the C2CA technology. The finer Freement (Figure 2.16 D) contains mainly unhydrated cement and silica particles. This fraction has the potential to be used as secondary cement; however additional separation device is needed to remove silica particles (Florea et al., 2014). According to van Breugel (2007), the estimated maximum unhydrated cement content in EoL concrete is 30% for WCF=0.4. More information regarding the recycling possibilities of these materials can be found in Section 2.2.

2.1.4.5. Environmental and economic impact

The environmental performance of the SC recycling was only studied in the IPG report (2015). This study is not representative of the current state of development of the SC system. It was assumed that the recycled sand and gravel could be used for up to 90% in concrete, while based on the current knowledge (see 2.2), they can be used even up to 100%. In addition, it was considered that about 80% of primary cement can be replaced by unhydrated cement obtained by the SmartRefiner, a fact that is not yet possible. Based on the above assumptions, IPG report (2015) concluded that the environmental footprint of concrete could be reduced by 50%. However, this outcome must be verified using more recent data. Reliable information regarding economic consequences of this recycling system could not be found

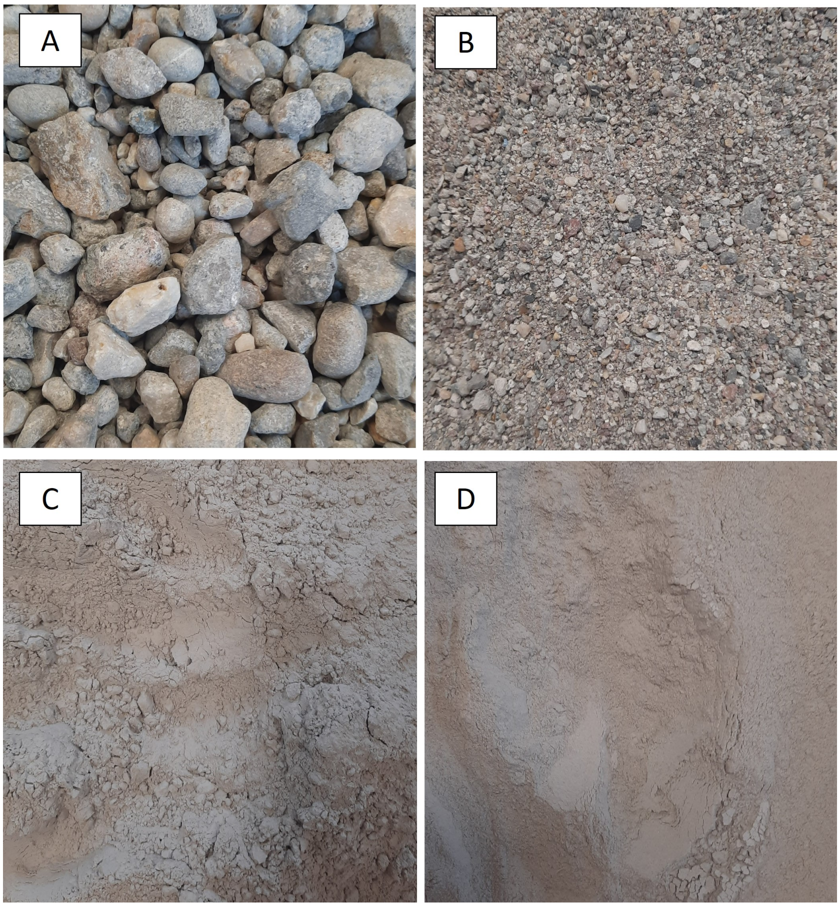

Figure 2.16: Samples of A)Freegravel (4-32 mm), B) Freesand (0.125-4 mm), C) Freefiller (65 - 125 μm) and D) Freement (0 - 65 μm) products of the SC system

2.1.5. Summary

The features of the discussed recycling technologies are summarised in Table 2.1. Of all recycling systems, mobile TC plants (TC-M) seem the least effective solution for concrete recycling. Despite the cost-benefits from operating on-site, the potential for up-cycling TRCAs is limited due to their low quality. Hence, this system is more suitable for low-grade recycling applications such as sub-base material for road construction (down-cycling). On the contrary, stationary TC plants (TC-S) produce cleaner TRCAs (medium quality) able to substitute up to 50% of primary gravel in concrete. The productivity, in this case, is the highest among the studied systems (up to 350 t/hr); however, transport of EoL concrete from the demolition site to the recycling plant is required. For long distances, this solution might be economically and environmentally inefficient. In any case, both stationary and mobile TC configurations cannot recover the old sand and cementitious material from EoL concrete. Thus, the ultimate goal of closing the material loop of the construction sector cannot be achieved with traditional methods.

With wet processing (WP), it is possible to produce clean secondary gravel for concrete production; however, the recycling cost is considerably higher than the traditional practice. On top of that, the fine material <4 mm (sand and cement) is also wasted with the WP method. Another issue of this system is the production of sludge which is often disposed of in landfills or treated further at a high cost. Furthermore, the electrical fragmentation (EF) and microwave heating (MH) are two recycling methods with similar features. They can produce clean aggregates (sand and gravel); however, recovery of the cementitious material is still impossible. Beyond that, these techniques are still at an early development stage, so additional research is required before they industrialise.

The two innovative recycling systems, C2CA and SC, demonstrate the best features among the other tech-

Table 2.1: Summary of concrete recycling technologies. Note: "E" stands for electricity, "D" for diesel. ● represents that the technology has the feature, ◐ denotes that the technology has partially the feature and ○ the technology does not have the feature. For the TC recycling, both stationary (TC-S) and mobile (TC-M) configurations were considered.

Feature	**TC-S**	**TC-M**	**ADR**	**HAS**	**SL**	**SR**	**WP**	**EF**	**MH**
Production of clean gravel	◐	○	●	○	●	○	●	●	●
Production of clean sand	○	○	○	●	○	●	○	●	●
Production of hydrated cement	○	○	○	●	○	●	○	○	○
Production of unhydrated cement	○	○	○	○	○	◐	○	○	○
Sludge generation	○	○	○	○	○	○	●	○	○
Mobility	○	●	●	●	●	●	○	○	○
Industrial scale	●	●	●	◐	●	●	●	○	○
Maximum capacity	350	100	50	3	60	40	150	○	○
Energy source	E	D	E	D	E	E	E	E	E

nologies, with a high potential to contribute to the EU sustainability goal of 2050 (European Commission, 2018). In Table 2.1, the C2CA system is represented by the ADR and HAS technologies, whereas the SC system by the SmartLiberator (SL) and the SmartRefiner (SR), respectively. With both innovative systems, it is possible to recover all concrete components almost at their initial quantities. The coarse and fine secondary aggregates can be reused in concrete manufacturing by substituting the total amount of primary aggregates. The main advantage of these technologies is the recovery of the cementitious material (RCP) from EoL concrete. Despite its limited use, RCP has the potential to bring along significant environmental and economic improvements by reducing the consumption of cement. Beyond that, both systems can operate on-site, with additional benefits from reducing transport. Nevertheless, a drawback of these systems over the TC is their productivity, especially for the C2CA system, where the semi-industrial HAS system has a capacity of only 3 t/hr. Consequently, both systems require more time to recycle the same amount of EoL concrete.

Nevertheless, there are also a few differences in the performance of the two innovative systems. A significant difference is related to the quality of the produced RCP. On the one hand, the C2CA technology produces this material as one fraction of a size smaller than 125 μm. As mentioned in Section 2.1.3, this fraction contains most of the cementitious material, particularly hydrated cement and silica particles. On the other hand, the SC system achieves a finer separation of the RCP in two size fractions, 0 - 65 μm (Freement) and 65 - 125 μm (Freefiller). The additional separation by the SR aims to capture the unhydrated and partially hydrated cement particles, which can potentially be used as a reactive binder in new concrete.

Another essential difference between the two recycling systems is observed in the pre-crushing phase. More specifically, the C2CA system involves two traditional crushers in this phase to reduce the material's size down to 22 mm. On the contrary, the SC system uses only one impact crusher, which crushes the material up to 50 mm. As a result of the more intense pre-crushing in the former case, the RCP from the HAS system is expected to have higher silica content than in the case of the SR. Since silica does not contribute to the chemical reactions of cement hydration, it can be concluded that the SC recycling system produces cementitious material of higher quality with a higher potential to be used as a cement replacement in concrete. This issue is taken into account by the philosophy of the SmartLiberator, which does not cause further damage to the original aggregate, and thus, no additional silica is produced. In any case, both C2CA and SC systems have already made significant steps in cement recycling, providing the opportunity for a further upgrade of the cementitious product in the future through additional treatment.

Another issue is that the results of the CROW-CUR Recommendation 127 (2021) reveal higher water absorption in the recycled gravel (IRCA) from the C2CA compared to the respective material from the SC system. This is an indication of higher cement paste content on the material. Hence, one may conclude that the SC system is more efficient in removing the cement stone from the original aggregates and, therefore, produce IRCA of higher quality compared to the C2C2 system.

Finally, in this research, only the innovative C2CA and SC were investigated as possible alternatives to the traditional recycling method. Despite the advantages of the two innovative systems, it is not yet clear whether they bring along environmental and financial improvements in the supply chain of recycled concrete. Although there is already some research on the environmental and economic performance of the two systems, a comprehensive comparison with the current recycling practice (TC) is missing. On top of that, most of the data used in the previous studies are not representative of the current situation of the C2CA and SC systems, which might lead to underestimation of the results. Last but not least, both recycling systems are relatively new developments; hence, there is a lack of knowledge regarding the driving factors that cause the highest impact (environmental and economic) within the recycling process.

2.2. Use of recycled materials in concrete

This section provides information regarding the maximum replacement rates of primary by recycled materials in concrete production. In this thesis, the following types of recycled materials were considered:

1. **Traditional recycled coarse aggregates (TRCA):** The coarse material produced from the traditional crushing recycling method (TC)
2. **Innovative recycled coarse aggregates (IRCA):** Clean gravel (> 4 mm) produced by the C2CA and SC systems;
3. **Innovative recycled fine aggregates (IRFA):** Clean sand (0.125 - 4 mm) produced by the C2CA and SC systems;
4. **Recycled concrete powder (RCP):** The cementitious material (< 0.125 mm) produced by the C2CA and SC systems.

The maximum substitution rates according to the current European standards and the existing research were specified for each material. It is pointed out that the rates provided in the following sections refer to the maximum limit until which the structural calculations of concrete design are not influenced.

2.2.1. Traditional recycled coarse aggregates (TRCA)

The maximum replacement rates of primary gravel by TRCAs are provided by the NEN-EN206 + NEN 8005 (2017). This standard defines TRCAs as recycled coarse aggregates with grain size > 4mm, which are further classified into four categories. The classification is based on the dry density ρ_{rd} and the composition of the material. In particular, Type A1 and A2 aggregates refer to concrete granules with dry densities larger than 2200 kg/m^3 and 2000 kg/m^3, respectively. The density difference between the two types is associated with the amount of adhered cement paste on the original aggregate. Lower density indicates higher mortar content and, thus, lower quality of the recycled material. As illustrated in Table A (see Table 2.2) in NEN-EN206 + NEN 8005 (2017), Type A1 and A2 recycled aggregates can be used in concrete up to 30% and 20% respectively for all environmental classes and up to 50% for the class X0.

Table 2.2: Replacement percentages of different types of TRCAs according to Table A NEN-EN206 + NEN 8005 (2017)

Secondary material	ρ_{rd} [kg/m^3]	**Environmental class** X0	**Environmental class** All other classes
Type A1 (concrete granules)	≥ 2200	50%	30%
Type A2 (concrete granules)	≥ 2000	50%	20%
Type B (mixed granules)	≥ 2000	50%	20%
Type C (masonry granules)	≥ 1500	25%	10%

However, it is suggested by CROW-CUR Recommendation 112 (2014) that Type A1 aggregates can be used up to 50% for all environmental classes and strength classes up to C50/60. This value complies with the EN 12620 requirements and is expected to be adopted in the next version of NEN-EN206 + NEN 8005 (2017). Furthermore, Type B and Type C aggregates represent mixed and masonry granules, respectively. Type B can be used at the same portions as Type A2, while Type C is limited to 10% for most environmental classes. Finally, secondary sand produced by conventional recycling methods is not allowed for concrete production by these standards.

2.2.2. Innovative recycled coarse (IRCA) and fine (IRFA) aggregates

The up-cycling rates of IRCA (4 - 32 mm) and IRFA (0.125 - 4 mm) from the C2CA and SC systems was investigated within CROW-CUR Recommendation 127 (2021). In this research, the performance of various concrete mixtures which incorporate different quantities of innovative recycled materials was tested. It was indicated that up to 100% replacement of primary gravel and 60% of primary sand is possible with IRCAs and IRFAs. The recommended values are applicable for:

- concrete strength classes C12/15 - C40/50;
- all environmental classes;
- dry density of IRCA $\geqslant$ 2200 kg/m^3 (Type A1).

Although at these replacement percentages the structural properties of concrete were maintained at reasonable levels, the combination of secondary coarse and fine aggregates resulted in relatively high water absorption (up to 9%) with detrimental effect on the fresh properties. As supported by the CROW-CUR Recommendation 127 (2021), this is due the very wet starting condition of the EoL concrete. As a result, a considerable amount of cementitious material could not be separated from the fine aggregates by the two technologies. To overcome this issue and obtain sufficient consistency and workability, more supeplasticizer should be added. The above observation shows the sensitivity of the C2CA and SC systems in the initial moisture content of the processed concrete rubble.

Ning (2012) has investigated the possibility of full sand replacement by IRCA from the SC system with promising results. In addition, Di Maio et al. (2020) support that full replacement of primary aggregates (coarse and fine) by IRCA and IRFA is also possible. In both cases, even higher water absorption values were reported had to be balanced with additional water and superplasticizer. The above studies though, were executed in controlled and ideal laboratory conditions with regards the initial moisture content. Thus, it is unclear whether these findings still hold in a real practical application where moisture content and eventually the water absorption of the mix will be much higher.

2.2.3. Recycled concrete powders (RCP)

The use of RCP in concrete production has not been established yet in European standards. Its complicated structure and chemical composition are the main constrain for up-cycling this material. As discussed in Chapter 2, RCP mainly comprises hydrated cement particles. Depending on the hydration development of the original cement, unhydrated or partially hydrated cement particles can also be found in this fraction. A partially hydrated cement particle (see Figure 2.17) consists of an outer hydrated layer and an inner unhydrated/reactive core. The hydrated zone's formation starts from the original cement's particle boundary (with a size of around 65 μm) and expands to both sides. A fully hydrated cement particle may reach up to 125 μm. Furthermore, RCP also contains a minor portion of silica (very finely crushed sand) generated during the crushing processes. According to Florea et al. (2014), silica particles do not contribute to the strength development of cement.

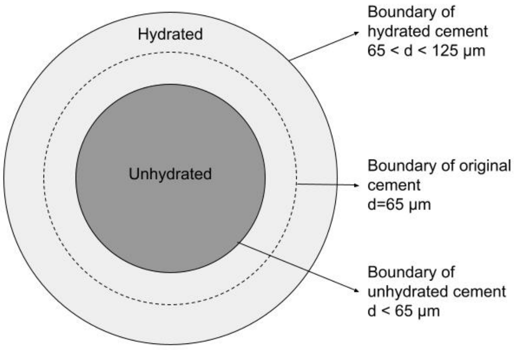

Figure 2.17: Partial hydration of a cement particle.

Several authors have investigated various ways to reactivate the RCP through dehydration (thermal treatment). This process can ideally bring the hydrated cement paste particles back to their initial unhydrated state and use them as a direct replacement for Portland clinker. Alternatively, dehydrated RCP can act as an activator of supplementary cementitious materials (SCMs), namely, fly ash and blast furnace slag (Ottele and Schenk, 2020). In both cases, achieving the same or better concrete quality with less Portland cement is possible.

According to Florea et al. (2014), before the material dehydrates completely (at 800 ^oC or higher), a transformation phase of the structure of silica particles takes place at around 570 ^oC, with negative consequences to the final product's quality. Thus, to upgrade the recovery possibilities of the cementitious material, a new separation device to remove silica is required (Florea et al. (2014), Gastaldi et al. (2015)).

Lower-grade recycling applications of RCP have also been studied in the literature. Such applications can be, for instance, in the production of clinker. The RCP already has the required chemical composition to form clinker; thus, it can be used as a replacement for primary minerals such as limestone (Gastaldi et al., 2015). Another application of RCPs is to be used as filler material to improve the properties of concrete (Awoyera et al., 2019). In this thesis, only the use of RCP as filler is further analysed since dehydration of RCP seems to be an energy-intensive procedure.

2.2.3.1. Fillers

Fillers are ultrafine materials with a size of 65 - 125 μm. They can be found as a natural material or as by-products from the mineral and metallurgical industry or may occur naturally (Awoyera et al., 2019). They are typically used to improve concrete's fresh and hardened properties (workability, mechanical and durability) to reduce cement content. From an environmental and economic point of view, fillers are considered an effective solution to reduce waste disposal (of the industries mentioned above) and cement consumption (Awoyera et al., 2019). Furthermore, fillers may have a different function in concrete depending on the chemical composition. Hence, EN 206-1 (2001) further distinguished fillers based on their function as Type I and Type II.

Type I fillers such as limestone filler (LF) are primarily used to improve the pore structure of cement paste. Their size and shape are suitable for filling the voids between cement and aggregate particles and making a more homogeneous and compacted pore system. A denser pore system yields higher strength and resistance to chemical attacks (Elgalhud et al., 2016). According to (EN 206-1, 2001), Type I fillers do not have binding properties upon contact with water; therefore, they should not be considered in calculating the water-cement factor (WCF). EN 197-1 (2011) allows for partial clinker replacement by LF (Type I filler) up to 35% for the production of cement CEM II. However, many researchers, Elgalhud et al. (2016) suggest limiting the use of LF in cement up to 25% when strength and durability are essential for the structural design.

Type II fillers, apart from functioning as Type I fillers, also demonstrate pozzolanic (binding) activity. In the literature, Type II fillers are commonly known as supplementary cementitious materials (SCMs). Examples of SCMs are fly ash, granulate blast furnace slags and silica fume. Upon contact with water, these materials react and develop binding properties similar to Portland clinker (Habert, 2014). The current European standard EN 197-1 (2011) allows the use of alternative types of cement which contain SCMs at various rates as clinker replacement. These rates are expressed by the factor k, provided per type of cement in Table 1 EN 197-1 (2011). Type II fillers must be considered in calculating the WCF (EN 206-1, 2001). Finally, a combination of Type I and Type II fillers may enhance their effect on concrete ((Müller, 2012) and (Habert, 2014)).

2.2.3.2. RCP as filler

Gastaldi et al. (2015) tested the use of hydrated cement as an alternative raw meal for clinker production. In this study, a pure hydrated cement powder (< 90 μm) was prepared and used as raw meal (limestone and schist) replacement (30% and 55%) for producing new clinker. At a 30% replacement, the mineralogical composition of the new clinker was found to be similar to the reference Portland clinker. On the contrary, the sample composition with 50% replacement of raw meal deviated significantly from the reference clinker. In reality however, RCP contains not only hydrated cement particles but also unhydrated (and/or partially hydrated cement) and silica which might influence the above results.

In the study of Oksri-Nelfia et al. (2016), RCP was used as SCM (Type II filler) to replace part of Portland cement. The RCP used in this study was prepared by crushing a five-year-old concrete at a maximum size of 80μm. The old concrete was initially produced with Portland cement (CEMI 53.5), limestone aggregates and fly ash (23 % by weight of cement). Different mortar samples made of RCP and LF of various substitution rates were tested and compared with a reference mortar (entirely made of CEMI). The tests showed that the RCP mortars had similar or better performance and faster cement hydration than LF mortars, especially for low replacement levels (25%). This is attributed to the residual reactivity of the unhydrated cement contained in the RCP, which became accessible to water after crushing. Another reason is the presence of fly ash in the RCP, which has some pozzolanic reactivity. It was also found that RCP mortars had at least equal strength with LF mortars. Based on these findings, the authors concluded that RCPs could be effectively used as Portland cement replacement up to 25% without altering the properties of concrete. This conclusion is also in line with the findings of Elgalhud et al. (2016).

Florea et al. (2014) studied the pozzolanic reactivity of untreated and thermally treated (dehydrated) RCP produced by a lab-scale SmartLiberator. The origin of RCP was EoL concrete made of CEMI 42.5. The RCP was treated at 20^{o}C (untreated), 500^{o}C and 800^{o}C. RCP mortar samples of different substitution percentages (up to 30%) of CEMI 42.5 by RCP. Compared to the reference mortar (100% CEMI), the untreated and 800^{o}C treated RCPs, showed similar performance at 20% replacement. At this replacement percentage, the 28 days compressive strength of the two samples was reduced by 23% and 16%, respectively. At 10% substitution, this value was less than 10% in both cases. It was also shown in this study that thermally treated RCPs could also be used as activators of SCMs. A 10% substitution of blast furnace slag cement (70% slag content) by dehydrated RCPs (500^{o}C and 800^{o}C) increased the compressive strength of mortar by 15%-20%. No activation was noted in the case of untreated RCPs with the same replacement rate.

The use of RCP from the C2CA recycling system as SCM was tested in the study of Moreno-Juez et al. (2020). The ultrafine fraction (< 0.125 mm) from HAS technology was used to produce new mortars made of CEMII 42.5/A-LL and various combinations of RCP content (up to 10% replacement). The reduction of the compressive and flexural strength of the mortar sample with 5% RCP was minimal (< 4.5%) compared to the reference sample (100% CEMII). At 10% replacement, the reduction of both strengths reached around 10%. This result is in line with the findings of the previous study of (Florea et al., 2014) (for untreated RCP from SC) indicating the similarities of the RCP from the C2CA and SC technologies.

Finally, the possibility of using 20% of RCP as filler in combination with full replacement of primary sand and gravel (by IRCA and IRFA) was tested in the CROW-CUR Recommendation 127 (2021). The tested concrete mixture demonstrated comparable properties with the reference concrete (which uses only primary materials) apart from the creep and shrinkage which were significantly higher. It was discussed that this is a result of the high water absorption of secondary aggregates.

2.2.4. Summary

The use of secondary coarse and fine aggregates in concrete is already well regulated by the current Standards. Until now, TRCAs are allowed to replace 50% of primary gravel in concrete. In the case of the innovative C2CA and SC, the produced IRCAs and IRFAs can be used in concrete to replace 100% of gravel and 60% of sand. Full replacement of both gravel and sand is still not allowed; however, it is supported in the literature that IRFAs can be used even up to 100% with additional use of superplasticer. Similarly, lack of standards also occurs regarding the use of RCP in concrete.

In the present thesis, it was decided to investigate as an ideal scenario the environmental and financial implications of using 100% IRCA and IRFA from the C2CA and SC systems. This hypothesis assumes perfect conditions of storing the EoL concrete and water absorption within acceptable limits. It is stressed out that such scenario might not be applicable in reality due possible higher water absorption values. In addition to that, 20% of cement replacement by RCP was considered in the same scenario. Due to limited research on RCP up-cycling, it was decided to use the findings of Florea et al. (2014) as a baseline for this thesis. This study covers all aspects of using RCP from SC in concrete, while it can be applied to the case of the C2CA technology as well.

The findings of the above review are summarized in Table 2.3. These values were used for the analysis part of this thesis in Chapter 4, which examines various scenarios in concrete recycling.

Table 2.3: Maximum replacement percentages of primary by secondary materials in the production of concrete.

Recycled material	**Size**	**Standards**	**Literature**
Traditional recycled coarse aggregates (TRCA)	4 - 32 mm	50%[1]	-
Innovative recycled coarse aggregates (IRCA)	4 - 32 mm	100%[2]	100%[3]
Innovative recycled fine aggregates (IRFA)	0.125 - 4 mm	60%[2]	100%[3]
Recycled concrete powder (RCP)	0 - 0.125 mm	-	20%[4]

[1] From CROW-CUR Recommendation 112 (2014);
[2] From CROW-CUR Recommendation 127 (2021);
[3] From Di Maio et al. (2020);
[4] From Florea et al. (2014)

2.3. Life Cycle Assessment (LCA)

2.3.1. General

LCA is a calculation method to quantify a product's or process's environmental impact over its life cycle. The inputs (energy, resources, etc.) and outputs (emissions and pollutants) are first defined, and their environmental impact is determined for several environmental problems. Nowadays, most businesses are primarily concerned about their carbon footprint, which is associated with the potential global warming. Nevertheless, environmental issues such as marine and human ecotoxicity, which can be effectively addressed through an LCA, might be equally important.

Furthermore, LCA in businesses has become more popular in the past years due to its several benefits. First, it enables companies to make informed decisions based on the environmental impact of their activities. Moreover, breaking down the impact of all contributors (energy, resources, etc.) throughout companies' supply chains allows for making effective adjustments to optimize their environmental performance. Beyond that, minimizing a product's or process's environmental impact by saving energy or resources also brings financial benefits to a company.

2.3.2. Methodological framework

According to the international standards ISO 14040 (2006) and ISO 14044 (2006), an LCA is executed in the following steps: I) Goal and scope definition, II) Life-cycle inventory analysis (LCI), III) Life-cycle impact assessment (LCIA), IV) Interpretation of the results.

2.3.2.1. Goal and scope definition

In the first step of an LCA, the goal must be clearly defined by stating the intended application, the target audience and the reasons for conducting the analysis. The scope of an LCA includes the geographical region to which the LCA results refer and the boundary conditions of the problem. The latter is a critical step of an LCA since it must specify which phases of a product's life cycle are considered and which are outside the scope. In this step, the functional unit of the problem is also defined. A functional unit may represent a particular service (e.g. production of 1 m^3 of concrete), serving as a reference, especially in comparative studies. In addition, a detailed description of the examined product (or process), assumptions, limitations and decisions must also be stated in the scope.

2.3.2.2. Inventory analysis

The inventory analysis involves data collection and background calculations of all inputs and outputs of each life-cycle phase. A large amount of data is required for this purpose, which are obtained from databases in most cases. In general, performing an inventory analysis is an iterative process, and often changes in the goal and scope definition need to be made to overcome issues that might arise. Such issues might be the inability to retrieve specific data, for which assumptions must be made.

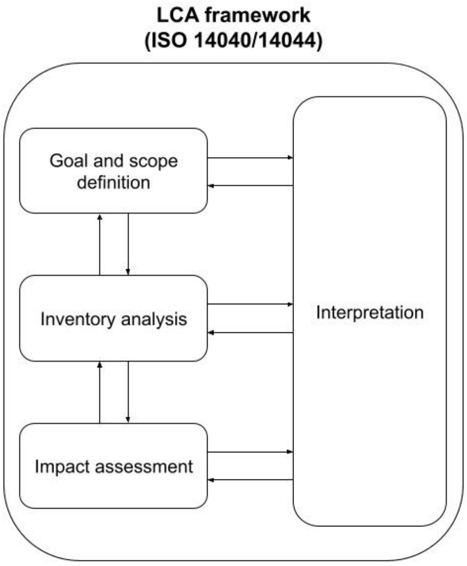

Figure 2.18: LCA framework based on ISO 14040 (2006) and ISO 14044 (2006)

2.3.2.3. Impact assessment

In the impact assessment step, the results from the inventory analysis are further analysed, calculating the environmental impact of the inputs and outputs of each phase for a number of impact categories. In general, there are two types of impact categories in an LCA; the midpoints and endpoints. The former represents specific environmental issues such as global warming potential, ecotoxicity, depletion of fossil fuels etc. Endpoints address more generic environmental themes, namely human health and ecosystem damage. The results at this level are expressed in indicators assigned to each midpoint. For example, the indicator of the global warming potential category is typically expressed in kg CO_2 equivalent. Presenting the results at endpoint-level is optional. Normalisation and weighting of the results are also optional impact assessment steps according to ISO standards. Finally, a sensitivity and uncertainty analysis may also be conducted to quantify the sensitivity and robustness of the results on specific data and methods chosen for the LCA study.

2.3.2.4. Interpretation

The final step of an LCA deals with interpreting the results, where the goals and objectives of the LCA study are addressed. It may, for example, include identification of the most significant elements, evaluation of sensitivity results, as well as a statement of limitations and conclusions of the whole study.

2.4. Life Cycle Costing (LCC)

2.4.1. General

The LCC is a method for cost-evaluation of products[1] throughout their life cycle. It is not suitable for accounting but rather for comparing the cost of various alternative products. It is also suitable for exploring various alternatives for minimizing the overall cost of a product over its life cycle.

Initially, it was used strictly for accounting purposes, such as monitoring all costs occurring from the acquisition until the EoL phase of a product; the so-called "internal costs" (SETAC, 2008). The LCC in this form is also known as "Conventional LCC". Nevertheless, due to the growing interest in incorporating sustainability issues in the cost-evaluation of products, two additional types of LCC were developed, the "Environmental LCC" and the "Societal LCC" (SETAC, 2008). These types of LCC expand the boundaries of the Conventional LCC by considering "external costs" as well as illustrated in Figure 2.19.

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[1] The term product in both LCA and LCC can be a product, process or service.

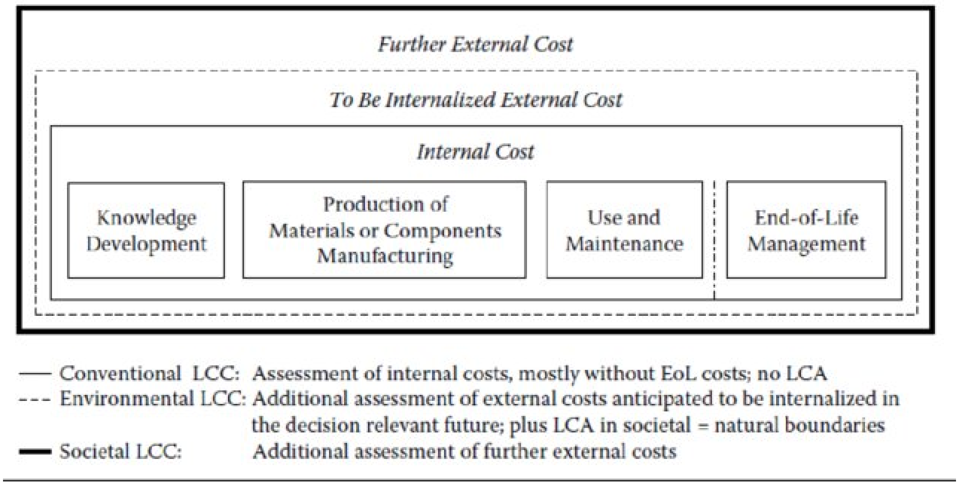

Figure 2.19: The three types of LCC (De Menna et al., 2016)

2.4.1.1. Internal costs

As mentioned above, the internal costs are the expenses occurring during the production (including delivery and installation), use (energy consumption, maintenance and insurance) and EoL (recycling or disposal) phase of a product. These costs are typically covered by the responsible actors involved in each phase (e.g. producer, user, etc.). Moreover, internal costs can be easily determined and understood; therefore, they are directly related to business costs.

2.4.1.2. External costs

As defined by SETAC (2008), external costs or externalities are the side-effects of business activities that are not included in their scope and planning. In practice, external costs refer to the socio-environmental effects of an activity that may negatively or positively impact society. The external cost of a product can be, for instance, problems associated with air, ground, and noise pollution or an increase in unemployment caused during its life-cycle.

Currently, external costs do not have a direct market value yet. The main reason is the difficulty of accurately quantifying the socio-environmental impacts and assigning a monetary value to them. Even though external costs are not included in market transactions, society pays for them in various ways. For instance, through environmental taxes induced by governments (e.g. for emitting CO_2), expenses for installing emission control systems in factories (covered by companies), healthcare and insurance due to possible upcoming health problems and many more (Biernacki, 2015). This model (”$society - pays - principle$”) is not sustainable for society since it encourages polluters to continue their activities without any consequences. Therefore, it is crucial to switch to a more sustainable model in which the responsible actors (polluters) pay the external costs of their actions (”$polluter - pays - principle$”). To achieve that, the external costs must be internalised in the sales price of a product. The transition to a more sustainable economy is shown in Figure 2.20.

Numerous methodologies have already been proposed for monetising external costs; however, their applicability is often controversial (SETAC, 2008). For instance, such a method could measure the cost needed to recover or prevent damage caused by a particular activity. This approach was adopted in the Environmental Prices Handbook-EU28, which determines environmental prices, the so-called "Shadow costs" for various pollutants, midpoints and endpoints. In the Netherlands, shadow costs are also known as environmental cost indicators (ECI), expressed in euros per kg of pollutant (Environmental Prices Handbook-EU28). In an LCA, the shadow prices can be used as weighting factors in the impact assessment step, allowing for the summation of the impacts over the different midpoints in a single monetary value. This value can eventually be used as an external cost in financial evaluations such as LCC.

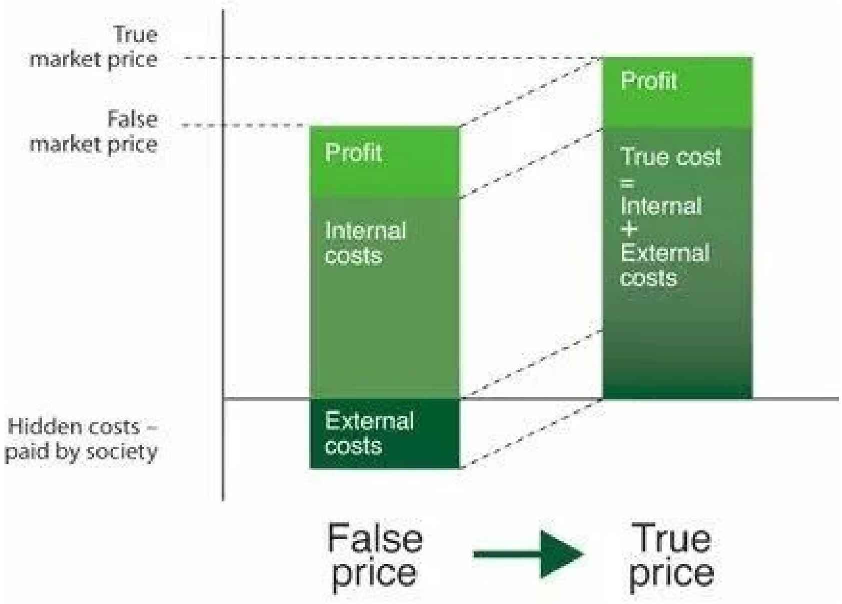

Figure 2.20: Internalization of external costs in the sale price of a product (ECONATION, 2022).

2.4.2. Types of LCC

2.4.2.1. Conventional LCC

As mentioned above, businesses and governments commonly use the conventional LCC to assess their own costs (Martinez-Sanchez et al., 2015). It can be executed either from the producer's or the consumer's point of view. Socio-environmental considerations are not included in this type of LCC. Depending on the goal, a conventional LCC may focus only on the service life of a product while other life cycle stages (i.e. end-of-life) can be excluded (De Menna et al., 2016).

2.4.2.2. Environmental LCC

In contrast with conventional LCC, the environmental LCC expands the cost-evaluation to all parties involved, including external costs anticipated to be internalized in the near future (Hoogmartens et al., 2014). Figure 2.21 illustrates an example of a conceptual environmental LCC framework.

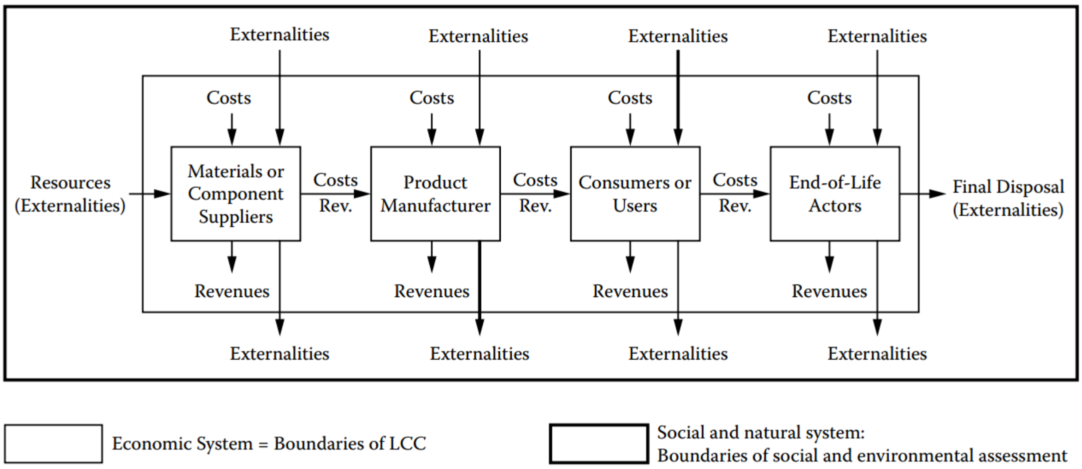

Figure 2.21: Conceptual framework of environmental LCC (SETAC, 2008)

An environmental LCC is not meant to be applied as an independent cost-evaluation but rather as a supplementary to an LCA analysis (Biernacki, 2015). The results from the LCA analysis (e.g. kg of CO_2 emissions) may be used as input data for calculating external costs. Therefore, environmental LCC and LCA must share common system boundaries and functional units to be consistent (SETAC, 2008).

2.4.2.3. Societal LCC

Societal LCC expands further the field of application of LCC, considering all kinds of costs covered by anyone in society (SETAC, 2008). The result of a societal LCC represents the "social cost" of a product. The social cost emerges from a simple summation of the internal and monetized external cost. As mentioned in Section 2.4.1.2, assigning monetary values to all external costs is challenging. A societal LCC must also be coupled with an LCA study, as in the case of the environmental LCC.

Both environmental and societal LCC provides the opportunity to study a product's cost-effectiveness alongside its environmental implications. Combining these LCC types with an LCA provides the opportunity to search for products with the lowest environmental impact and cost.

2.4.3. Methodological framework

According to SETAC (2008), an LCC follows a similar approach to an LCA, and it is executed in three mandatory steps: I) Goal and scope definition, II) Life-cycle inventory analysis (LCI), III) Interpretation of the results. The "Impact assessment" step is optional though, since it is already clear that a lower cost indicates better economic performance (SETAC, 2008). Nevertheless, this step can be included to investigate the cost for different cost categories (e.g. maintenance, energy, insurance, personnel, etc.)

3

Research definition

3.1. Research aim and objectives

Based on the previous Literature review, there is a lack of knowledge regarding the use of the innovative concrete recycling systems C2CA and Smart crushing in the concrete supply chain. Thus, this thesis aims to investigate the feasibility of these novel systems as alternatives to the traditional concrete recycling route. To this end, the three recycling systems must be evaluated and compared from environmental and economic perspectives. Beyond that, the present thesis also focuses on identifying the driving factors that influence the efficiency of each recycling system.

3.2. Research questions

The principle goals of this thesis were achieved by addressing the main research question of this thesis:

Are the C2CA and Smart crushing viable alternatives to the Traditional crushing recycling method in the current construction industry?

To answer all aspects of the main research question, the following sub-questions are formulated:

1. What are the environmental and economic implications of the C2CA and Smart crushing technologies in the concrete supply chain?
    1.1 What environmental and financial benefits can be achieved by following the current standards?
    1.2 What are the potentials of using higher replacement rates of primary by recycled materials from the C2CA and Smart Crushing systems?
2. What are the system hot spots with the greatest influence on the environmental and economic impact of concrete recycling?
    2.1 Which processes have the most impact on the recycling procedure?
    2.1 What are the most critical external factors influencing the total impact of concrete recycling?

3.3. Research methodology

An integrated LCA&LCC analysis methodology was developed to approach the above research questions (see Figure 3.1). The new methodology was inspired by the study of Zhang et al. (2019), aiming to analyse and compare the environmental and economic impacts of the examined recycling systems under different scenarios. In this study, the overall performance of the recycling systems was evaluated based on their social cost. More specifically, the environmental impacts that emerged from the LCA study were monetised (shadow costs) and then internalised into the actual costs (internal costs) from the LCC. Finally, the resulting social costs refer to the costs covered by the concrete manufacturer.

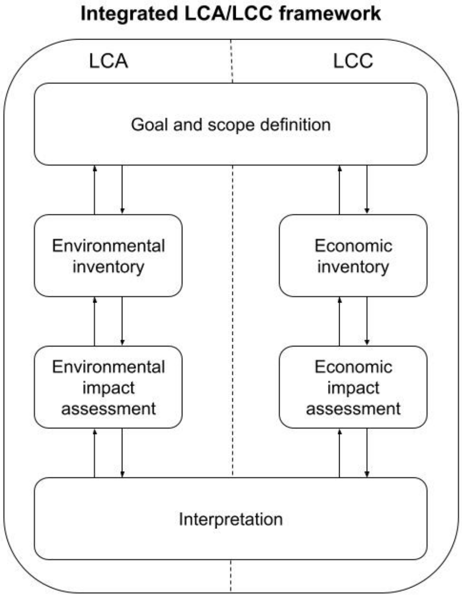

Figure 3.1: Integrated LCA/LCC framework

The environmental evaluation in this thesis was carried out with a life cycle assessment (LCA) analysis according to ISO 14040 (2006) and ISO 14044 (2006) standards (see Figure 2.18). The environmental inventory was synthesised with data from existing research and personal communication with Rutte Groep (2022). The environmental impact assessment calculations were performed in the OpenLCA 1.7.4. software based on the Dutch $CML - IA\ Baseline$ method (Guinee et al., 2002). Then, the resulting environmental impacts were monetised by adopting the environmental cost indicators (ECI) suggested by the Dutch regulations (Bepalingsmethode Milieuprestatie Bouwwerken 2022).

The economic evaluation was conducted in a simplified conventional LCC framework following the SETAC (2008) code of practice. For simplicity, the conventional LCC in this thesis will be referred to as LCC. Similar data sources to the LCA study were also used for the LCC to calculate the internal costs of each recycling system using Microsoft Excel.

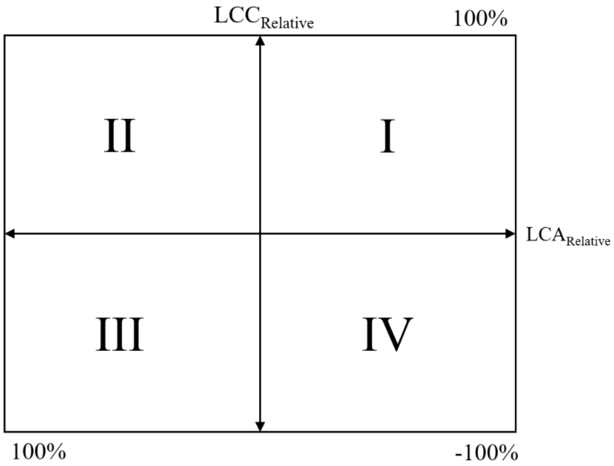

Figure 3.2: Relative environmental and economic impact graph (Zhang et al., 2019)

Although the LCA and LCC results are essential to investigate the environmental and economic efficiencies of the recycling systems separately, they do not provide standalone information regarding their overall performance. That was achieved by integrating the LCA and LCC, resulting in a unified social cost value. A common goal and scope definition step was necessary to reach compatible results from the two analyses. Finally, the inventory and impact assessment steps were executed separately but focused on the supply chain's elements (phases).

In the next part of this thesis, the innovative systems' LCA and LCC results were expressed relative to the traditional recycling method. The relative impacts were then visualized in a two-dimensional diagram with the X and Y axes representing the relative LCA and LCC impacts, respectively (see Figure 3.2). Negative values in the graph denote a relative decrease in the impact and, thus, a positive outcome. Based on that, Zone III represents the most favourable situation, where environmental and financial benefits occur, while Zone I indicates the exact opposite. Finally, Zones II and IV show intermediate situations with only environmental or economic benefits. In the final part of this thesis, the robustness of the LCA and LCC results on changes in the input data was measured with a sensitivity analysis. Through this process, the driving factors of each recycling system could be identified.

4

Analysis

4.1. Goal and scope definition

4.1.1. Goal definition

The main goal of the LCA analysis is to evaluate and compare the environmental impacts of Traditional crushing (TC) and innovative C2CA and Smart crushing (SC) recycling systems. Furthermore, the cost-effectiveness of these systems is assessed through a supplementary LCC analysis. This study also aims to identify the most contributing factors and to evaluate their sensitivity to the final results through a sensitivity analysis.

4.1.2. Scope definition

This evaluation treated the three recycling systems as an intermediate phase in the recycled concrete supply chain. More specifically, recycled materials were used as primary material replacements in different concrete mixtures. For this purpose, the five scenarios illustrated in Table 4.1 were considered to investigate different options for implementing the C2CA and SC systems. This study is based on the geographic scope of the Netherlands and for the year 2021.

Table 4.1: Investigated scenarios.

Scenario	**Replacement rates**
TC	50% TRCA[1]
C2CA1	60% IRFA[2]+ 100% IRCA[3]
C2CA2	100% IRFA + 100% IRCA + 20% RCP[4]
SC1	60% IRFA + 100% IRCA
SC2	100% IRFA + 100% IRCA + 20% RCP

[1] Traditional recycled coarse aggregates;
[2] Innovative recycled fine aggregates;
[3] Innovative recycled coarse aggregates;
[4] Recycled concrete powder.

The defined scenarios adopt the maximum replacement percentages of secondary materials according to Table 2.3. In particular, the first scenario (TC) represents the traditional crushing recycling method used as a reference in this comparative study. In this scenario, 50% of the primary gravel is replaced by traditional recycled coarse aggregates (TRCA). The C2CA1 and SC1 scenarios allow for 60% and 100% use of innovative recycled coarse (IRCA) and fine aggregates (IRFA) in concrete. The above scenarios follow the provisions of the current standards. Similarly, the C2CA2 and SC2 scenarios explore the possibility of replacing the total amount of primary aggregates. In addition to that, the produced recycled concrete powder (RCP) from the innovative systems is also used as SCM in the concrete recipe to replace cement by 20%. These scenario assumes dry condition of EoL concrete (low starting moisture content) and water absorption withing acceptable limits (see Section 4.1.5). Furthermore, low-quality recycled materials (unsuitable for concrete production) from all systems were used as road foundation materials, as this application is typical for these materials (see Chapter 1).

4.1.2.1. Methods and tools

The LCA analysis was conducted according to ISO 14040 (2006) and ISO 14044 (2006) provisions. Following the NEN-EN 15804+A1 (2013)[1] methodology, the problem was approached as an EPD (Environmental Product Declaration) for recycled concrete. Furthermore, the LCC analysis followed a similar methodology focusing on the financial aspects of the problem (see Section 2.4). All calculations were performed in Microsoft Excel, apart from the environmental impact assessment step. For this case, the OpenLCA 1.7.4. software was supported by the Ecoinvent 3.4 database (Wernet et al., 2016).

4.1.2.2. Recycling plants

The LCA and LCC calculations were executed based on recycling plants designed for this thesis. Each plant simulates the material flow and other process information, such as energy consumption and operating duration of the individual steps. Table 4.2 summarizes the material mass balance of each recycling plant according as elaborated in more detail in Appendix A. It is mentioned that these values are based on the assumption of pure EoL concrete (see Section 4.1.5).

Table 4.2: Material mass balance distribution of the proposed recycling plants

	TC plant[1]	**C2CA plant[2]**	**SC plant[3]**
Input:			
EoL concrete	100%	100%	100%
Outputs:			
TRCA or IRCA	80%	42%	35%
IRFA	-	21%	26%
RCP	-	5.6%	9%
L-RCA	-	30%	-
L-RFA	20%	-	30%

[1] From Di Maria et al. (2018);
[2] From Kalliopi (2019);
[3] From Rutte Groep (2022);

4.1.3. Functional unit

The functional unit of this study is the production of 1 m^3 of concrete. For each scenario, a different concrete mix was designed using Table 4.1 substitution rates. The new mix designs were formulated based on a reference mix (see Appendix D), provided by Rutte Groep (2022). The reference mix is exclusively made of primary materials and implies the following properties:

- Strength class: C30/37;
- Exposure class: XC2;
- Slump class: F4;
- Water-cement factor (wcf): 0.5;
- Largest grain: 32 mm;

Table 4.3: Mix designs for 1 m^3 concrete C30/37XC2F4

Material	**Scenario Replacement %[1]**	**Ref. 0-0-0 kg/m^3**	**TC 50-0-0 kg/m^3**	**C2CA1 100-60-0 kg/m^3**	**C2CA2 100-100-20 kg/m^3**	**SC1 100-60-0 kg/m^3**	**SC2 100-100-20 kg/m^3**
Gravel	Primary	1000.8	500.4	-	-	-	-
	Secondary	-	500.4	1000.8	1000.8	1000.8	1000.8
Sand	Primary	815.7	815.7	326.3	-	326.3	-
	Secondary	-	-	489.4	815.7	489.4	815.7
CEM III/A 42.5N	Primary	340.0	340.0	340.0	272.0	340.0	272.0
Filler	Primary[2]	25.0	25.0	25.0	25.0	25.0	25.0
	Secondary[3]	-	-	-	68.0	-	68.0
Effective water (WE)		170.0	170.0	170.0	170.0	170.0	170.0
Absorbed water (WA)		19.0	46.5	68.6	83.0	68.6	83.9
Total water (W)		189.0	216.5	238.6	253.0	238.6	253.0
wcf		0.5	0.5	0.5	0.5	0.5	0.5
Superplasticizer[4]		1.29	1.29	1.29	1.29	1.29	1.29
Total		**2364**	**2392**	**2414**	**2427**	**2414**	**2427**

[1] Replacement percentages of primary by secondary material. The percentages are provided for the order G/S/C (Gravel/Sand/Cement);

[2] Limestone powder;

[3] Recycled concrete powder used as supplementary cementitious material (SCM);

[4] Superplasticezer MasterGlenium SKY 648 (Master Builders Solutions©).

The reference and the new concrete recipes are provided in Table 4.3. In the calculations of the mix designs, it was also taken into account the water absorption (WA) of all materials with additional water[2]. As already explained in Chapter 2, recycled materials absorb more water than natural ones. The WA rate depends on the amount of cement paste on the material. Hence, the missing amount of water for cement hydration was added to maintain a constant water-cement factor (i.e. WCF = 0.5) for all scenarios according to the following expression:

$$W\,(kg) = WE\,(kg) + WA\,(\%) \times m\,(kg) \tag{4.1}$$

Where:
- W: Total water content;
- WE: Effective water;
- WA: Water absorption ratio of the material;
- m: The mass of the material.

The effective water WE is the amount required for cement hydration (i.e 170 kg), while the water absorption ratio WA represents the amount of water absorbed for every kg of material. The latter property is different for every material and is typically determined through on-site tests. In the context of this thesis, the values of Table 4.4 as obtained from empirical tests performed by Rutte Groep (2022) were used for this purpose.

4.1.4. System boundaries

The system boundaries of the problem were limited to the supply and transportation phases of raw materials. In this case, raw materials for the production of recycled concrete refer to both primary and secondary

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[1] The NEN-EN 15804+A1 (2013) standard focuses on EPDs for construction works and products such as concrete.

[2] It is stressed out that in this thesis the amount of superplasticer takes into account use of IRCA only. When IRFA are also implemented and especially in the C2CA2 and SC2 scenarios, more superplasticizer would be required to compensate the loss of consistency and workability. For simplicity, it was assumed the same for all scenarios.

Table 4.4: Water absorption ratios of recycled materials (Rutte Groep, 2022)

Secondary material	WA (%)
NCA	0 %
NFA	0.6 %
TRCA	6.5%
IRCA	4%
IRFA	3.5%

materials. Figure 4.1 illustrates the system boundaries of the examined recycling technologies.

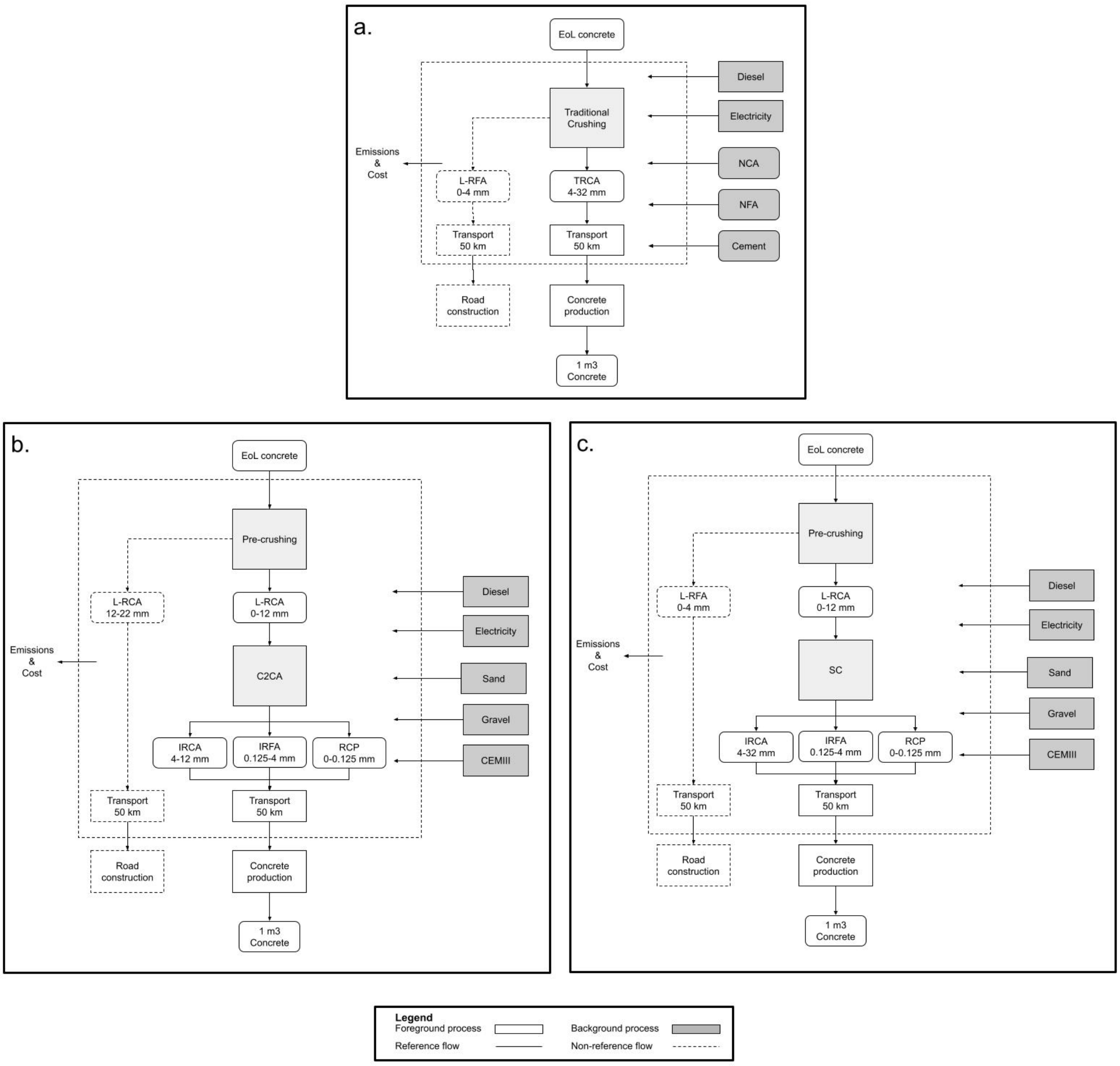

Figure 4.1: System boundaries of a. Traditional crushing, b. C2CA, c. Smart crushing recycling systems

As described in Section 4.1.2.2, the type and quantities of each plant's recycled materials differ. Therefore, to meet each scenario's requirements, a different input mass of EoL concrete was assigned in each case. As shown in Table 4.5, a part of the produced (P) material was utilised (U) in concrete production. A surplus (S) amount of materials also occurred in some instances. The impact of future utilisation of the surplus material in concrete production was also included in the calculations.

Table 4.5: Input mass of EoL concrete and produced (P), used (U) and surplus (S) recycled materials per scenario

	Scenario:	**TC**	**C2CA1**	**C2CA2**	**SC1**	**SC2**
Secondary material	**Input [tn]:**	**0.63**	**2.21**	**2.93**	**2.86**	**3.14**
RCA	P	500.4	1000.8	1324.4	1000.8	1098.0
	U	500.4	1000.8	1000.8	1000.8	1000.80
	S	-	-	323.6	-	97.3
RFA	P	-	616.4	815.7	743.5	815.7
	U	-	489.4	815.7	489.4	815.7
	S	-	127.0	-	254.0	-
RCP	P	-	154.1	203.9	257.3	282.3
	U	-	-	68.0	-	58.0
	S	-	154.1	135.9	257.3	214.3
L-RCA	P	-	442.8	586.0	-	-
	U	-	-	-	-	-
	S	-	442.8	586.0		
L-RFA	P	125.1			857.8	941.2
	U	-	-	-	-	-
	S	125.1			857.8	941.2

Furthermore, the low-quality recycled materials (unsuitable for concrete production) were treated as secondary sub-base material in road construction. In this case, it was considered that an equal amount of primary materials was saved. It was also assumed that the road construction industry could absorb all the low-quality materials produced during the recycling process. Therefore no restrictions were applied regarding their use.

4.1.5. Assumptions

The following assumptions were made in this study:

1. The received concrete debris in the recycling plants was treated as pure EoL concrete obtained by selective demolition. Thus, no waste (metals, plastics, wood, etc.) generation was considered during the recycling process;

2. The Traditional crushing was realised in a stationary plant to secure the sufficient quality of TRCAs. In particular, it was assumed that TRCAs comply with the requirements of Type A1 aggregates. The TC plant was located 50 km away from the demolition site.

3. Both C2CA and SC recycling plants were placed at the demolition site (0 km) to take advantage of their portability.

4. The concrete mix of the C2CA2 and SC2 scenarios (100% lRCA + 100% lRFA + 20% RCP) can be realised in practice. In this case the increased water absorption can be compensated by additional water and superplasticer.

5. The C2CA and SC plants produce recycled materials of the same quality and properties.

6. All materials are transported by typical lorries (by road). According to Bepalingsmethode Milieuprestatie Bouwwerken 2022, when the locations are not known, then a distance of 50 km may be assumed for all transports. In addition, the lorries were considered to curry 25% less cargo during the return journeys (Bepalingsmethode Milieuprestatie Bouwwerken 2022).

4.2. Inventory analysis

The data collection for the environmental and economic inventories was categorized into the foreground and background processes. Foreground processes refer to the operation of the recycling equipment, while background processes include energy and primary materials consumption as well as transportation.

4.2.1. Environmental inventory

4.2.1.1. Foreground processes

The results of the environmental inventory for the recycling equipment are provided in Table 4.6. First, data regarding each machine's unit capacity and energy consumption were collected. Based on the mass flow of each step, the total energy consumption was calculated according to Equation 4.2. More detailed calculations are provided in Appendix B.

$$EC_{total,i}\,(kWh) = EC_{unit,i}\left(\frac{kWh}{t}\right) \times m_{input,i}\,(t) \tag{4.2}$$

Where:
-$EC_{Total,i}$: Total energy consumption of machine i;
-$EC_{unit,i}$: Unit energy consumption of machine i;
-$m_{input,i}$: Mass of the input material processed by machine i.

Subsequently, the operating duration T_i required in each step was determined based on the number of machines n and the unit productivity P_i as follows:

$$T_i\,(hr) = P_{unit,i}\left(\frac{t}{hr}\right) \times m_{input,i}\,(t) \times n \tag{4.3}$$

Where:
-T_i: Operating duration of machine i;
-$P_{unit,i}$: Average unit productivity of machine i;
-$m_{input,i}$: Mass of the input material processed by machine i; -n: Number of machine i.

4.2.1.2. Background processes

As illustrated in Table 4.7, most of the background processes in LCA were modelled with the Ecoinvent 3.4 database (Wernet et al., 2016). The database provides the required input and output flows[3]. The Ecoinvent 3.4 (Wernet et al., 2016) is linked with the OpenLCA 1.7.4. (2022) software providing the required information for the environmental impact assessment step (see Section 4.3.1). Data for the primary cement (CEM III/A) were obtained by the Nationale Milieudatabase (NMD, 2022). Regarding transports, it is noted that the return journey was also included in the calculations. As specified by Bepalingsmethode Milieuprestatie Bouwwerken 2022, the transported weight, in this case, must be taken 25% reduced (see Equation 4.4.

$$TW_i\,(tkm) = 1.75 \times m_i + d\,(km) \tag{4.4}$$

Where:
-TW_i: Transported weight of material i;
-m_i: Mass of transported material i;
-d: Transport distance. In this thesis was taken 50 km for all transports.

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[3] Flows in an LCA are elementary components extracted or realised directly to the environment (ISO 14044, 2006). For example, flows could be natural materials, energy or space needed to execute a process for the impact assessment step.

Table 4.6: Process data of the recycling equipment

Machine	**P$_{unit,i}$ [t/h]**	**EC$_{unit,i}$ [kWh/t]**	**Investment €/unit**	**Data source**
TC recycling plant				
Excavator[1]	350	0.06	€ 135,000.00	Coelho and de Brito (2013)
Vibrating feeder	350	0.05	€ 114,000.00	Coelho and de Brito (2013)
Magnet #1	350	0.02	€ 47,522.00	Coelho and de Brito (2013)
Vibrating screen #1	350	0.05	€ 82,325.00	Coelho and de Brito (2013)
Jaw crusher	238	0.10	€ 130,000.00	Coelho and de Brito (2013)
Magnet #2	350	0.02	€ 47,522.00	Coelho and de Brito (2013)
Vibrating screen #2	350	0.05	€ 82,325.00	Coelho and de Brito (2013)
Impact crusher	250	2.50	€ 790,000.00	Rutte Groep (2022)
Air sifters	100	0.02	€ 100,000.00	Coelho and de Brito (2013)
Eddy current	350	0.05	€ 98,114.00	Coelho and de Brito (2013)
Vibrating screen #3	350	0.05	€ 82,325.00	Coelho and de Brito (2013)
Conveyor belts	350	0.03	€ 68,833.00	Coelho and de Brito (2013)
C2CA recycling plant				
Excavator[1]	250	0.06	€ 135,000.00	Coelho and de Brito (2013)
Jaw crusher	238	0.10	€ 130,000.00	Coelho and de Brito (2013)
Impact crusher	250	2.50	€ 790,000.00	Rutte Groep (2022)
Horizontal screen	350	0.05	€ 82,325.00	Coelho and de Brito (2013)
ADR	50	0.46	€ 1,674,600.00	Zhang et al. (2019)
HAS[1]	3	0.01	€ 294,600.00	Zhang et al. (2019)
Conveyor belts	350	0.03	€ 68,833.00	Coelho and de Brito (2013)
SC recycling plant				
Excavator[1]	250	0.06	€ 135,000.00	Coelho and de Brito (2013)
Impact crusher	250	2.50	€ 790,000.00	Rutte Groep (2022)
Sieve tower[2]	125	0.30	€ 763,000.00	Rutte Groep (2022)
Air separator	90	0.30	€ 838,000.00	Rutte Groep (2022)
SmartLiberator	50	0.10	€ 990,000.00	Rutte Groep (2022)
Horizontal screen	80	0.15	€ 560,000.00	Rutte Groep (2022)
Smartrefiner	40	0.55	€ 500,000.00	Rutte Groep (2022)
Conveyor belts[3]	125	0.20	€ 1,725,000.00	Rutte Groep (2022)

[1] Powered by diesel (Lt/t)

[2] Includes a combined system of multi-deck screens.

[3] Includes all conveyor belts and magnetic separators of the SC recycling plant.

4.2.2. Economic inventory

4.2.2.1. Foreground processes

Each machine's energy, maintenance, insurance, and personnel costs synthesised the economic inventory for the foreground processes. The total energy cost was calculated by multiplying the total energy consumption (see Table 4.6) of each machine by the electricity price (see Table 4.8). Furthermore, the total maintenance cost of the machines was determined based on the following equation:

$$C_{M,total}\,(€) = T_i\,(hr) \times C_{M,annual,i}\left(\frac{€}{year}\right) \times n \tag{4.5}$$

Where:

-$C_{M,total,i}$: The total maintenance cost of machine i for a specific operating duration T_i;

Table 4.7: Environmental impact data for the background processes from Ecoinvent 3.4 and NMD (2022) databases.

Product	**Data source**
River gravel	Ecoinvent 3.4
River sand	Ecoinvent 3.4
CEM III/A	NMD (2022)
Electricity	Ecoinvent 3.4
Diesel	Ecoinvent 3.4
Transport	Ecoinvent 3.4

-$C_{M,annual,i}$: Annual maintenance cost of machine$i$. The calculation of annual working hours was made based on 8 hours working hours and 250 working days per year
-n: Number of machines.

For simplicity, the insurance cost of the recycling equipment was taken as 1% of the initial investment (Rutte Groep, 2022). Finally the personnel cost of each recycling plant was determined as follows:

$$C_{I,total}\ (€) = T_i\ (hr) \times 1\% \times investment_i \left(\frac{€}{year}\right) \times n \tag{4.6}$$

$$C_{P,total}\ (€) = T_i\ (hr) \times C_{P,annual} \left(\frac{€}{year}\right) \times n \tag{4.7}$$

Where:
-$C_{I,total,i}$: The total insurance cost of machine i for a specific operating duration T_i;
-$C_{P,total,i}$: Personnel cost of machine i for a specific operating duration T_i;
-$C_{P,annual,i}$: Annual average wage for construction workers for machine i. The calculation of annual working hours was made based on 8 hours working hours and 250 working days per year
-n: Number of machines.

4.2.2.2. Background processes

The unit prices for the background processes are demonstrated in Table 4.8. It is noted that the cost of the background processes depends strongly on the time-frame of the analysis (more information are provided in Section 4.7).

Table 4.8: Economic inventory for material supply cost C_I

Product	**Unit price**	**Data source**
Primary materials		
Primary gravel (4-32 mm)	21.3 €/t	Rutte Groep
Primary sand (1-4 mm)	15.5 €/t	Rutte Groep
CEM III	95 €/t	Rutte Groep
Utilities		
Electricity price	0.124 €/kWh	CBS-Statistics Netherlands (2022)
Diesel price	1.53 €/L	Fuelo (2022)
Average wage	22 €/man-hr	Salary Expert (2022)
Transport cost[1]	0.11 €/tkm	Zhang et al. (2019)

[1] The price was normalised based on the change in the diesel prices from 2019 until 2021.

4.3. Impact assessment

4.3.1. Environmental impact assessment

In this step, the environmental impacts of the input and output flaws were analysed using the OpenLCA 1.7.4. (2022) software. The software contains the characterisation factors of the *CML Baseline* method (Guinee et al., 2002), which enable allocation of the different flows into the impact categories. The 11 impact categories considered defined in the *CMLBaseline* method are illustrated in Table 4.9. These categories comply with the NEN-EN 15804+A1 (2013) requirements. In the updated version NEN-EN 15804+A2 (2019), the number of impact categories is expanded from 11 to 19. Nevertheless, it was decided to follow the NEN-EN 15804+A1 (2013) since the updated version does not support yet monetization[4] of environmental impacts (see Section 4.3.1.1).

Therefore, the environmental impact of the impact category j was calculated for the supply chain phases (primary materials supply, recycling and transports) according to the following equation:

$$LCA_j\ (equivalent\ unit) = LCA_{P,j} + LCA_{S,j} + LCA_{T,j} \tag{4.8}$$

Where:
- $LCA_{P,j}$: Environmental impact of primary materials production activities (in equivalent units of impact category j);
- $LCA_{S,j}$: Environmental impact of the recycling process(in equivalent units of impact category j);
- $LCA_{T,j}$: Environmental impact of transports (in equivalent units of impact category j).

4.3.1.1. Monetization

The results of an LCA are typically expressed in different units (equivalent units) for each impact category. In this form, it is impossible to make a straightforward comparison of the results nor to obtain insight regarding the magnitude of the impacts. This study overcame this issue by converting the environmental impacts into monetary values. The conversion was realised with the environmental cost indicators (ECI) provided in Table 4.9. These indicators were obtained from the Dutch regulations Bepalingsmethode Milieuprestatie Bouwwerken 2022. This way, the environmental impacts could be compared and summed up based on a unified value. On top of that, monetised environmental impacts (shadow costs) can be communicated easier to businesses which might not have the appropriate specialities to evaluate the results. Hence, the total environmental costs (shadow cost) of each scenario LCA_i were calculated according to Equation 4.9.

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[4] Environmental cost indicators (ECI) are only available for the 11 midpoints included in the *CML Baseline* method.

Table 4.9: Impact categories and ECI values of *CML Baseline* method

Impact category	Abbreviation	Reference unit	ECI [2]
Abiotic depletion	ADP-minerals	kg Sb eq	€ 0.16
Abiotic depletion (fossil fuels)[1]	ADP-fossil	kg Sb eq	€ 0.16
Acidification	AP	kg SO2 eq	€ 4
Eutrophication	EP	kg PO4 eq	€ 9
Fresh water aquatic ecotoxicity	FAETP	kg 1,4-DB eq	€ 0.09
Global warming	GWP100	kg CO2 eq	€ 0.05
Human toxicity	HTP	kg 1,4-DB eq	€ 0.09
Marine aquatic ecotoxicity	MAETP	kg 1,4-DB eq	€ 0.0001
Ozone layer depletion	ODP	kg CFC-11 eq	€ 30
Photochemical oxidation	POCP	kg C2H4 eq	€ 2
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq	€ 0.06

[1] It is noted the software uses MJ as reference unit for the "ADP-fossil" impact category, while the the respective shadow cost is expresses in Sb-equivalent units. According to Guinee et al. (2002), the following unit conversion can be used: 1 Sb-equivalent = 4.81E-4 MJ.

[2] From Bepalingsmethode Milieuprestatie Bouwwerken 2022

$$LCA_i\ (€) = \sum LCA_j \times ECI_j \tag{4.9}$$

Where:
- LCA_j: Environmental impact (in reference units) of midpoint j;
- ECI_j: Environmental cost indicator of midpoint j expressed in euros/reference unit.

It is pointed out that the monetization step is optional according to ISO 14044 (2006). However, it was included in this LCA to allow integration with the LCC results by considering the shadow costs as external costs in the LCC study. As discussed in Section 2.4.1.2, the shadow cost of a product can be internalized in the sales price, eventually bringing the product to a sustainable level ($polluter - pays - approach$).

4.3.2. Economic impact assessment

The economic impact represents the total internal cost throughout the supply chain phases as shown in Equation4.10.

$$LCC_i\ (€) = C_{P,i} + C_{R,i} + C_{T,i} \tag{4.10}$$

Where:
- C_P: Purchase cost of primary materials in scenario i (in euros);
- C_R: Recycling cost in scenario i (in euros);
- C_T: Transport cost in scenario i (in euros).

4.3.3. Integrated LCA/LCC

Finally, the total performance of each scenario was determined based on the integrated shadow and internal costs. Thus, the resulting social cost was calculated by the following expression. In practice, the social cost in this study represents the total cost of producing recycled concrete if environmental aspects are included. Eventually, this cost is transferred to the consumer.

$$Social\ cost\ (€) = LCC_i + LCA_i \tag{4.11}$$

4.4. Results

This section presents the results of the LCA and LCC analyses individually for each phase of the supply chain of recycled concrete. The performance of the five scenarios is evaluated based on their shadow (environmental), internal and social cost per m^3 of concrete. Additional information for background calculations can be found in Appendix B and C.

4.4.1. Primary materials

The shadow costs for producing the primary materials required for each scenario are shown in Figure 4.2 (top). It can be observed that for all scenarios, cement was by far the most contributing material. In the case of TC, C2CA1 and SC1 scenarios where the cement was used at the full amount (i.e. 340 kg), the total shadow cost was 10.79 €/m^3 of concrete. By replacing 20% of cement with RCP in C2CA2 and SC2, the impact was reduced proportionally to 8.6 €/m^3. The impacts of primary gravel and sand were negligible for all scenarios. In the TC scenario for instance, the shadow cost for using 50% primary gravel (500 kg) and 100% sand (815 kg) was found 0.6 €/m^3 and 1 €/m^3 respectively. Furthermore, as can be observed in Appendix C, it can also be observed that the global warming potential (GWP) is the most critical impact category in this phase.

From a financial point of view, cement was also the material with the highest contribution. The LCC results shown in bottom Figure 4.2, indicate that the purchase cost of cement was more than double that of primary gravel and sand. As expected, from all scenarios, the TC displayed the highest internal cost in this phase (55.6 €/m^3). In the C2CA2 and SC2 scenarios, the respective cost was 25.85 €/m^3.

4.4.2. Recycling

Regarding the recycling phase, the C2CA technology had the highest environmental impact (see top Figure 4.3). In particular, the shadow costs of the C2CA1 and C2CA2 for this phase were accounted for 2.1 €/m^3 and 3.3 €/m^3, respectively. On the other hand, these values for SC1 and SC2 scenarios were considerably lower (0.58 €/m^3 and 0.64 €/m^3). Even lower impact (0.09 €/m^3) was reported in the TC scenario. Furthermore, the GWP is a critical category also for the recycling phase of all scenarios (see Appendix C).

The deviation of the C2CA and SC results was less for the LCC analysis (see bottom Figure 4.3). More specifically, the internal costs of the C2CA1, SC1 and SC2 scenarios were found on the same scale ranging from 9.15 €/m^3 (SC1) until 11.50 €/m^3 (C2CA1). In contrast, the C2CA2 scenario with the highest recycling cost reached 16.10 €/m^3. The TC recycling presented a minimum cost of 0.09 €/m^3 compared to the previous scenarios.

4.4.3. Transport

As illustrated in the top Figure 4.4, the highest environmental impact in the transportation phase was realised in the C2CA2 scenario (4.92 €/m^3) and the lowest in the TC scenario (3.48 €/m^3). Apart from the GWP category, a significant impact was noted in the HTP (Human toxicity potential) and MAETP (Marine aquatic ecotoxicity potential) categories. All scenarios' transport costs followed similar trends with their environmental impacts (see bottom Figure 4.4). A maximum internal cost of 38.4 €/m^3 was calculated for the C2CA2 scenario, and a minimum cost of 27.22 €/m^3 for the traditional method (TC).

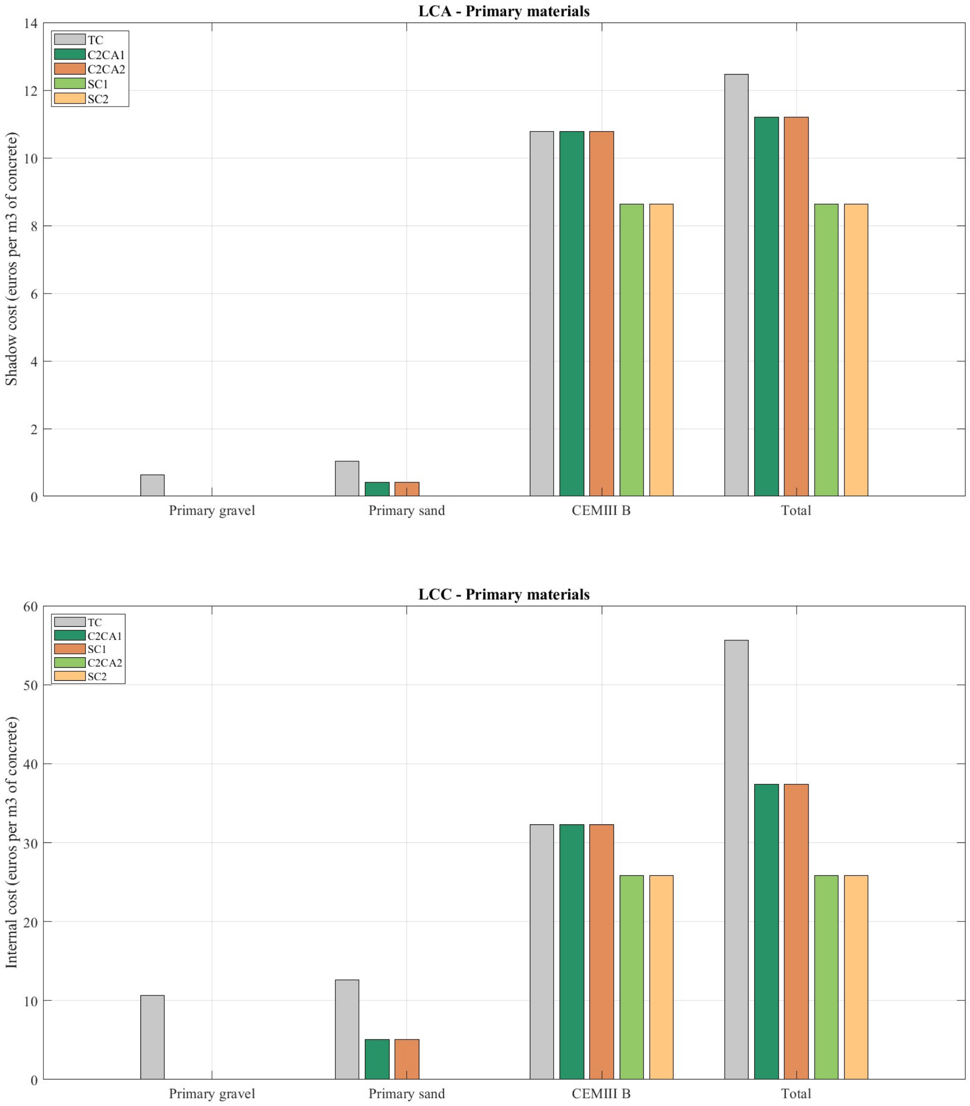

Figure 4.2: Shadow cost (top) and internal cost (bottom) of the production of primary materials required in each scenario.

4.5. Total impacts

The top Figure 4.5 illustrates the constitutive shadow costs of the three phases. From all scenarios, the SC2 presented the lowest overall environmental impact (13.36 €/m^3). The C2CA technology displayed the worst environmental performance for the same requirements as SC2, reaching a total shadow cost of around 16 €/m^3. Similar impacts with the latter scenario were also reported in the TC, C2CA1 and SC1 scenarios. In all scenarios, the most impact was caused due to the production of primary materials. The environmental impact of recycling was the lowest among the three phases, apart from the C2CA scenarios, where it was comparable with the environmental impact of transport.

From the middle Figure 4.5, it can be observed that the TC scenario had the highest total internal cost (83.72 €/m^3). A slightly lower cost of about 3-4 €/m^3 was noted in the SC1 and C2CA2 scenarios. In addition, a cost-benefit of 6.60 €/m^3 was achieved when using the C2CA1 scenario. In the case of the SC2 scenario, though, this benefit reached almost 16 €/m^3. From the LCC results, it can also be seen that the influence of the primary materials decreased when using the innovative systems. In the C2CA1 and SC1 scenarios, the purchase cost of primary materials was similar to the transport costs. Transports were the

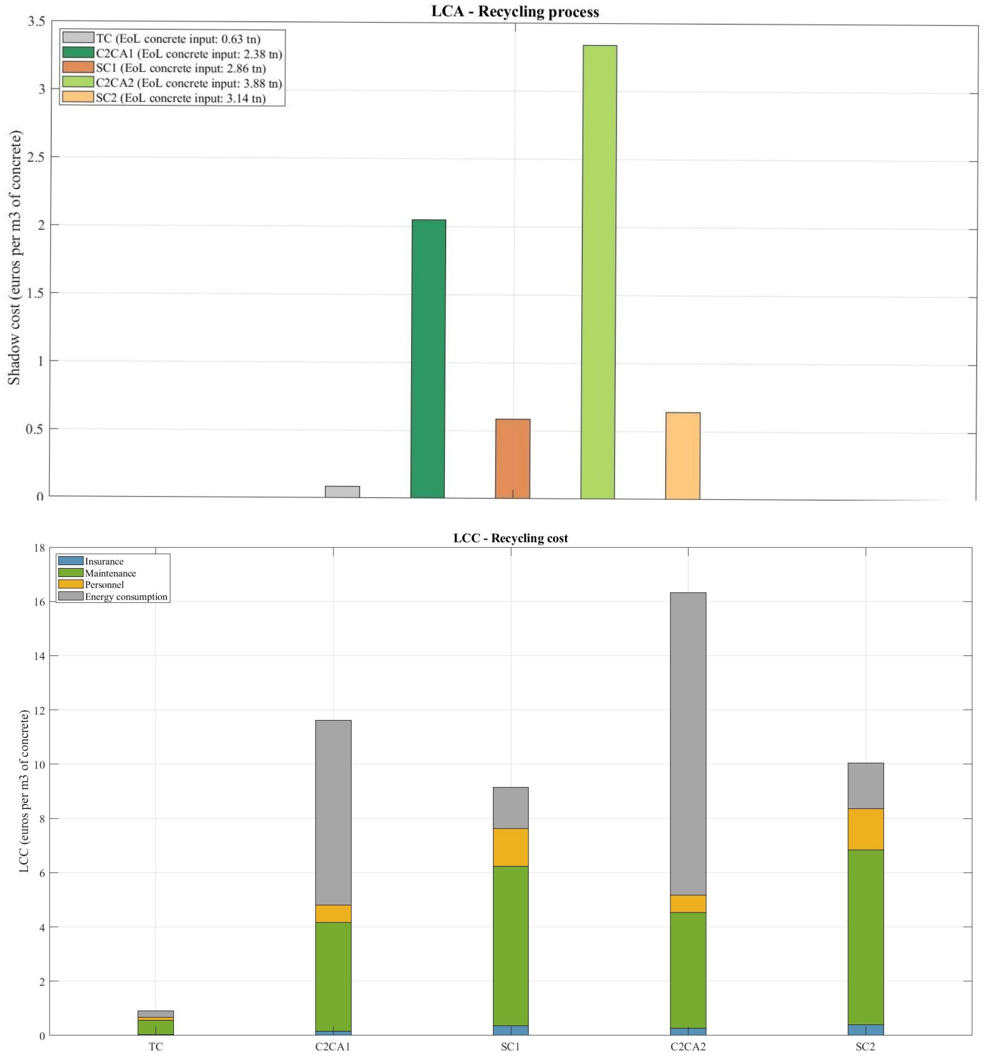

Figure 4.3: Shadow cost (top) and internal cost (bottom) of the recycling phase

main contributor to the total cost of the C2CA and SC2 scenarios. The cost of the recycling process of the TC scenario was negligible compared to the innovative systems.

Finally, when internalising the shadow costs in each scenario's actual cost, the best overall performance was achieved in the SC2 scenario (see bottom Figure 4.5) with 81.15 €/m^3. On the contrary, the traditional method was the worst-case scenario when considering its social cost, reaching almost 100 €/m^3. About 6.8 €/m^3 social cost improvement was realised in the C2CA1 scenario. The improvement of the C2C2 and SC1 scenarios was even smaller (3-4 €/m^3).

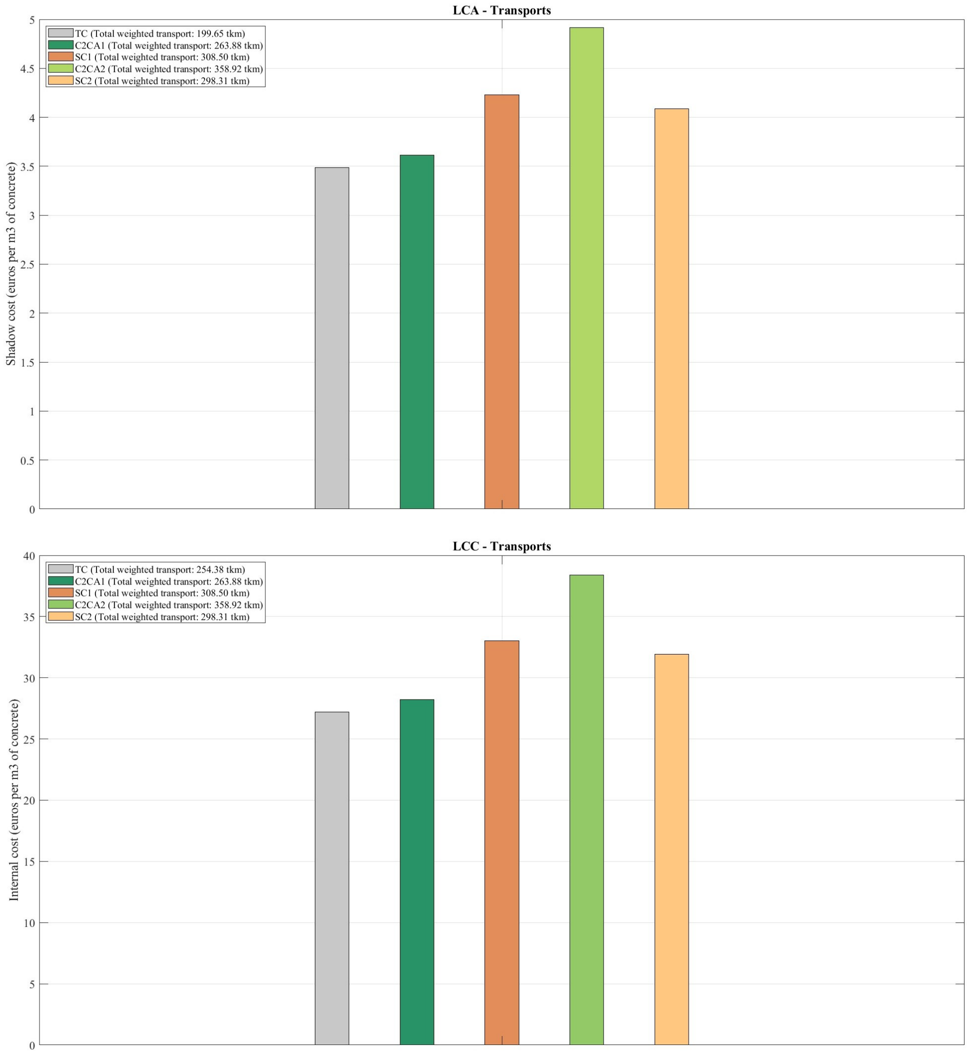

Figure 4.4: Shadow cost (top) and internal cost (bottom) of transports.

4.6. Interpretation of the results

4.6.1. Relative impact assessment

This thesis's relative impact assessment aims for a straightforward comparison between the traditional and the innovative recycling systems. Hence the LCA and LCC results of the innovative systems were expressed in relation to the traditional method as follows:

$$LCA_{relative,i}\,(\%) = \frac{LCA_{innovative,i} - LCA_{traditional}}{LCA_{traditional}} \times 100\%$$

$$LCC_{relative,i}\,(\%) = \frac{LCC_{innovative,i} - LCC_{traditional}}{LCC_{traditional}} \times 100\%$$

Where:
-i: Denotes C2CA or SC scenarios;
-$LCA_{innovative}$: The total environmental cost scenario i ;

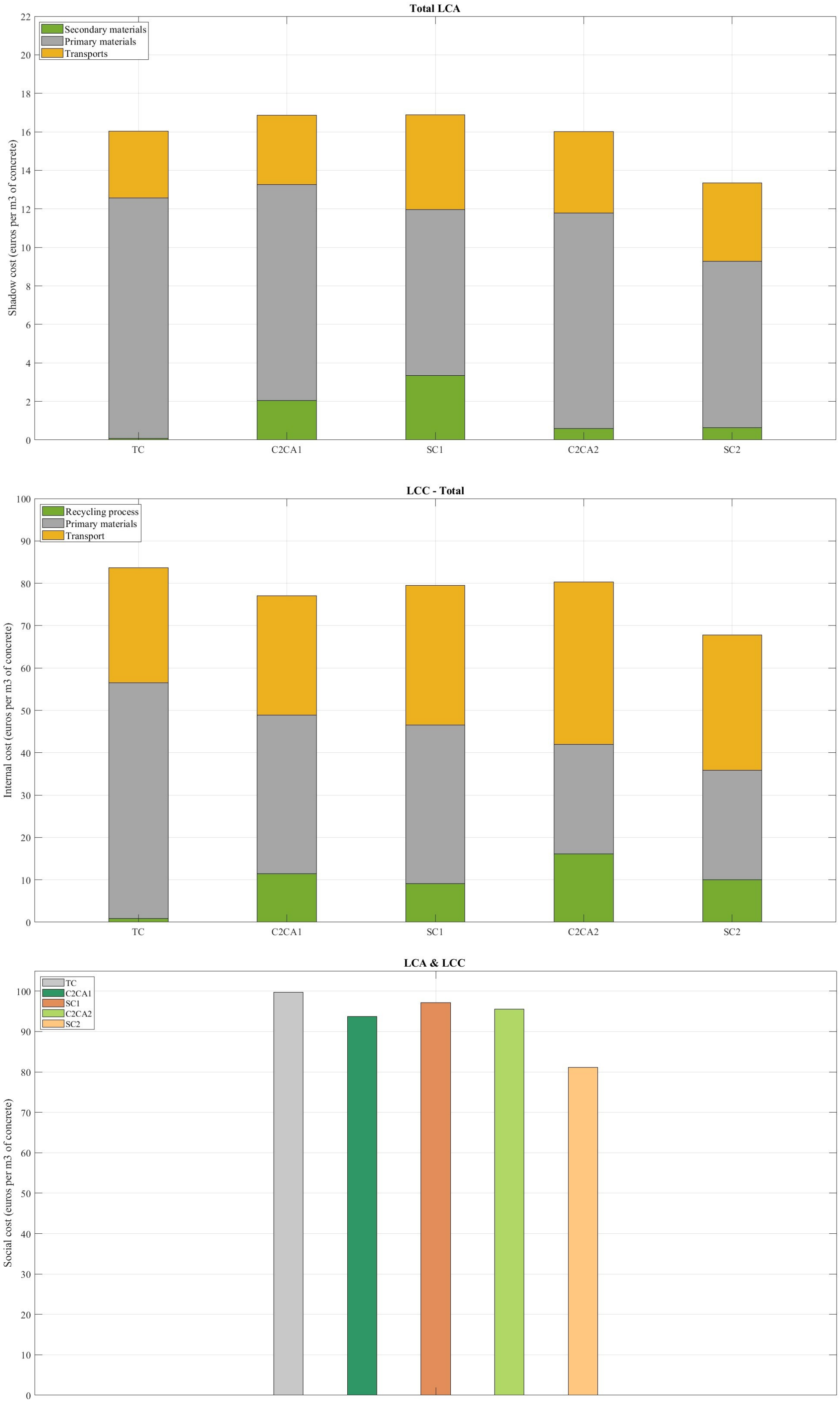

Figure 4.5: Total shadow costs (top), internal costs (middle) and social costs (bottom) of each scenario

-$LCA_{traditional}$: The total environmental cost of TC;

-$LCC_{innovative}$: The total internal cost of scenario i ;
-$LCC_{traditional}$: The total internal cost of TC;

The relative impacts were plotted in the 2-D diagram (see Figure 4.6), where the vertical and horizontal axes represent the environmental and economical relative impacts, respectively. The results reveal that compared to the traditional method, the innovative recycling system brings financial benefits in any of the defined scenarios. The best performance was reported in the SC2 scenario, where the total internal cost was reduced by up to 19%. When considering the C2CA1 scenario, the cost-benefits were calculated for 8%, while those of the C2CA2 and SC2 were no higher than 5%. However, from an environmental point of view, improvement was only realised in the SC2 scenario (-17%). On the contrary, the shadow cost in both scenarios of the C2CA technology was about 5% increased, whereas that of the SC1 scenario was comparable with the traditional recycling method.

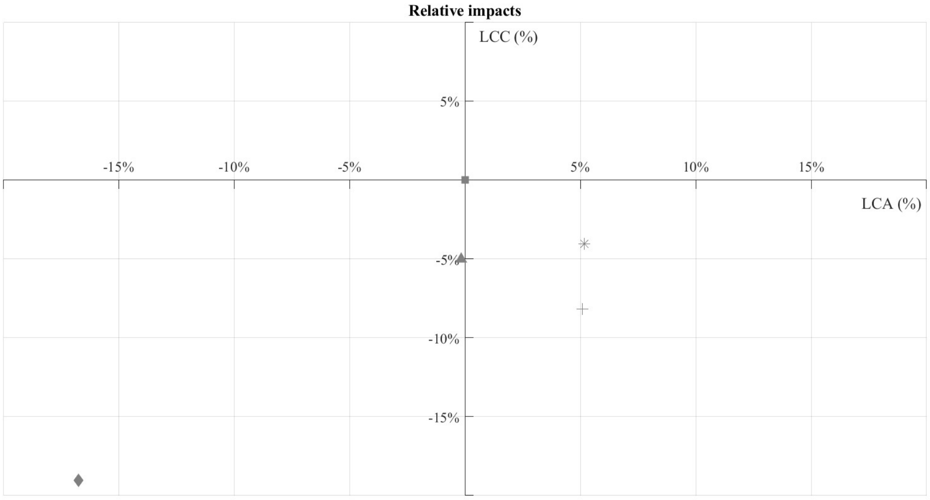

Figure 4.6: Relative environmental and economic impacts

4.6.1.1. Unit impacts

The above results provide information only to concrete manufacturers. In the case of evaluating the results from the recycling contractor's perspective, the unit shadow and internal costs should be considered. For this reason, the LCA and LCC results of this phase were determined for an input volume of 1 ton of EoL concrete for all scenarios. For the innovative recycling systems, the unit impacts were calculated based on the C2CA1 and SC1 results only[5].

Table 4.10: Unit environmental and economic impacts of the recycling process

Recycling plant	TC	C2CA	SC
Input [tn]	0.63	2.38	2.86
Total LCA [€]	0.09	2.05	0.58
Total LCC [€]	0.90	11.49	9.15
Unit LCA [€/tn]	**0.14**	**0.86**	**0.20**
Unit LCC [€/tn]	**1.44**	**4.14**	**3.20**

Based on Table 4.10, it can be concluded that for recycling the same amount of EoL concrete, the C2CA

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[5] The unit impacts when considering the C2CA2 and SC2 scenarios would reach the same result

systems have the highest impact. The unit environmental and economic impacts in this case were 0.86 €/tn and 4.14 €/tn respectively. The lowest impact during the recycling process was reported in the traditional method with a unit shadow cost of 0.14 €/tn and 1.44 €/tn unit internal cost. Furthermore, although the unit environmental impact of the SC recycling system (0.20 €/tn) is not considerably higher than that of the TC method, its unit internal cost is more than double (3.20 €/tn).

4.6.2. Contribution analysis of the recycling equipment

This section provides information regarding the contribution of the recycling equipment to the performance of each recycling plant. The contribution was determined as a percentage of the total shadow and internal cost of the recycling phase.

4.6.2.1. TC recycling

The contribution of the TC recycling equipment is shown in Figure 4.7. The critical machine in this system was the impact crusher. Due to its relatively high energy consumption and maintenance cost, it is responsible for about 68% and 77% of the whole plant's total environmental and economic impact. The hydraulic excavator also plays an important role, especially from an environmental point of view. Around 20% of the total shadow cost was due to the operation of this machine, while the rest machines together contributed to only 12%. The higher impact of the hydraulic excavator is mainly due to diesel consumption.

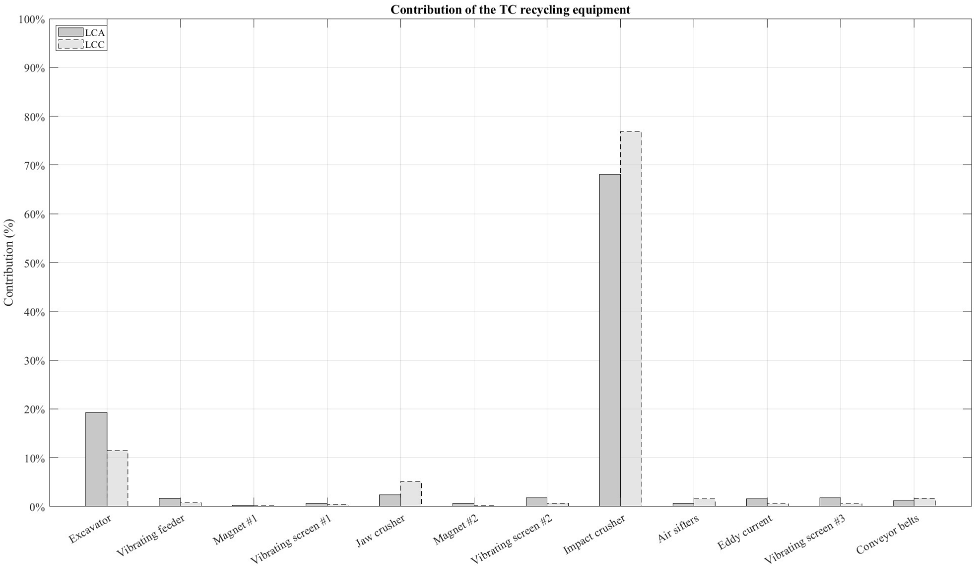

Figure 4.7: Contribution of the TC recycling equipment

4.6.2.2. C2CA recycling

Regarding C2CA technology, the HAS system is the critical machine. Around 80% of the total environmental impact of the recycling process emerged from this machine. The high energy consumption and, thus, the high environmental impact of the HAS system is realised when compared with the hydraulic excavator, which also consumes diesel. In addition, the HAS system was responsible for about 53% of the total internal cost of the recycling process, primarily due to energy consumption. It is worth noting that the exact impact crusher with the TC system contributed to the C2CA plant by less than 20%. Finally, even though the ADR system had a minimum environmental impact (2%), it exhibited relatively high operating costs (22%) due to maintenance.

4.6.2.3. SC recycling

From an environmental point of view, the impact crusher was the most contributing machine taking up about 60% of the total shadow cost. The rest of the machines did not exceed 10% apart from the hydraulic excavator (13%). When focusing on the financial aspects, the impact crusher is equally expensive as the

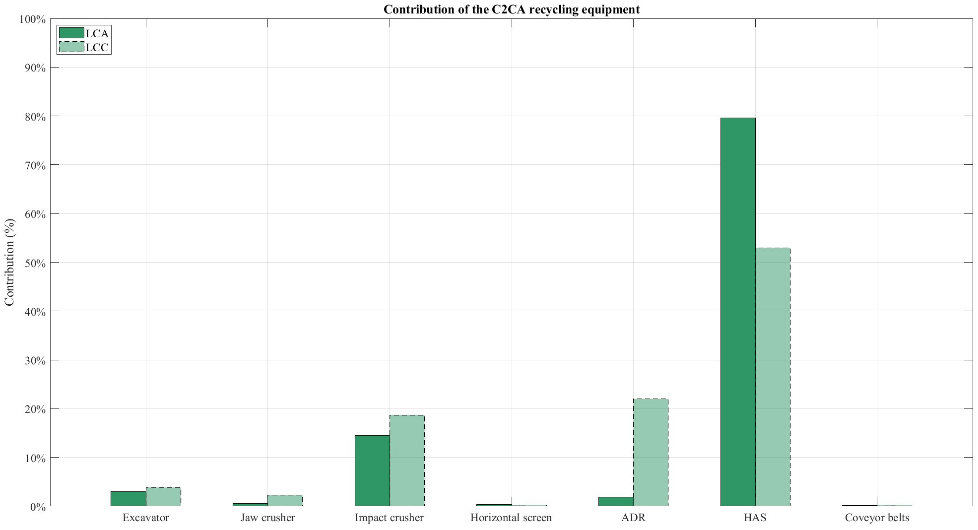

Figure 4.8: Contribution of the C2CA recycling equipment

SmartLiberator. Their contribution was about 29% and 26% respectively. The air separator is also of interest from a financial perspective (17%). The high cost of the machines above occurs primarily due to maintenance.

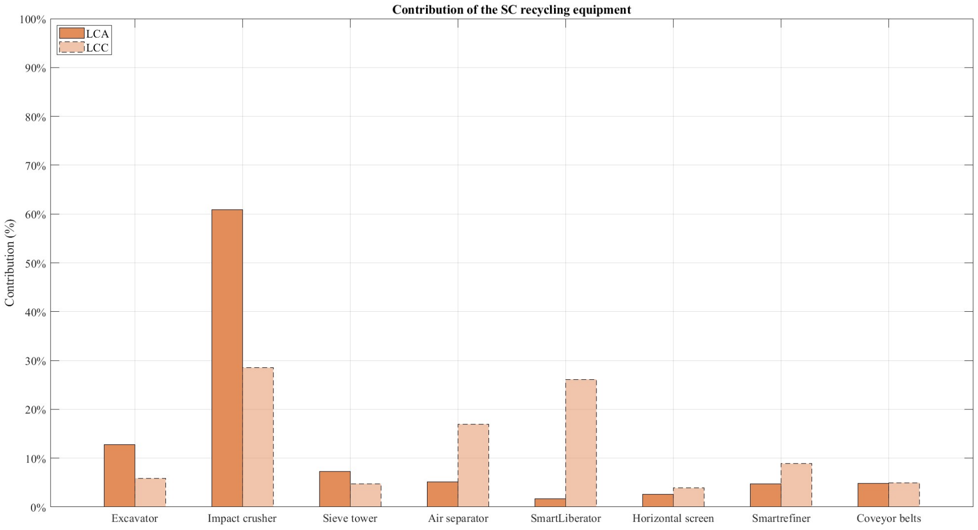

Figure 4.9: Contribution of the SC recycling equipment

4.6.3. Sensitivity analysis

The present sensitivity analysis focuses on the most critical factors of the supply chain of recycled concrete (see Table 4.11). These factors mainly concern process and financial data relevant to the recycling equipment. In addition, the sensitivity of certain decisions made during this study, such as transport distances and cement replacement ratio, was also investigated. The sensitiveness was measured by increasing one factor at a time by 20%[6] (see Figure 4.10).

Table 4.11: Sensitivity analysis critical factors

Data type	Factor	Note
Unit process data	f1	Energy consumption of Impact crusher
	f2	Energy consumption of ADR
	f3	Energy consumption of HAS
	f4	Energy consumption of SmartLiberators
	f5	Energy consumption of Smartrefiners
Cost data	f6	Maintenance cost of Impact crusher
	f7	Maintenance cost of ADR
	f8	Maintenance cost of HAS
	f9	Maintenance cost of SmartLiberators
	f10	Maintenance cost of Smartrefiners.
	f11	Diesel price
	f12	Electricity price
	f13	Primary materials price
Global data	f14	Transport distance
	f15	Cement replacement %
	f16	Renewable energy
	f17	Off-site recycling

It can be observed that the diesel price (f11) had a significant influence on the LCC results. Especially in the C2CA2 scenario, an increase of 20% resulted in an internal cost growth of about 12%. On the other hand, the sensitivity of the TC scenario in diesel was about half (5.5%). However, the diesel price did not influence only the energy cost of the recycling equipment (i.e. HAS and excavator) but also the cost of transportation. At this point, it was assumed that the transportation cost changed proportionally (by the same rate) with the diesel price. Furthermore, the purchase price of primary materials (f13) was also a sensitive parameter for all scenarios, especially for the TC (13.3%). It is worth mentioning that the sensitivity of the LCA results due to 20% increase of the cement replacement rate (from 20% to 24%) was about 2.5% and 3% for the C2CA2 and SC2 scenarios.

Moreover, the energy consumption rates of the recycling equipment did not significantly influence the results except for the HAS system (f3). Particularly in the C2CA2 scenario, a change of 20% of the HAS diesel consumption affected the total LCA and LCC results by 3.6% and 2.3%, respectively. The sensitivity of other machines did not exceed 1%. Nevertheless, since the recycling plants considered in this thesis are primarily powered by electricity, it is still interesting to examine the possibility of the transition to renewable energy sources (f18). In this situation, the environmental footprint was reduced by up to 4.8% for the SC2 scenario, while financial savings of around 2.5% were achieved.

Another critical factor was the transport distances (f16). By increasing all distances from 50 km to 60 km (20% rise), the total environmental impact of all scenarios grew within a range of 4.4% (TC) and 7.4% (SC2). Under this change, the LCC results were affected by 5.5% and 9.4%, respectively. Beyond that, as an additional scenario, it was also investigated the possibility of off-site recycling (f19). In this hypothetical scenario, the EoL concrete of each scenario must be transported to the recycling plants. The distance between the

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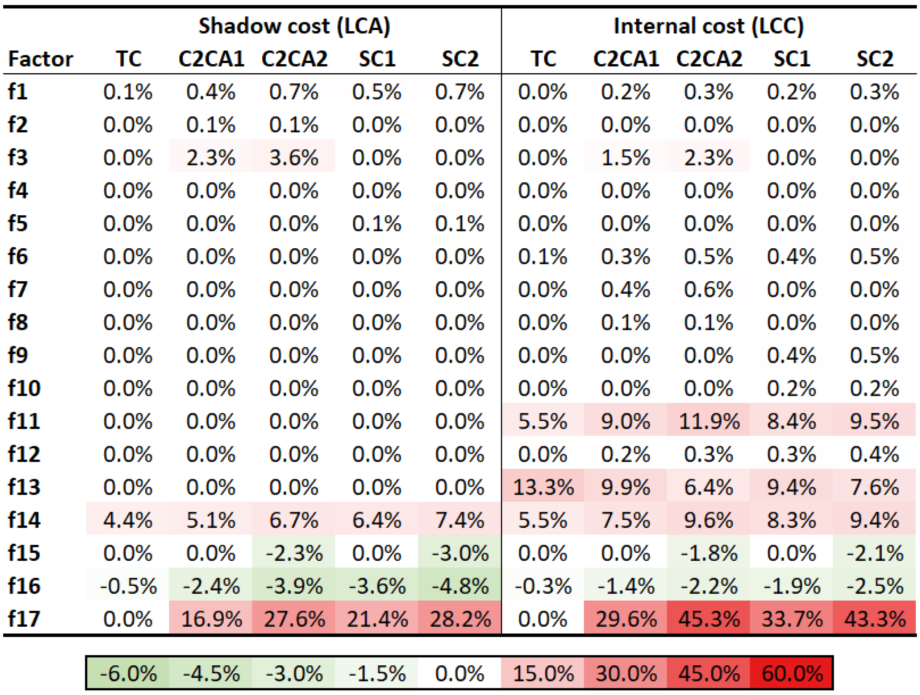
[6] The choice of the particular increase rate was random; however, it must be the same for all factors for comparative purposes.



	Shadow cost (LCA)					Internal cost (LCC)				
Factor	TC	C2CA1	C2CA2	SC1	SC2	TC	C2CA1	C2CA2	SC1	SC2
f1	0.1%	0.4%	0.7%	0.5%	0.7%	0.0%	0.2%	0.3%	0.2%	0.3%
f2	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
f3	0.0%	2.3%	3.6%	0.0%	0.0%	0.0%	1.5%	2.3%	0.0%	0.0%
f4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
f5	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
f6	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%	0.4%	0.5%
f7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.6%	0.0%	0.0%
f8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
f9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.5%
f10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%
f11	0.0%	0.0%	0.0%	0.0%	0.0%	5.5%	9.0%	11.9%	8.4%	9.5%
f12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.3%	0.3%	0.4%
f13	0.0%	0.0%	0.0%	0.0%	0.0%	13.3%	9.9%	6.4%	9.4%	7.6%
f14	4.4%	5.1%	6.7%	6.4%	7.4%	5.5%	7.5%	9.6%	8.3%	9.4%
f15	0.0%	0.0%	-2.3%	0.0%	-3.0%	0.0%	0.0%	-1.8%	0.0%	-2.1%
f16	-0.5%	-2.4%	-3.9%	-3.6%	-4.8%	-0.3%	-1.4%	-2.2%	-1.9%	-2.5%
f17	0.0%	16.9%	27.6%	21.4%	28.2%	0.0%	29.6%	45.3%	33.7%	43.3%

-6.0%	-4.5%	-3.0%	-1.5%	0.0%	15.0%	30.0%	45.0%	60.0%

Figure 4.10: Results of sensitivity analysis

demolition site and the recycling plants was also 50 km. This change greatly affected the innovative recycling systems, which were initially assumed as mobile units. Specifically, the total environmental impact of the C2CA2 and SC2 scenarios increased by up to 28%, while the influence on the total internal cost reached 45%.

4.6.3.1. Location investigation

Given the high impact of transports, this section investigates further the social costs of each scenario for different locations of the recycling plants and the quarries. The aim is to specify the maximum distances until which each scenario maintain its benefits.

TC plant: Variable (0 - 50 km)
Innovative plants: On-site (0 km)

The initial results of this thesis were based on the assumption that the innovative recycling plants were operating on-site (0 km from the demolition site), while the TC plant was placed off-site at a distance of 50 km from the demolition site. However, the TC plant can be potentially placed at a closer distance in reality. Therefore, in this hypothetical scenario, different locations of the TC plant were tested (0 - 50 km) while keeping the innovative plants on-site.

As shown in Figure 4.11, the TC recycling becomes already inefficient for relatively short transport distances. More specifically, the C2CA1 and SC1 scenarios bring benefits in the supply chain for TC recycling plant locations locations of about 6 km and 18 km away from the demolition site respectively. In the case of the C2CA2 scenario, the TC plant must be placed at minimum 30 km away in order to have better performance, while the SC2 scenario, is always a better option no matter the location of the TC plant.

TC plant: Variable (0 - 50 km)
Innovative plants: Variable (0 - 50 km)

In addition, the option of on-site recycling with the innovative systems may not be always possible. Therefore, different locations (0 - 50 km) of all recycling plants were also examined to take this possibility into account. In this case, only the SC2 scenario presents benefits over the traditional method for locations of up to 23 km away from the demolition site (see Figure 4.12). On the contrary, the rest scenarios, demonstrated an

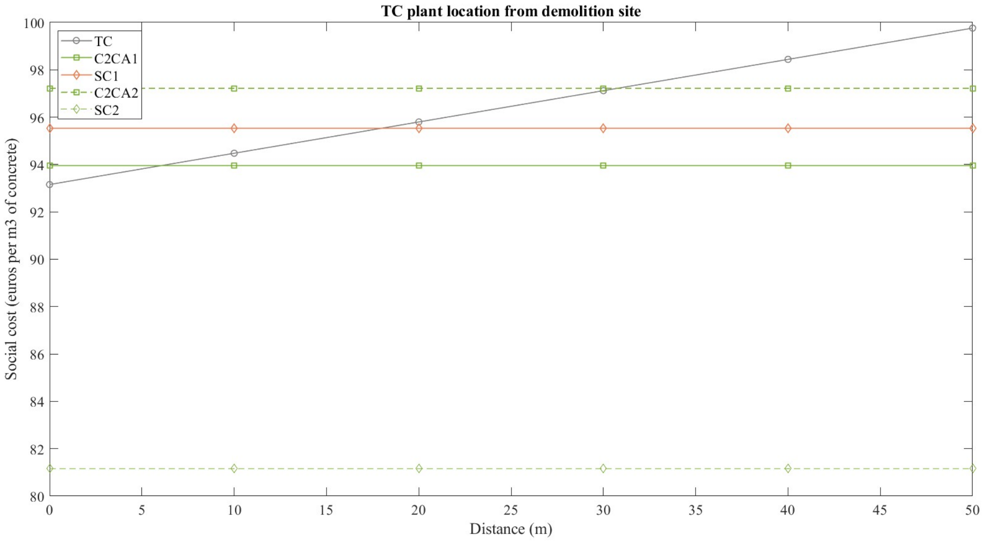


Figure 4.11: Social costs for on-site innovative recycling plants (0 km) and variable locations of the TC recycling plant (0 - 50 km)

increasing social cost which is always higher than the TC scenario as moving away from the demolition site. Therefore, under this conditions, the SC2 scenario is the only efficient option.

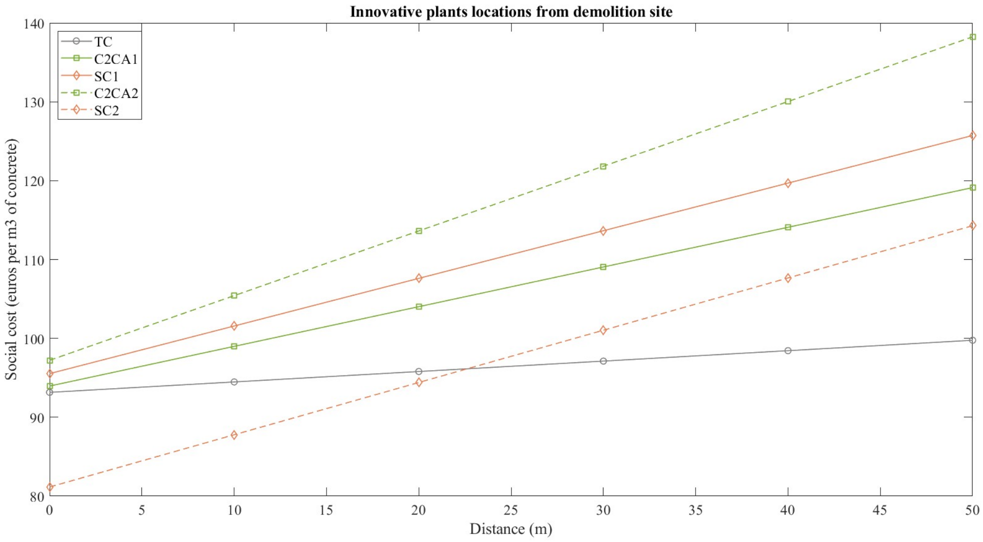


Figure 4.12: Social costs for variable locations of the innovative and TC recycling plants (0 - 50 km)

TC plant: Off-site (50 km)
Innovative plants: Variable (0 - 50 km)

The social costs were also measured for variable locations of the innovative recycling plants and fixed TC plant at 50 km from the demolition site. In this situation, the innovative systems present lower social costs compared to the traditional method only for short distances (close to the demolition site). In the best case, the SC2 scenario maintained its benefits for a distance of up to 27 km (see Figure 4.13). For the rest scenarios, the maximum distance until the innovative systems were still effective ranged between 4 - 11 km. All scenarios demonstrate lower performance at 50 km.

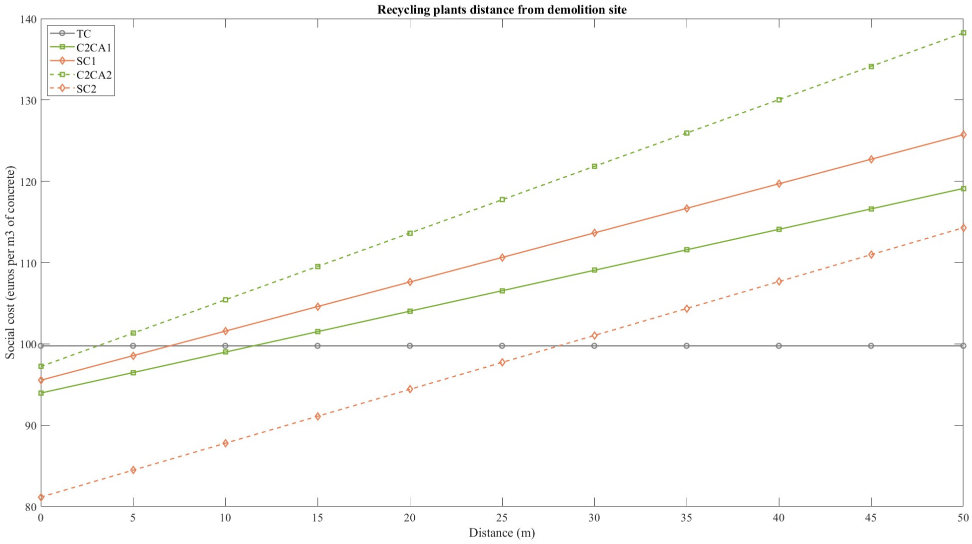


Figure 4.13: Social costs for off-site TC recycling (50 km) and variable innovative recycling plants (0 - 50 km)

TC plant: Off-site (50 km)
Innovative plants: On-site (0 km)
Quarries: Variable (50 - 100 km)

On the other hand, the TC scenario is affected the most when the distance between the quarries and the mixing plant increases (see bottom Figure 4.14). This is due to the higher volume of primary materials that must be transported.

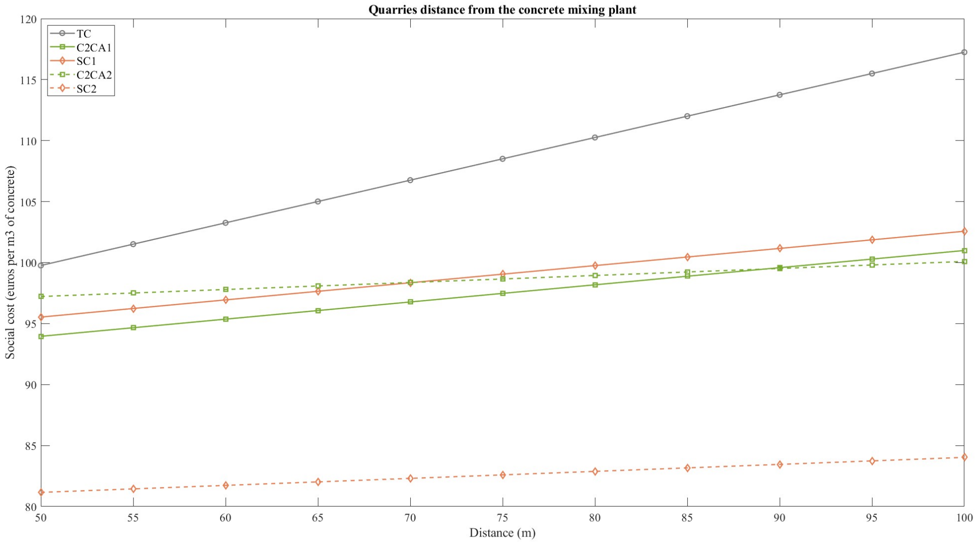


Figure 4.14: Social costs for off-site TC recycling (50 km), on-site innovative recycling plants (0 km) and variable locations of the quarries (50 - 100 km)

4.7. Discussion

In this section, the LCA and LCC results are discussed for each phase of the supply chain of recycled concrete.

Supply of primary materials

As expected, the TC scenario had the highest environmental impact in this phase since it involved the highest amounts of primary materials. Cement was the most critical material taking about 86% of the shadow cost of this phase, while the rest 14% was allocated equally to sand and gravel. The main reason for this difference is the high energy consumption[7] during the production of Portland clinker. As a result, of the high CO_2 emissions, most of the environmental impact was concentrated in the GWP impact category. When considering the C2CA1 and SC1 scenarios (100% gravel and 60% sand replacement), the environmental footprint was reduced by 10% compared to the TC scenario. The high contribution of cement was confirmed in the C2CA2 and SC2 scenarios (100% gravel and sand and 20% cement replacement), where the environmental performance was improved by 30%.

From a financial point of view, the TC was also the most expensive scenario in this phase. The purchase cost of primary materials could be reduced by 33% with the C2CA1 and SC1 and more than 50% with the C2CA2 and SC2 scenarios. It noted that the unit price of each material is a variable parameter. In fact, it is expected to increase over the years as a measure by the governments to reduce their consumption and eventually meet the European sustainability goal of 2050 (European Commission, 2018). In this case, using the innovative systems would increase revenues.

However, the influence of the assumptions made in this research on the final results should also be discussed. In this case, the applicability of these concrete mixtures is questionable. Furthermore, it was considered that the innovative recycling systems produce materials of the same quality and properties. In reality, the C2CA technology produces IRCAs with higher water absorption (CROW-CUR Recommendation 127, 2021). This is an indication that the C2CA and particularly the ADR system, is less effective in removing the adhered cement paste compared to the counterpart SmartLiberator. In addition to that, the replacement rates of the C2CA2 and SC2 systems are probably ambitious which in reality might yield to very high water absorption values (see Section 2.2). Therefore the feasibility of the potential concrete mixtures and especially C2CA2, is questionable.

The quality of RCP from the innovative systems is also not the same in practice. As discussed in Chapter 2, the silica content in RCP from the C2CA is expected to be higher due to the intense pre-crushing phase. Since silica does not contribute to cement hydration (strength development), it is expected that RCP from the C2CA technology are less reactive (less cementitious material) and, therefore, able to replace less cement compared to RCP from the SC recycling systems. On top of that, the Freement (0 - 65 μm) and Freefiller (65 - 125 μm) products of the SC were treated as one material in this thesis. Nevertheless, the former fraction contains mainly unhydrated cement particles, making it more reactive than the latter material. More cement could likely be replaced by using more of the Freement as a secondary binder in concrete. Based on the above, the SC system presents advantages over its counterpart C2CA regarding cement recycling.

Finally, it is stressed out that the cement type used in this thesis (CEMIII/A) already has a lower environmental footprint than commercial Portland cement (CEMI). Based on MRPI-EPD© (2020), the unit shadow cost of a CEMI type cement is 51 €/tn, while that of a CEMIII/A is only 20 €/tn. Thus, replacing CEMI with RCP would bring double environmental benefits. Nevertheless, as discussed in Section 2.2, RCP can activate alternative binding materials such as blast furnace slag, providing additional strength and durability properties to concrete. On the other hand, it is not clear how RCP would react when mixed with regular CEMI cement (without blast furnace slag) and if the assumption of 20% would still hold. In any case, the reactivity of RCP when used with different cement types must be tested beforehand.

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[7] The chemical reactions required to form the Portland clinker occur at around 1450^oC.

Recycling process

In general, the recycling phase had minimum contribution in all scenarios. Especially in the traditional recycling method, this phase accounts for only 0.6% of the total environmental impact and 1.2% of the total internal cost. The reason for the overall low impact (environmental and economic) is the low demand for recycled materials. Specifically, in this study, the required amount of TRCAs (i.e. 500 kg) for the TC scenario could be produced by recycling only 630 kg of concrete rubble with minimum environmental impact and cost. As a result, any changes in the recycling equipment, such as energy consumption, barely influence the overall impact of recycled concrete's supply chain. However, in reality, the total cost of the TC recycling is expected to be much higher than the innovative recycling systems. Generally, a stationary TC recycling plant requires a significant initial investment due to the large space and machines needed to set up the facility.

The recycling phase had a more significant impact when using the C2CA technology, taking about 13% and 20% of the total shadow and internal cost, respectively. The critical machine, in this case, was the HAS system. Due to its low capacity (i.e. 3 t/hr), it required a significant amount of energy (diesel) for the thermal treatment of ADR fines. On top of that, using diesel as an energy source is, by default, an environmentally hazardous and costly solution. The lower performance of C2CA2 compared to the C2CA1 scenario verifies the high contribution of diesel consumption. More specifically, the additional energy required to produce more recycled materials in the C2CA2 scenario balanced the benefits of saving primary materials. Another limitation of the C2CA recycling process that was not considered in this thesis is the incompatible capacities of the ADR and HAS systems. In particular, the production rate of fines (0 - 4 mm) by the ADR is 20 t/hr[8]. In contrast, the semi-industrial scale HAS system can only process 3 t/hr. Therefore, to achieve a continuous production line, the number of HAS systems should be increased to 7 to support one ADR unit. As a result, the initial investment would be increased as well. Another issue with regards to the C2CA recycling system is the maximum size of material (i.e. 16 mm) that the ADR system can receive/process. It requires a more intense pre-crushing to achieve such a relatively small particle size generating more silica and fines. On top of that, the material > 16 mm, which cannot be processed by the ADR, is eventually "lost" in low-value recycling applications. Finally, the material mass balance used for the C2CA recycling process (as obtained from the literature) is questionable. More specifically, the production rate of fines used for the C2CA recycling was lower than that for the SC recycling. However, one would expect that the C2CA would produce more fines due to the more intense pre-crushing phase.

The SC recycling process also has a relatively small impact on the supply chain of recycled concrete. From the total environmental impact, SC recycling is responsible for less than 5%, with the impact crusher being the critical machine. When considering the financial aspects of the recycling phase, the maintenance cost of the recycling equipment is the most important taking up to 65% of the total internal cost. Apart from the impact crusher, high maintenance costs also occurred in the SmartLiberator. The main limitation of the SC recycling procedure is the high production of low-quality fines from the pre-crushing phase. This fraction contains a considerable amount of the old sand and cementitious material of EoL concrete, which ends up in a mix of dirt and soil from the demolition activities. As discussed in the recommendations of Chapter 5, additional cleaning and separating devices are required to recover and reuse this fraction in the production of concrete.

Moreover, the present research did not include important aspects of concrete recycling that play a vital role in reality. For instance, the environmental impact assessment in the LCA analysis was based exclusively on the energy consumption of the recycling equipment, while other environmental issues relevant to concrete recycling were omitted. The production of noise and dust during the recycling process are two important aspects which might disturb possible nearby residential areas. The $CML - Baseline$ assessment method used in this thesis cannot handle these issues. However, other more appropriate methods for this purpose include additional impact categories, also relevant to noise and dust pollution. In addition, these two parameters can possibly be the critical factors that determine the location of the recycling plant so that a sufficient distance from the residential areas is maintained. If the plants cannot be placed close to the demolition site, additional transport with detrimental environmental and economic impact is required.

Finally, it must also be mentioned that the economic evaluation of the recycling phase in this research

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[8] The ADR system can process 50 tons of pre-crushed concrete per hour, from which 60% results in ADR coarse aggregates (30 tons) and 40% in ADR fines (20 tons)

focused only on the operating costs of the recycling equipment (energy, maintenance, insurance and personnel costs). However, other types of costs such as initial investment, landfill taxes or the cost of the land acquisition were not taken into account. These costs are expected to play an essential role in the case of a stationary TC recycling plant which involves more machines and requires more extensive space.

Transports

The results showed that transport had a significant environmental and economic impact on the supply chain. The highest impact was realised from all scenarios in the C2CA2 scenario (due to the highest transported weight). In each scenario, a standard amount of materials (primary and secondary) required for the concrete mix had to be transported to the mixing plant. However, the difference in the transported weights between the scenarios is attributed to the different production rates. For instance, the C2CA system can produce 22 tons of clean sand for every ton of EoL concrete, while the SC system produces 26 tons for the same input volume. Therefore, the former system needs to recycle more material to achieve the same result. At the same time, the rest fractions are still produced and often exceed the mix design's demand. Thus, the surplus material must be eventually transported, increasing the total environmental impact and cost.

Furthermore, the sensitivity analysis showed that the innovative systems could bring along environmental and financial benefits over the traditional recycling method only if they performed close to the demolition site. In an opposite scenario, the EoL concrete must be transported from the demolition site to the recycling plants with a significant increase in the total shadow and internal costs. In fact, for equal transport distances and up to 23 km, only the SC2 scenario becomes more efficient than the TC method. However, the benefits of using the innovative systems over the traditional method increase as the distance between the quarries and the concrete mixing plant increases.

Total impact

Focusing on the total LCA and LCC results, it emerged that the SC2 was the best case scenario. In this case, the increased environmental impact and costs of the recycling and transport phases were compensated by saving primary materials, especially cement. Relatively to the TC scenario, the SC2 presented about 18 - 19% lower shadow and internal costs. When the SC system was used for partial replacement of primary aggregates (SC1), the total cost was only 5% lower than the TC scenario without improvements on the environmental footprint. The utilisation of RCP was the main reason for the difference between the two SC scenarios. It is also worth noting that both C2CA scenarios reported similar environmental performance (5% increased compared to the TC scenario); however, the cost-benefits of the C2CA1 (-8%) were double the benefits of the C2CA2 scenario due to the increased diesel consumption. Based on the above, it can be concluded that the SC recycling system becomes more effective for higher up-cycling rates. In contrast, the efficiency of the C2CA systems reduces as the demand for recycled materials increases.

Both innovative systems displayed better performance when their social costs were considered. For lower up-cycling rates, the C2CA system (C2CA1) was more effective with about 5.8% less social cost than the TC system, whereas, for higher rates, the SC system(SC2) reached the best overall performance with about 19% improvement. For the best case scenario SC2, the benefit is quantified as 18.60 €/m^3 of concrete. Assuming that a regular concrete mixing plant can produce 90 - 120 m^3/hr, then the annual benefits of this scenario would range between € 2,700,000 and € 3,500,000[9].

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[9] Based on 200 working days per year and eight working hours per day.

5

Conclusions and recommendations

5.1. Conclusions

This thesis investigates the viability of the C2CA and Smart Crushing as alternative systems to the Traditional crushing (TC) recycling method. For this purpose, an integrated LCA&LCC study was conducted to evaluate the environmental and economic implications of the three recycling systems in the supply chain of recycled concrete. In this study, the monetised environmental impacts (shadow costs) were internalised in the actual costs of each phase (supply of primary materials, recycling, transport). Furthermore, the evaluation was based on five scenarios where different utilisation rates of recycled materials from each system were tested. In the final part of this thesis, a sensitivity and contribution analysis were also conducted to identify the driving factors within the supply chain. Based on the findings of this thesis, the sub-questions of this research are first addressed, which leads to the main research question.

First sub-question: What are the environmental and economic implications of the C2CA and Smart crushing technologies in the concrete supply chain?

The findings of this thesis revealed that both innovative systems present advantages as well as limitations over the TC method. In particular, when following the replacement rates suggested by the current European standards, the C2CA and SC systems demonstrated an overall cost reduction of about 8% and 5%, respectively, compared to the TC method. From an environmental perspective, though, no benefits were realised by the SC system, while the shadow cost of the C2CA was found to 5% increase. In this case, the coarse and fine materials produced by the innovative recycling systems (IRCA and IRFA) were used for 100% gravel and 60% sand substitution. Regarding the TC recycling method, only the coarse (TRCAs) material was allowed in concrete, replacing 50% primary gravel.

In a different scenario, the maximum potentials of the innovative systems were examined by using their products to substitute 100% primary aggregates and 20% cement. Under these conditions, the innovative systems presented opposite trends. On the one hand, the SC system in this scenario (SC2) resulted in about 18 - 19% lower environmental impact and cost than the traditional recycling method. On the other hand, the cost-benefits from the C2CA2 scenario were reduced to 4%, while the environmental remaining 5% increased. These opposite trends indicate the high impact (environmental and economic) of diesel consumption of the HAS and the increased transport. The more material is processed by the C2CA technology, the less the benefits of saving primary materials are.

Second sub-question: What are the system hot spots with the greatest influence on the environmental and economic impact of concrete recycling?

In order to answer this question, first, the most critical recycling machines should be identified. The contribution analysis showed that the critical machine in the TC recycling process was the impact crusher used for secondary crushing. Regarding the C2CA system, the HAS was by far the most crucial. Its high diesel consumption played a detrimental role in the environmental and economic performance of the whole plant.

In the case of SC recycling, although most of the environmental impact was caused by the impact crusher in the pre-crushing phase, the SmartLiberator and the air separator were also of interest from a financial perspective. When evaluating the unit impacts of the three recycling plants, it turned out that the C2CA recycling process has the highest environmental impact and cost.

Despite the larger impact of the critical machines, the sensitivity analysis revealed that possible changes in the recycling equipment had negligible influence on the supply chain. Even if renewable energy sources powered the recycling plants, the environmental and financial benefits were no higher than 5%. However, diesel price changes significantly influenced all scenarios due to the increased transport cost. Especially in the C2CA scenarios, the sensitivity was even higher due to the additional contribution of the HAS system. Furthermore, the purchase price of primary materials was more critical in the TC scenario, which utilised the highest quantities. Mobility was essential for the innovative systems, which initially were assumed as mobile units (on-site recycling). Their benefits could be achieved only for locations close to the demolition site, while maintaining a relatively larger distance of TC recycling plant. On the contrary, for the same transport distances, only the SC2 scenario showed benefits over the traditional method.

Main question: Are the C2CA and Smart crushing viable alternatives of the Traditional crushing recycling method?

The main conclusion of the present thesis is that the innovative recycling systems can be viable alternative solutions to the traditional recycling method only if they are placed at a strategic location close to the demolition site. For the boundary conditions of this thesis, the innovative systems demonstrated a general cost-reduction and a slight increased environmental impact in the case of the C2CA system. However, the resulting social costs of all scenarios upon internalisation of the environmental costs were lower than the traditional recycling practice. The best overall performance was observed when using the SC system with maximum utilisation of its recycled materials. In this case, the total social cost was up to 19% lower than the TC system. For replacement rates according to the standards, the C2CA system performed better with an overall social cost reduction of 7%. The overall impact was increased considerably in a hypothetical scenario of placing the innovative recycling plants 50 km away from the demolition site. In the best case, the SC2 scenario showed a 15% higher social cost than the TC method. This value reached almost 20% for the C2CA1 scenario.

Before this research, there was a lack of knowledge regarding the opportunities of the C2CA and SC recycling systems. With the outcomes of this thesis, one can get a first impression of the possible environmental and financial implications of using these technologies in the supply chain of recycled concrete. The different scenarios, in combination with the sensitivity analysis, covered various aspects of the innovative recycling systems, providing information for their optimal use. By shedding light on this topic, this thesis contributes to the transition from the current to a more sustainable model of recycling concrete by adopting these innovative technologies. Furthermore, this research provides a great set of data especially for the Smart crushing recycling system which would be valuable for future research. Finally, on a practical level, the results of this research can be used to assist decision-makers involved in the concrete supply chain. For instance, concrete recycling and manufacturing companies can estimate their environmental footprint and cost when they involve traditional or innovative concrete recycling methods.

5.2. Recommendations

The conclusions of this research indicate that a possible shifting from the traditional C&DW management practice to a more sustainable model using the C2CA and SC recycling systems would bring environmental and financial advantages to the concrete industry. However, certain issues must be taken into consideration. The following sections provide recommendations for future research and practical applications regarding the C2CA and SC recycling systems.

Research recommendations

First, the present study was carried out based on a limited number of data, making the data collection process challenging. Especially for the C2CA technology, most of the required process and financial data of the recycling equipment were obtained from one or two sources. Some reasonable assumptions had also to be made to cover missing data. Beyond that, it is very likely that the C2CA technology has been further developed until today. Therefore, the information retrieved from previous studies might lead to an underestimation of its performance. Similar issues also apply to the equipment of the TC recycling plant. Therefore, additional case studies with more recent data are required to verify the outcomes of this thesis.

In addition, it is declared that this research was based on several assumptions which might deviate from reality. For instance, the assumption of full replacement of primary aggregates and 20% of cement in the potential scenarios is considered as ambitious or ideal. In reality to achieve a concrete mix with the specific replacement rates can be a challenging or even impossible task due to higher water absorption. To obtain a better understanding on this issue, more tests are required to verify the findings of the previous research (which used as baseline for this thesis).

Moreover, to get a more realistic impression of each recycling method's actual environmental and economic impacts, the LCA and LCC studies must be expanded by including additional parameters. For instance, the noise and dust pollution of the recycling process are important aspects which are expected to have a crucial role in the LCA results. It would add valuable knowledge if these parameters were studied along with their influence on the location choice and, consequently, on transportation. In future research, other costs such as the initial investment, landfill taxes, entry fee and land acquisition must also be included in the economic evaluation.

The actual composition of C&DW, along with different demolition methods, is another topic of interest that would bring valuable knowledge regarding using the C2CA and SC systems. The two innovative systems can only accept "clean" concrete rubble from selective demolition. However, selective demolition is often more expensive and time-consuming than traditional demolition methods. This additional cost is transferred from the demolition to the recycling company and eventually added to the recycled materials sales price. On the other hand, achieving the same quality of recycled materials by processing mixed concrete rubble (from traditional demolition) would require additional cleaning and separation devices with an additional initial investment and operating costs. Hence, additional research is recommended to investigate the environmental and economic consequences of the C2CA and SC systems when different demolition methods are used.

Practical recommendations

From a practical point of view, the effectiveness of the innovative recycling systems can be potentially further improved with a few adjustments. For example, in the case of the C2CA technology, upgrading the HAS system and achieving compatible capacity with the coupled ADR system is necessary. As elaborated in Section 4.7, the HAS system should have at least 20 t/hr capacity to support a 50 t/hr ADR system. From such an upgrade, the HAS technology will be able to process the same amount of material with one unit only, reducing relevant costs (maintenance, initial investment). Furthermore, if possible, using biofuels instead of diesel would considerably improve the environmental performance of the HAS system. Adjustments in the ADR system are also necessary to increase the maximum size of material that can be processed so that the pre-crushing phase can only be done in one step. A maximum size of 50 mm would be for this purpose. This modification will reduce the amount of silica in RCP and eventually enhance its reactivity.

For the SC recycling system, adjustments must be made to reduce the low-quality fines produced from the pre-crushing phase. To achieve that, the impact crusher must be replaced by another type of crusher which does not cause significant damage to the natural aggregates. Beyond that, to recover all of the sand and cementitious material from the EoL concrete, the discarded 0 - 4 mm low-quality fines must be processed by additional cleaning and separation devices. Ideally, if this fraction can be cleaned enough, it can be reincorporated in the SmartRefiner to retrieve the full amount of the initial sand and cementitious material. Moreover, the up-cycling rates of the recovered cementitious material from both innovative systems could be further improved by separating the cement from the silica particles. To do so, a new separation technology needs to be developed which will be used after the HAS and the SmartRefiner.

Finally, it is necessary to change the current policies to promote up-cycling applications of EoL concrete and, through that, the innovative recycling technologies C2CA and SC. Currently, the inclusion of the environmental impacts in the sales price of a product/process is only allowed for specific emissions such as CO_2. The reason is the difficulty in defining a monetary value for the different pollutants and emissions. This thesis uses the Environmental Cost Indicators (ECI) to monetise the environmental impacts over the defined categories; however, the proposed values are only applicable in the Netherlands and for the impact categories of the $CML - Baseline$ method. Thus, it is necessary to develop a harmonised methodology which can be used for all environmental impact assessment methods and in all countries.

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A

Recycling plants description

Traditional crushing recycling plant

The traditional crushing (TC) recycling plant used in this thesis was designed based on the general flow process diagram proposed by Weihong (2004). In addition, data for the recycling equipment were obtained by Di Maria et al. (2018). The TC recycling plant of this thesis is able to process up to 350 tons of C&DW per hour. According to Di Maria et al. (2018) and (Coelho and de Brito, 2013), from the initial input volume of EoL concrete, around 80% results in coarse aggregates (TRCAs), while the rest 20% consists of low-quality fines and dirt (L-RFA) . For the present thesis, the former material was regarded as a medium quality product able to substitute up to 50% of the original gravel in concrete (see Section 2.2). On the contrary, the L-RFAs were not suitable for concrete production due to their low-quality. Thus, they were used for down-cycling as fine sub-base material in road constructions by replacing equal amount of primary sand. Table A.1 shows the material mass balance of the proposed TC recycling plant.

Table A.1: Material mass balance for processing 1 ton of EoL concrete with the TC recycling plant

		Size	Mass [t]	Global share [w.t.%]	Product
System	**Input:**				
	EoL concrete	0-0.5 m	1	100%	
	Outputs:				
	TRCA	4-32 mm	0.8	80%	Target
	L-RFA	0-4 mm	0.2	20%	By-product

Analytical description

This section provides an analytical description of the individual steps of the TC recycling process. The flow process diagram of the TC recycling system is illustrated in Figure A.1.

1. Excavator
The TC recycling process starts with a hydraulic excavator breaking the large chunks of EoL concrete in smaller fractions.

2. Vibrating feeder
As soon as the material reaches a size that can fit in the primary crusher, it is loaded by the excavator into a vibrating feeder belt. At this point the material is also pre-separated in fractions above and below 80 mm.

3.1. Magnet #1
The fraction < 80 mm passes through a first magnet to remove large metal pieces (Coelho and de Brito,

2013). Despite this thesis considered that the input EoL concrete is free of other materials (metals, wood, etc.), in reality some minor pollutants will be present in the material. Therefore, the cleaning and metal separation steps in this process were also included.

3.2. Vibrating screen #1
Then, the material is separated by a first vibrating screen in sizes 0 - 4 mm and 4 - 8 mm. The fraction below 4 mm is collected as a low-quality product (L-RFA), while above 4 mm proceeds to a second metal separation step.

4. Jaw crusher
Simultaneously, the coarser fraction > 80 mm from the vibrating feeder in step 2, is fed in the jaw crusher (primary crushing) to reduce the size down to 40 mm.

5. Magnet #2
The resulting material from the primary crushing and screening steps (4 - 80 mm) passes through a second magnet to remove the remained ferrous metals.

6. Vibrating screen #2
A second vibrating screen separates the incoming material into sizes larger and smaller than 32 mm. The latter (< 32 mm) is driven towards the air sifters (step 8). The fraction above 32 mm proceeds to the secondary crushing by the impact crusher.

7. Impact crusher
The impact crushers operates in a closed-loop with the second vibrating screen until all reach the desired size (< 32 mm).

8. Air sifters
Air sifters are used in the next step to clean the material from potential light contaminants (wood, cardboard, plastics) with air-sifters.

9. Eddy current
The remained non-ferrous metals in the material are removed by an eddy current metal separation.

10. Vibrating screen #3
A third multi-deck vibrating screen separates the material in sizes of 0 - 4 mm and 4 - 32 mm.

11. Conveyor belts
Between the steps, the material is transferred via one or more conveyor belts.

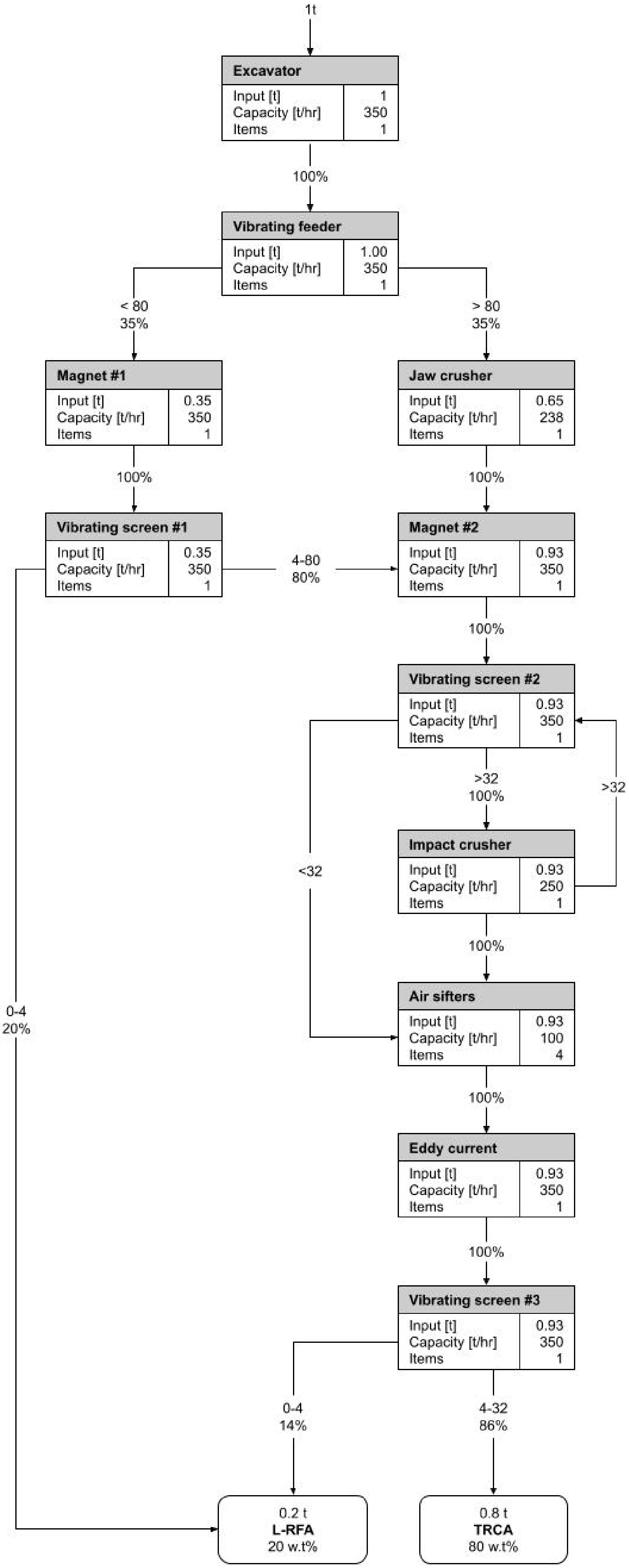


Figure A.1: Flow process of the TC recycling plant

C2CA recycling plant

The C2CA recycling plant in this thesis was designed based on information provided by Kalliopi (2019), Zhang et al. (2020a) and Zhang et al. (2019). With an average capacity of 250 t/hr, it produces clean gravel (IRCA) and sand (IRFA) as well as cementitious material (RCP). The material mass balance of C2CA plant is shown in Table A.2.

Table A.2: Material mass balance for processing 1 ton of EoL concrete with the C2CA recycling plant

		Size	Mass [t]	Share		Product
System	**Input:**			**Local**	**Global**	
	EoL concrete	0-0.5 m	1.00	100%	100%	
Pre-crushing	**Input:**					
	EoL concrete	0-0.5 m	1.00	100%	100%	
	Outputs:					
	L-RCA	0-12 mm	0.70	70%	70%	Intermediate
	L-RCA	12-22 mm	0.30	30%	30%	By-product
ADR	**Input:**					
	L-RCA	0-12 mm	0.70	100%	70%	
	Outputs:					
	IRCA	4-12 mm	0.42	60%	42%	Target
	ADR fines	0-4 mm	0.28	40%	28%	Intermediate
HAS	**Input:**					
	ADR fines	0-4 mm	0.28	100%	0.28	
	Outputs:					
	IRFA	0.125-4 mm	0.21	75%	21%	Target
	RCP	0-0.125 mm	0.056	20%	6%	Target
	Moisture	-	0.014	5%	1%	By-product

Analytical procedure

This section provides an analytical description of the individual steps of the C2CA recycling process. The flow process diagram of the C2CA system is illustrated in Figure A.2.

1. Excavator
The C2CA recycling process starts with a hydraulic excavator breaking the large chunks of EoL concrete in smaller fractions.

2. Jaw crusher
Then the excavator feeds a jaw crusher with the EoL concrete for primary crushing. The jaw crusher used in this recycling plant was assumed the same as the one in the TC recycling plant.

3. Impact crusher
After the primary crushing, the material passes through a secondary crushing step using an impact crusher. The two crushing steps aim to reduce the particle size down to 22 mm. The impact crusher used in the C2CA plant was assumed the same as the one in the TC and SC plants.

4. Vibrating screen
Operating in a closed-loop with the impact crusher, a vibrating screen is used to separate the pre-crushed material in sizes of 0-12 mm and 12-22 mm. The former material proceeds to the next step (ADR) for further treatment, while the latter is discarded as by-product.

5. ADR

Subsequently, the 0-12 mm L-RCAs (low-quality recycled coarse aggregates) are driven in the ADR system which separates the coarse 4-12 mm (IRCA) from the fine 0-4 mm material.

6. HAS

In the last step of the C2CA recycling process, the ADR fines (0-4 mm) are treated by the HAS system producing IRFAs (0.125-4 mm) and RCP (<0.125 mm). Furthermore, about 5% of the ADR fines is moisture which is evaporated after the thermal treatment.

7. Conveyor belts

Between the steps, the material is transferred via one or more conveyor belts.

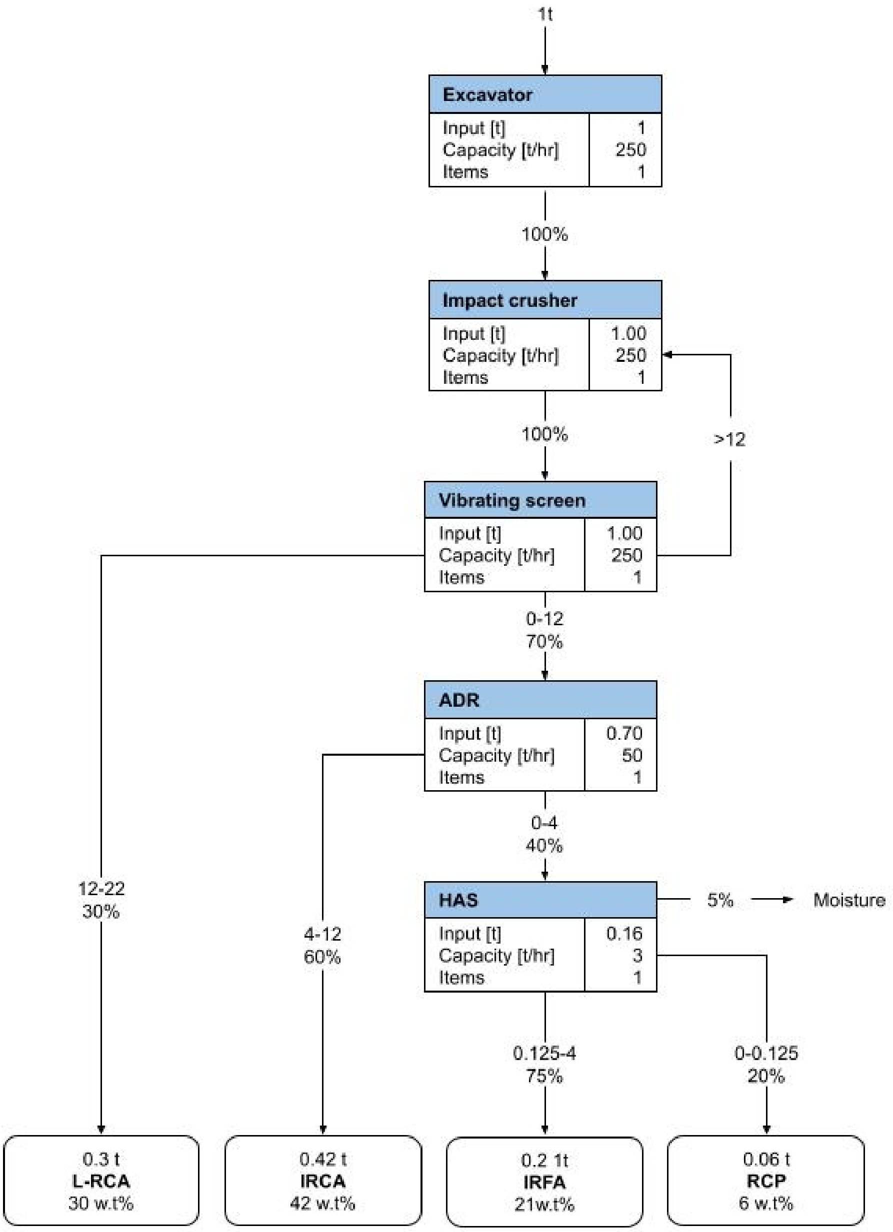


Figure A.2: Flow process of the C2CA recycling plant

Smart Crushing recycling plant

The Smart crushing (SC) recycling plant for this thesis was designed according to information provided by Rutte Groep (2022). This plant was designed for an average capacity of 250 t/hr producing clean gravel (IRCA), sand (IRFA) and cementitious material (RCP) according to Table A.3.

Table A.3: Material mass balance for processing 1 ton of EoL concrete with the SC recycling plant

		Size	**Mass [t]**	**Share**		**Product**
System	**Input:**			**Local**	**Global**	
	EoL concrete	0-0.5 m	1	100%	100%	
Pre-crushing	**Input:**					
	EoL concrete	0-0.5 m	1	100%	100%	
	Outputs:					
	L-RCA	4-55 mm	0.7	70%	70%	Intermediate
	L-RFA	0-4 mm	0.3	30%	30%	By-product
SmartLiberator	**Input:**					
	L-RCA	4-55 mm	0.7	100%	70%	
	Outputs:					
	IRCA	4-32 mm	0.35	50%	35%	Target
	L-RFA	0-4 mm	0.35	50%	35%	Intermediate
SmartRefiner	**Input:**					
	L-RFA	0-4 mm	0.35	100%	0.35	
	Outputs:					
	IRFA	0.125-4 mm	0.259	74%	26%	Target
	RCP	0-0.125 mm	0.091	26%	9%	Target
		65-125 μm	0.077	22%	8%	
		0-65 μm	0.014	4%	4%	

Analytical description

This section provides an analytical description of the individual steps of the SC recycling process. The flow process diagram of the SC system is illustrated in Figure A.3.

1. Excavator:
The SC recycling process starts also with a hydraulic excavator breaking the large concrete chunks in order to fit in the impact crusher.

2. Impact crusher:
A mobile impact crusher unit takes place for pre-crushing the material at maximum size of 55 mm. The impact crusher unit is equipped with a vibrating feeder and a magnet.

3. Sieve tower:
The pre-crushed material is transferred to sieve tower which contains combinations of multi-deck screens. The sieve tower separates the inlet material into low-quality fines 0-4 mm (L-RFA) and low-quality coarse 4-55 mm (L-RCA). The coarser fraction L-RCA proceeds for further processing, while the low-quality fines (L-RFA) are discarded as by-product.

4. Air separator
In the next step, the 4-55 mm pre-crushed material is cleaned from light contaminants using an air separator.

5. SmartLiberator
Then, the SmartLiberator is used to remove the adhered cement paste from the original aggregates. The

separation is done through applying low-pressure crushing on the material.

6. Vibrating screen
The output material of SmartLiberator is sieved by a vibrating screen to separate the 0 - 4 mm low-quality fines (L-RFA) and the 4-32 mm clean gravel (or Freegravel as called by Rutte Groep).

7. SmartRefiner
In the final step, the 0-4 mm fraction is further separated by the SmartRefiner in three sizes, 0 - 65 μm, 65 μm - 250 μm and 0.125 - 4 mm. According to Rutte Groep (2022), the first two fractions called Freement and Freefiller, contain most of the cementitious material, while the coarser 0.125-4 mm material can be regarded as clean sand (Freesand).

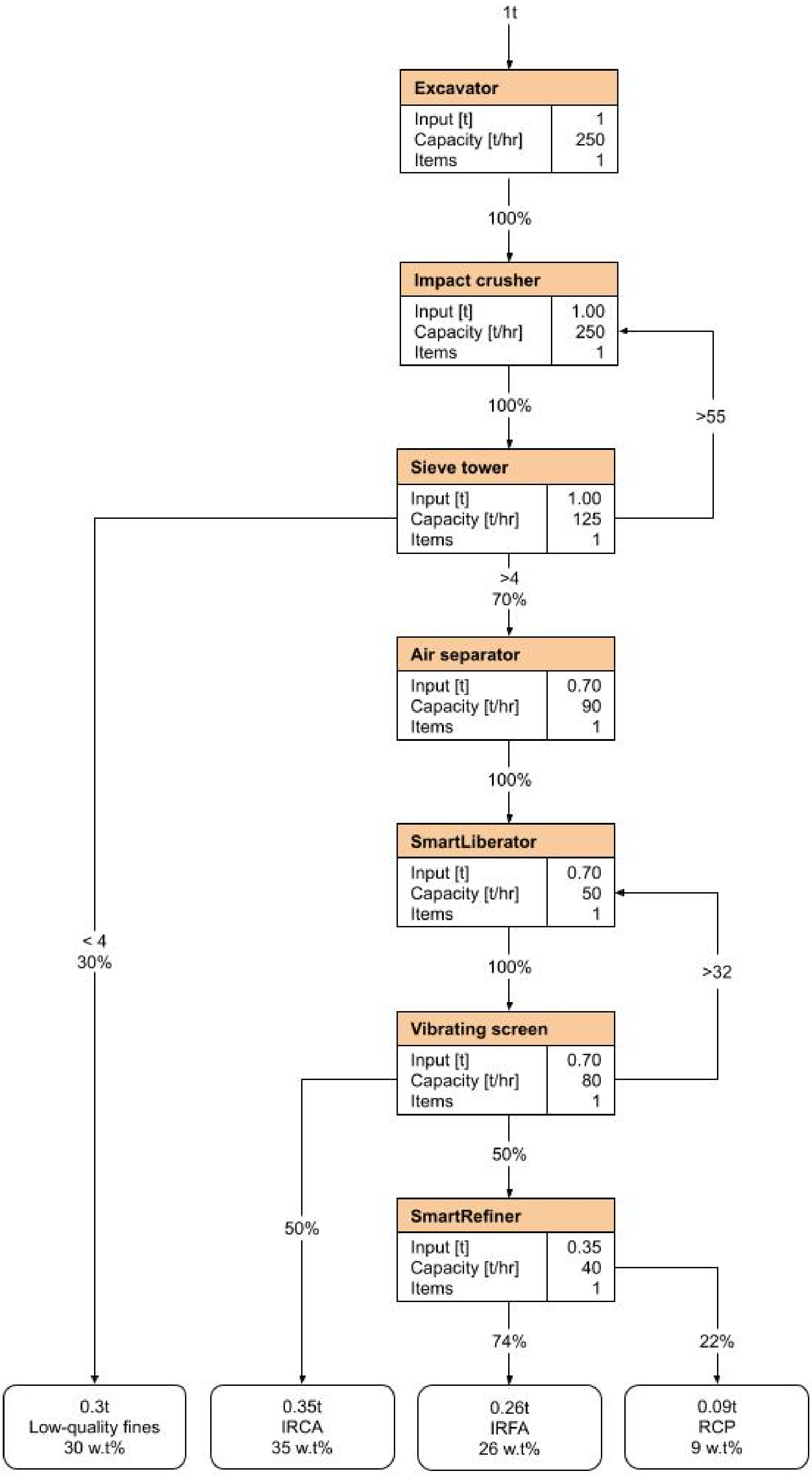


Figure A.3: Flow process of the SC recycling plant

B

LCC background calculations

Supply of primary materials

The cost for purchase the primary materials for each scenario are provided in Table B.1. The considered unit prices for the primary materials were obtained from personal communication with Rutte Groep (2022).

Table B.1: Internal cost of primary material supply

Material	**Primary gravel**		**Primary sand**		**CEMIII**		
Unit price [€/t]	**21.3**		**15.50**		**95**		
Scenario	**Mass [t]**	**Cost [€]**	**Mass [t]**	**Cost [€]**	**Mass [t]**	**Cost [€]**	**Total cost [€]**
TC	0.50	€ 10.66	0.82	€ 12.64	0.34	€ 32.30	**€ 55.60**
C2CA1	0.00	€ -	0.33	€ 5.06	0.34	€ 32.30	**€ 37.36**
C2CA2	0.00	€ -	0.00	€ 0.00	0.27	€ 25.84	**€ 25.84**
SC1	0.00	€ 0.00	0.33	€ 5.06	0.34	€ 32.30	**€ 37.36**
SC2	0.00	€ -	0.00	€ -	0.27	€ 25.84	**€ 25.84**

Recycling process

TC recycling

Process and financial data for the TC recycling plant were obtained by the study of Coelho and de Brito (2013). Only for the secondary crushing step, the respective data for the impact crusher were provided by Rutte Groep (2022). The calculations of the constitutive costs of the TC plant are shown in Tables B.2-B.3. Therefore, the total recycling cost of the TC scenario is calculated as follow:

$$C_{R,TC} = \text{€}0.23 + \text{€}\ 0.02 + \text{€}\ 0.53 + \text{€}\ 0.12 = \text{€}\ 0.90$$

Table B.2: Calculation of the energy cost of the TC recycling process.

TC recycling plant	**Items**	**Operators**	**Input [tn]**	**T$_i$ [hr]**	**P$_{unit,i}$ [t/h]**	**EC$_{unit,i}$ [kWh/t]**	**EC$_{total,i}$ [kWh]**	**Energy [€]**
TC								
Excavator [1]	1	1	0.63	0.002	350	0.06	0.04	€ 0.06
Vibrating feeder	1	-	0.63	0.002	350	0.05	0.03	€ 0.00
Magnet #1	1	-	0.22	0.001	350	0.02	0.00	€ 0.00
Vibrating screen #1	1	-	0.22	0.001	350	0.05	0.01	€ 0.00
Jaw crusher	1	1	0.41	0.002	238	0.10	0.04	€ 0.01
Magnet #2	1	-	0.58	0.002	350	0.02	0.01	€ 0.00
Vibrating screen #2	1	-	0.58	0.002	350	0.05	0.03	€ 0.00
Impact crusher	1	1	0.47	0.002	250	2.50	1.16	€ 0.14
Air sifters	4	-	0.58	0.006	100	0.02	0.01	€ 0.00
Eddy current	1	-	0.58	0.002	350	0.05	0.03	€ 0.00
Vibrating screen #3	1	-	0.58	0.002	350	0.05	0.03	€ 0.00
Conveyor belts	6	-	0.63	0.002	350	0.03	0.02	€ 0.00
Total								**€ 0.23**

[1] Powered by diesel (energy consumption rate in Lt/t)

Table B.3: Calculation of the maintenance, insurance and personnel cost of the TC recycling process.

TC recycling plant	**Investment**	**Insurance**			**Maintenance**			**Personnel**
	[€]	**[€/year]**	**[€/t]**	**[€]**	**[€/year]**	**[€/t]**	**[€]**	**[€]**
TC								
Excavator	€ 135,000.00	€ 1,350.00	€ 0.00	€ 0.00	€ 4,486.00	€ 0.01	€ 0.01	€ 0.04
Vibrating feeder	€ 114,000.00	€ 1,140.00	€ 0.00	€ 0.00	€ 1,330.00	€ 0.00	€ 0.00	€ 0.00
Magnet #1	€ 47,522.00	€ 475.22	€ 0.00	€ 0.00	€ 305.83	€ 0.00	€ 0.00	€ 0.00
Vibrating screen #1	€ 82,325.00	€ 823.25	€ 0.00	€ 0.00	€ 1,234.88	€ 0.00	€ 0.00	€ 0.00
Jaw crusher	€ 130,000.00	€ 1,300.00	€ 0.00	€ 0.00	€ 1,408.33	€ 0.00	€ 0.00	€ 0.04
Magnet #2	€ 47,522.00	€ 475.22	€ 0.00	€ 0.00	€ 305.83	€ 0.00	€ 0.00	€ 0.00
Vibrating screen #2	€ 82,325.00	€ 823.25	€ 0.00	€ 0.00	€ 1,234.88	€ 0.00	€ 0.00	€ 0.00
Impact crusher	€ 790,000.00	€ 7,900.00	€ 0.01	€ 0.01	€ 350,000.00	€ 0.50	€ 0.50	€ 0.04
Air sifters	€ 100,000.00	€ 1,000.00	€ 0.00	€ 0.00	€ 1,583.33	€ 0.00	€ 0.01	€ 0.00
Eddy current	€ 98,114.00	€ 981.14	€ 0.00	€ 0.00	€ 305.83	€ 0.00	€ 0.00	€ 0.00
Vibrating screen #3	€ 82,325.00	€ 823.25	€ 0.00	€ 0.00	€ 305.83	€ 0.00	€ 0.00	€ 0.00
Conveyor belts	€ 68,833.00	€ 688.33	€ 0.00	€ 0.00	€ 1,089.86	€ 0.00	€ 0.01	€ 0.00
Total				**€ 0.02**			**€ 0.53**	€ 0.12

C2CA recycling

The C2CA recycling plant was synthesized based on various sources. In particular, the excavator, the jaw crushers, the vibrating screen and the conveyor belts were assumed the same machines as the ones used in the TC plant as taken by the study of Coelho and de Brito (2013). Furthermore, the impact crusher is the same for all three recycling plants (TC, C2CA and SC) using data from Rutte Groep (2022).

On the contrary, process data (energy consumption rates and capacity) for the ADR and HAS technologies were obtained by Moreno-Juez et al. (2020), while financial data for the two particular technologies were calculated based on certain assumptions due to limited available information. More specifically, according to Zhang et al. (2019) the hourly depreciation cost of the ADR and HAS systems are 83.73 €/hr and 14.73 €/hr respectively. Assuming approximately 200 working days per year and a 10-years service life, the initial investment of these machines was calculated as follow:

$$ADR\ investment = 83.73\frac{€}{hr} \times 8\ working\ hours \times 250\ working\ days \times 10\ years = €\ 1,674,600.00$$

$$HAS\ investment = 14.73\frac{€}{hr} \times 8\ working\ hours \times 250\ working\ days \times 10\ years = €\ 294,600.00$$

Moreover, the maintenance cost of the ADR system was taken as 1 €/ton of processed material based on IPG report (2015). Due to limited data sources, the maintenance cost of the HAS system was calculated proportionally to the ADR initial investment as follow:

$$HAS\ maintenance\ cost = ADR\ maintenance\ cost \times \frac{HAS\ investment}{ADR\ investment} = 1\ \frac{€}{t} \times \frac{€\ 294,600.00}{€\ 1,674,600.00} = 0.18\ \frac{€}{t}$$

Therefore, the total recycling cost of the C2CA scenarios is calculated as follow:

$$C_{R,C2CA1} = €\ 6.83 + €\ 0.16 + €\ 4.03 + €\ 0.64 = €\ 11.60$$
$$C_{R,C2CA2} = €\ 11.14 + €\ 0.26 + €\ 4.28 + €\ 0.64 = €\ 11.32$$

Table B.4: Calculation of the energy cost of the C2CA recycling process.

C2CA plant	**Items**	**Operators**	**Input [tn]**	**T_i [hr]**	**$P_{unit,i}$ [t/h]**	**$EC_{unit,i}$ [kWh/t]**	**$EC_{total,i}$ [kWh]**	**Energy [€]**
C2CA1								
Excavator[1]	1	1	2.38	0.010	250	0.06	0.14	€ 0.22
Jaw crusher	1	1	2.38	0.010	238	0.10	0.24	€ 0.03
Impact crusher	1	1	2.38	0.010	250	2.50	5.96	€ 0.74
Horizontal screen	1	-	2.38	0.007	350	0.05	0.13	€ 0.02
ADR	1	-	1.67	0.033	50	0.46	0.77	€ 0.09
HAS[1]	1	-	0.67	0.222	3	0.01	3.74	€ 5.73
Conveyor belts	3	-	2.38	0.007	350	0.03	0.07	€ 0.01
Total								**€ 6.83**
C2CA2								
Excavator[1]	1	1	3.88	0.016	250	0.010	0.23	€ 0.36
Jaw crusher	1	1	3.88	0.010	238	0.10	0.39	€ 0.05
Impact crusher	1	1	3.88	0.010	250	2.50	9.71	€ 1.20
Horizontal screen	1	-	3.88	0.007	350	0.05	0.21	€ 0.03
ADR	1	-	2.72	0.033	50	0.46	1.25	€ 0.15
HAS[1]	1	-	1.09	0.222	3	5.61	6.10	€ 9.34
Conveyor belts	3	-	3.88	0.007	350	0.03	0.12	€ 0.01
Total								**€ 11.14**

[1] Powered by diesel (energy consumption rate in Lt/t)

Table B.5: Calculation of the maintenance, insurance and personnel cost of the C2CA recycling process.

C2CA plant	**Investment**	**Insurance**			**Maintenance**			**Personnel**
	[€]	**[€/year]**	**[€/t]**	**[€]**	**[€/year]**	**[€/t]**	**[€]**	**[€]**
C2CA1								
Excavator	€ 135,000.00	€ 1,350.00	€ 0.00	€ 0.01	€ 2,670.24	€ 0.01	€ 0.01	€ 0.21
Jaw crusher	€ 130,000.00	€ 1,300.00	€ 0.00	€ 0.01	€ 1,005.95	€ 0.00	€ 0.00	€ 0.22
Impact crusher	€ 790,000.00	€ 7,900.00	€ 0.02	€ 0.04	€ 250,000.00	€ 0.50	€ 1.19	€ 0.21
Horizontal screen	€ 82,325.00	€ 823.25	€ 0.00	€ 0.00	€ 882.05	€ 0.00	€ 0.00	€ 0.00
ADR	€ 1,674,600.00	€ 16,746.00	€ 0.03	€ 0.06	€ 250,000.00	€ 0.50	€ 0.83	€ 0.00
HAS	€ 294,600.00	€ 2,946.00	€ 0.01	€ 0.00	€ 43,980.65	€ 0.09	€ 0.06	€ 0.00
Conveyor belts	€ 68,833.00	€ 688.33	€ 0.00	€ 0.01	€ 778.47	€ 0.00	€ 0.01	€ 0.00
Total				**€ 0.16**			**€ 4.03**	**€ € 0.64**
C2CA2								
Excavator	€ 135,000.00	€ 1,350.00	€ 0.00	€ 0.01	€ 2,670.24	€ 0.01	€ 0.02	€ 0.34
Jaw crusher	€ 130,000.00	€ 1,300.00	€ 0.00	€ 0.01	€ 1,005.95	€ 0.00	€ 0.01	€ 0.22
Impact crusher	€ 790,000.00	€ 7,900.00	€ 0.02	€ 0.06	€ 250,000.00	€ 0.50	€ 1.94	€ 0.34
Horizontal screen	€ 82,325.00	€ 823.25	€ 0.00	€ 0.01	€ 882.05	€ 0.00	€ 0.01	€ 0.00
ADR	€ 1,674,600.00	€ 16,746.00	€ 0.03	€ 0.09	€ 250,000.00	€ 0.50	€ 1.36	€ 0.00
HAS	€ 294,600.00	€ 2,946.00	€ 0.01	€ 0.01	€ 43,980.65	€ 0.09	€ 0.10	€ 0.00
Conveyor belts	€ 68,833.00	€ 688.33	€ 0.00	€ 0.02	€ 778.47	€ 0.00	€ 0.02	€ 0.00
Total				**€ 0.26**			**€ 4.28**	**€ 0.64**

SC recycling

All data regarding the SC recycling equipment were provided by Rutte Groep (2022). Specifically for this case, the energy consumption and costs of the magnetic separators are included in the calculations of the conveyor belts. Tables B.6 - B.7 show all the constitutive costs occurred during the SC recycling process. Therefore, the total recycling cost of the SC scenarios is calculated as follow:

$$C_{R,SC1} = € \, 0.38 + € \, 0.25 + € \, 3.02 + € \, 0.88 = € \, 9.15$$
$$C_{R,SC2} = € \, 0.42 + € \, 0.27 + € \, 3.32 + € \, 0.97 = € \, 10.04$$

Table B.6: Calculation of the energy cost of the TC recycling process.

SC plant	**Items**	**Operators**	**Input [tn]**	**T$_i$ [hr]**	**P$_{unit,i}$ [t/h]**	**EC$_{unit,i}$ [kWh/t]**	**EC$_{total,i}$ [kWh]**	**Energy [€]**
SC1								
Excavator[1]	1	1	2.86	0.011	250	0.06	0.17	0.26
Impact crusher	1	1	2.86	0.011	250	2.50	7.15	0.88
Sieve tower	1	-	2.86	0.023	125	0.30	0.86	0.11
Air separator	1	-	2.00	0.022	90	0.30	0.60	0.07
SmartLiberator	1	1	2.00	0.040	50	0.10	0.20	0.02
Horizontal screen	1	-	2.00	0.025	80	0.15	0.30	0.04
Smartrefiner	1	-	1.00	0.025	40	0.55	0.55	0.07
Conveyor belts	1	-	2.86	0.023	125	0.20	0.57	0.07
Total								**€ 0.38**
SC2								
Excavator[1]	1		3.14	0.013	250	0.06	0.19	0.29
Impact crusher	1		3.14	0.013	250	2.50	7.84	0.97
Sieve tower	1		3.14	0.025	125	0.30	0.94	0.12
Air separator	1		2.20	0.024	90	0.30	0.66	0.08
SmartLiberator	1		2.20	0.044	50	0.10	0.22	0.03
Horizontal screen	1		2.20	0.027	80	0.15	0.33	0.04
Smartrefiner	1		1.10	0.027	40	0.55	0.60	0.07
Conveyor belts	1		3.14	0.025	125	0.20	0.63	0.08
Total								**€ 0.42**

[1] Powered by diesel (energy consumption rate in Lt/t)

Transports

The transport costs are provided in Tables B.8 - B.10. The total transported weight was taken 75% increased to take also into account the return journey (see Chapter 4).

Table B.7: Calculation of the maintenance, insurance and personnel cost of the C2CA recycling process.

SC plant	**Investment**	**Insurance**			**Maintenance**			**Personnel**
	[€]	**[€/year]**	**[€/t]**	**[€]**	**[€/year]**	**[€/t]**	**[€]**	**[€]**
SC1								
Excavator	€ 135,000.00	€ 1,350.00	€ 0.00	€ 0.01	€ 2,670.24	€ 0.01	€ 0.02	€ 0.25
Impact crusher	€ 790,000.00	€ 7,900.00	€ 0.02	€ 0.05	€ 250,000.00	€ 0.50	€ 1.43	€ 0.25
Sieve tower	€ 763,000.00	€ 7,630.00	€ 0.02	€ 0.04	€ 50,000.00	€ 0.10	€ 0.29	€ 0.00
Air separator	€ 838,000.00	€ 8,380.00	€ 0.02	€ 0.03	€ 250,000.00	€ 0.50	€ 1.00	€ 0.00
SmartLiberator	€ 990,000.00	€ 9,900.00	€ 0.02	€ 0.04	€ 250,000.00	€ 0.50	€ 1.00	€ 0.88
Horizontal screen	€ 560,000.00	€ 5,600.00	€ 0.01	€ 0.02	€ 50,000.00	€ 0.10	€ 0.20	€ 0.00
Smartrefiner	€ 500,000.00	€ 5,000.00	€ 0.01	€ 0.01	€ 125,000.00	€ 0.25	€ 0.25	€ 0.00
Conveyor belts	€ 1,725,000.00	€ 17,250.00	€ 0.03	€ 0.10	€ 50,000.00	€ 0.10	€ 0.29	€ 0.00
Total				**€ 0.25**			**€ 3.02**	**€ 0.88**
SC2								
Excavator	€ 135,000.00	€ 1,350.00	€ 0.00	€ 0.01	€ 2,670.24	€ 0.01	€ 0.02	€ 0.28
Impact crusher	€ 790,000.00	€ 7,900.00	€ 0.02	€ 0.05	€ 250,000.00	€ 0.50	€ 1.57	€ 0.28
Sieve tower	€ 763,000.00	€ 7,630.00	€ 0.02	€ 0.05	€ 50,000.00	€ 0.10	€ 0.31	€ 0.00
Air separator	€ 838,000.00	€ 8,380.00	€ 0.02	€ 0.04	€ 250,000.00	€ 0.50	€ 1.10	€ 0.00
SmartLiberator	€ 990,000.00	€ 9,900.00	€ 0.02	€ 0.04	€ 250,000.00	€ 0.50	€ 1.10	€ 0.97
Horizontal screen	€ 560,000.00	€ 5,600.00	€ 0.01	€ 0.02	€ 50,000.00	€ 0.10	€ 0.22	€ 0.00
Smartrefiner	€ 500,000.00	€ 5,000.00	€ 0.01	€ 0.01	€ 125,000.00	€ 0.25	€ 0.27	€ 0.00
Conveyor belts	€ 1,725,000.00	€ 17,250.00	€ 0.03	€ 0.11	€ 50,000.00	€ 0.10	€ 0.31	€ 0.00
Total				**€ 0.27**			**€ 3.32**	**€ 0.97**

Table B.8: Calculation of transport cost of the TC scenario.

Material	**M_i [t]**	**From**	**To**	**d_i [km]**	**TW_i [tkm]**	**C_T [€]**
Primary gravel	0.50	Q	M	50	43.78	€ 4.7
Primary sand	0.82	Q	M	50	71.38	€ 7.6
CEMIII	0.34	Q	M	50	29.75	€ 3.2
EoL concrete	0.63	D	R	50	54.73	€ 5.9
TRCA	0.50	R	M	50	43.78	€ 4.7
L-RFA	0.13	R	C	50	10.95	€ 1.2
Total	**2.91**				**254.38**	**€ 27.2**

[*] Q: Quarry; M: Concrete mixing plant; D: Demolition site; R: Recycling plant; C: Road construction site.

Table B.9: Calculation of transport cost of the C2CA scenarios

Material	**M_i [t]**		**From**	**To**	**d_i [km]**	**TW_i [tkm]**		**C_T [€]**	
	C2CA1	**C2CA2**				**C2CA1**	**C2CA2**	**C2CA1**	**C2CA2**
Primary gravel	-	-	-	-	-	-	-	-	-
Primary sand	0.33	-	Q	M	50	28.55	-	€ 3.05	-
CEM III	0.34	0.27	Q	M	50	29.75	23.80	€ 3.18	€ 2.55
IRCA	1.00	1.63	R	M	50	87.57	142.75	€ 9.37	€ 15.27
RFA	0.50	0.82	R	M	50	43.79	71.37	€ 4.68	€ 7.64
RCP	0.13	0.22	R	M	50	11.68	19.03	€ 1.25	€ 2.04
L-RCA	0.71	1.17	R	M	50	62.55	101.96	€ 6.69	€ 10.91
Total	**3.02**	**4.10**				**263.88**	**358.92**	**€28.23**	**€38.40**

Q: Quarry; M: Concrete mixing plant; D: Demolition site; R: Recycling plant; C: Road construction site.

Table B.10: Calculation of transport cost of the SC scenarios

Material	**M_i [t]**		**From**	**To**	**d_i [km]**	**TW_i [tkm]**		**C_T [€]**	
	SC21	**SC2**				**SC21**	**SC2**	**SC21**	**SC2**
Primary sand	0.33	-	Q	M	50.00	28.55	-	€ 3.05	-
CEM III	0.34	0.27	Q	M	50.00	29.75	23.80	€ 3.18	€ 2.55
IRCA	1.00	1.10	R	M	50.00	87.57	96.08	€ 9.37	€ 10.28
IRFA	0.74	0.82	R	M	50.00	65.06	71.38	€ 6.96	€ 7.64
RCP	0.26	0.28	R	M	50.00	22.51	24.70	€ 2.41	€ 2.64
L-RFA	0.86	0.94	R	M	50.00	75.06	82.35	€ 8.03	€ 8.81
Total	**3.53**	**3.41**				**308.50**	**298.31**	**€ 33.01**	**€ 31.92**

Q: Quarry; M: Concrete mixing plant; D: Demolition site; R: Recycling plant; C: Road construction site.

C

LCA background calculations

This appendix provides the environmental impact background calculations of the three phases of the supply chain. The calculations were performed based on the unit environmental impacts of products and processes of Table C.1.

Table C.1: Unit environmental impacts for the 11 impact categories of the CML-Baseline method

Impact category	**Unit**	**River gravel**	**River sand**	**CEMI**	**CEMIII/A**	**Electricity**	**Diesel**	**Lorry 32t**	**ECI**
		[per t]	**[per t]**	**[per t]**	**[per t]**	**[per kWh]**	**[per Lt]**	**[per tkm]**	
Abiotic depletion	kg Sb eq	1.35E-07	1.35E-07	4.15E-05	5.01E-05	5.93E-07	2.13E-08	7.11E-10	€ 0.16
Abiotic depletion (fossil fuels)	kg Sb eq	2.27E-02	2.27E-02	1.84E+00	1.28E+00	4.70E-03	2.16E-02	6.67E-04	€ 0.16
Acidification	kg SO2 eq	2.29E-02	2.29E-02	9.91E-01	6.94E-01	1.60E-03	2.44E-02	2.93E-04	€ 4.00
Eutrophication	kg PO4 eq	7.36E-03	7.36E-03	1.43E-01	1.10E-01	3.66E-04	5.65E-03	6.46E-05	€ 9.00
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	2.18E+00	2.18E+00	4.31E-01	4.24E-01	1.80E-03	3.26E-01	1.25E-02	€ 0.09
Global warming	kg CO2 eq	4.07E+00	4.07E+00	8.50E+02	5.01E+02	6.41E-01	3.26E+00	8.99E-02	€ 0.05
Human toxicity	kg 1,4-DB eq	2.31E+00	2.31E+00	3.70E+01	2.65E+01	6.66E-02	3.99E-01	3.94E-02	€ 0.09
Marine aquatic ecotoxicity	kg 1,4-DB eq	5.07E+03	5.07E+03	1.87E+03	1.85E+03	7.80E+00	5.51E+02	2.64E+01	€ 0.00
Ozone layer depletion	kg CFC-11 eq	3.22E-07	3.22E-07	5.05E-06	5.86E-06	3.45E-08	5.57E-07	1.72E-08	€ 30.00
Photochemical oxidation	kg C2H4 eq	1.43E-03	1.43E-03	5.99E-02	4.21E-02	9.72E-05	5.30E-04	1.15E-05	€ 2.00
Terrestrial ecotoxicity	kg 1,4-DB eq	6.69E-03	6.69E-03	4.58E-01	2.68E-01	3.30E-03	1.11E-03	1.20E-04	€ 0.06

Supply of primary materials

Table C.2: Environmental impacts of the production of primary materials in the TC scenario

	Primary gravel	**Primary sand**	**CEMIII/A**	**Total**
Mass [tons]	**0.50**	**0.82**	**0.34**	
ADP-minerals	6.76E-08	1.10E-07	1.70E-05	
ADP-fossil	1.13E-02	1.85E-02	4.35E-01	
AP	1.15E-02	1.87E-02	2.36E-01	
EP	3.68E-03	6.00E-03	3.74E-02	
FAETP	1.09E+00	1.78E+00	1.44E-01	
GWP100a	2.04E+00	3.32E+00	1.70E+02	
HTP	1.16E+00	1.88E+00	9.01E+00	
MAETP	2.54E+03	4.14E+03	6.29E+02	
ODP	1.61E-07	2.63E-07	1.99E-06	
POCP	7.13E-04	1.16E-03	1.43E-02	
TETP	3.35E-03	5.45E-03	9.11E-02	
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00
ADP-fossil	€ 0.00	€ 0.00	€ 0.07	€ 0.07
AP	€ 0.05	€ 0.07	€ 0.94	€ 1.06
EP	€ 0.03	€ 0.05	€ 0.34	€ 0.42
FAETP	€ 0.10	€ 0.16	€ 0.01	€ 0.27
GWP100a	€ 0.10	€ 0.17	€ 8.52	€ 8.78
HTP	€ 0.10	€ 0.17	€ 0.81	€ 1.08
MAETP	€ 0.25	€ 0.41	€ 0.06	€ 0.73
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00
POCP	€ 0.00	€ 0.00	€ 0.03	€ 0.03
TETP	€ 0.00	€ 0.00	€ 0.01	€ 0.01
Total	**€ 0.64**	**€ 1.04**	**€ 10.79**	**€ 12.47**
	5%	**8%**	**86%**	**100%**

Table C.3: Environmental impacts of the production of primary materials in the C2CA1 and SC1 scenarios

	Primary gravel	**Primary sand**	**CEMIII/A**	**Total**	
Mass [tons]		**0.33**	**0.34**		
ADP-minerals		4.41E-08	1.70E-05		
ADP-fossil		7.40E-03	4.35E-01		
AP		7.47E-03	2.36E-01		
EP		2.40E-03	3.74E-02		
FAETP		7.10E-01	1.44E-01		
GWP100a		1.33E+00	1.70E+02		
HTP		7.54E-01	9.01E+00		
MAETP		1.66E+03	6.29E+02		
ODP		1.05E-07	1.99E-06		
POCP		4.65E-04	1.43E-02		
TETP		2.18E-03	9.11E-02		
ADP-minerals	€ -	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ -	€ 0.00	€ 0.07	**€ 0.07**	**0.6%**
AP	€ -	€ 0.03	€ 0.94	**€ 0.97**	**8.7%**
EP	€ -	€ 0.02	€ 0.34	**€ 0.36**	**3.2%**
FAETP	€ -	€ 0.06	€ 0.01	**€ 0.08**	**0.7%**
GWP100a	€ -	€ 0.07	€ 8.52	**€ 8.58**	**76.6%**
HTP	€ -	€ 0.07	€ 0.81	**€ 0.88**	**7.8%**
MAETP	€ -	€ 0.17	€ 0.06	**€ 0.23**	**2.0%**
ODP	€ -	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ -	€ 0.00	€ 0.03	**€ 0.03**	**0.3%**
TETP	€ -	€ 0.00	€ 0.01	**€ 0.01**	**0.0%**
Total	**€ -**	**€ 0.42**	**€ 10.79**	**€ 11.21**	**100.0%**
		4%	**96%**	**100%**	

Recycling process

Table C.4: Environmental impacts of the production of primary materials in the C2CA2 and SC2 scenarios

	Primary gravel	**Primary sand**	**CEMIII/A**	**Total**	
Mass [tons]			**0.27**		
ADP-minerals			1.36E-05		
ADP-fossil			3.48E-01		
AP			1.89E-01		
EP			2.99E-02		
FAETP			1.15E-01		
GWP100a			1.36E+02		
HTP			7.21E+00		
MAETP			5.03E+02		
ODP			1.59E-06		
POCP			1.15E-02		
TETP			7.29E-02		
ADP-minerals	€ -	€ -	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ -	€ -	€ 0.06	**€ 0.06**	**0.6%**
AP	€ -	€ -	€ 0.76	**€ 0.76**	**8.7%**
EP	€ -	€ -	€ 0.27	**€ 0.27**	**3.1%**
FAETP	€ -	€ -	€ 0.01	**€ 0.01**	**0.1%**
GWP100a	€ -	€ -	€ 6.81	**€ 6.81**	**78.9%**
HTP	€ -	€ -	€ 0.65	**€ 0.65**	**7.5%**
MAETP	€ -	€ -	€ 0.05	**€ 0.05**	**0.6%**
ODP	€ -	€ -	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ -	€ -	€ 0.02	**€ 0.02**	**0.3%**
TETP	€ -	€ -	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ -**	**€ -**	**€ 8.63**	**€ 8.63**	**100.0%**
			100%		

Table C.5: Environmental impacts of the TC recycling phase

	Excavator	**Vibrating feeder**	**Magnet #1**	**Screen #1**	**Jaw crusher**	**Magnet #2**	**Screen #2**	**Impact crusher**	**Air sifters**	**Eddy current**	**Screen #3**	**Conveyors**	**Total**	
ADP-minerals	8.01E-10	1.71E-08	2.47E-09	6.88E-09	2.43E-08	6.55E-09	1.83E-08	6.90E-07	6.21E-09	1.62E-08	1.83E-08	1.15E-08	**8.18E-07**	
ADP-fossil	8.10E-04	1.35E-04	1.96E-05	5.45E-05	1.93E-04	5.19E-05	1.45E-04	5.47E-03	4.92E-05	1.29E-04	1.45E-04	9.11E-05	**7.29E-03**	
AP	9.15E-04	4.60E-05	6.66E-06	1.86E-05	6.56E-05	1.77E-05	4.93E-05	1.86E-03	1.68E-05	4.37E-05	4.93E-05	3.10E-05	**3.12E-03**	
EP	2.12E-04	1.05E-05	1.52E-06	4.25E-06	1.50E-05	4.05E-06	1.13E-05	4.26E-04	3.83E-06	1.00E-05	1.13E-05	7.10E-06	**7.17E-04**	
FAETP	1.22E-02	5.18E-05	7.49E-06	2.09E-05	7.38E-05	1.99E-05	5.55E-05	2.09E-03	1.88E-05	4.92E-05	5.55E-05	3.49E-05	**1.47E-02**	
GWP100a	1.22E-01	1.84E-02	2.67E-03	7.44E-03	2.63E-02	7.08E-03	1.98E-02	7.46E-01	6.71E-03	1.75E-02	1.98E-02	1.24E-02	**1.01E+00**	
HTP	1.50E-02	1.92E-03	2.77E-04	7.73E-04	2.73E-03	7.36E-04	2.05E-03	7.75E-02	6.97E-04	1.82E-03	2.05E-03	1.29E-03	**1.07E-01**	
MAETP	2.07E+01	2.24E-01	3.24E-02	9.05E-02	3.20E-01	8.62E-02	2.40E-01	9.07E+00	8.16E-02	2.13E-01	2.40E-01	1.51E-01	**3.14E+01**	
ODP	2.09E-08	9.93E-10	1.44E-10	4.00E-10	1.41E-09	3.81E-10	1.06E-09	4.01E-08	3.61E-10	9.43E-10	1.06E-09	6.69E-10	**6.85E-08**	
POCP	1.99E-05	2.80E-06	4.04E-07	1.13E-06	3.99E-06	1.07E-06	3.00E-06	1.13E-04	1.02E-06	2.66E-06	3.00E-06	1.88E-06	**1.54E-04**	
TETP	4.17E-05	9.50E-05	1.37E-05	3.83E-05	1.35E-04	3.65E-05	1.02E-04	3.84E-03	3.46E-05	9.02E-05	1.02E-04	6.40E-05	**4.59E-03**	
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0%**
ADP-fossil	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**1%**
AP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**15%**
EP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**8%**
FAETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**2%**
GWP100a	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.04	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.05**	**59%**
HTP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**11%**
MAETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**4%**
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0%**
POCP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0%**
TETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0%**
Total	**€ 0.02**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.06**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	€ 0.09	**100%**
	19%	**2%**	**0%**	**1%**	**2%**	**1%**	**2%**	**68%**	**1%**	**2%**	**2%**	**1%**	**100%**	

Table C.6: Environmental impacts of the C2CA1 recycling phase

C2CA1	**Excavator**	**Jaw crusher**	**Impact crusher**	**Horizontal screen**	**ADR**	**HAS**	**Conveyors**	**Total**	
ADP-minerals	3.05E-09	3.05E-09	3.53E-06	7.49E-08	4.55E-07	8.39E-08	4.38E-08		
ADP-fossil	3.08E-03	3.08E-03	2.80E-02	5.94E-04	3.61E-03	8.08E-02	3.47E-04		
AP	3.49E-03	3.49E-03	9.53E-03	2.02E-04	1.23E-03	9.13E-02	1.18E-04		
EP	8.08E-04	8.08E-04	2.18E-03	4.62E-05	2.81E-04	2.12E-02	2.70E-05		
FAETP	4.66E-02	4.66E-02	1.07E-02	2.27E-04	1.38E-03	1.22E+00	1.33E-04		
GWP100a	4.66E-01	4.66E-01	3.82E+00	8.09E-02	4.92E-01	1.22E+01	4.73E-02		
HTP	5.70E-02	5.70E-02	3.97E-01	8.41E-03	5.11E-02	1.49E+00	4.92E-03		
MAETP	7.88E+01	7.88E+01	4.64E+01	9.85E-01	5.98E+00	2.06E+03	5.76E-01		
ODP	7.96E-08	7.96E-08	2.06E-07	4.36E-09	2.65E-08	2.09E-06	2.55E-09		
POCP	7.58E-05	7.58E-05	5.79E-04	1.23E-05	7.46E-05	1.98E-03	7.18E-06		
TETP	1.59E-04	1.59E-04	1.97E-02	4.17E-04	2.53E-03	4.18E-03	2.44E-04		
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.00	**€ 0.02**	**0.9%**
AP	€ 0.01	€ 0.00	€ 0.04	€ 0.00	€ 0.00	€ 0.37	€ 0.00	**€ 0.42**	**20.7%**
EP	€ 0.01	€ 0.00	€ 0.02	€ 0.00	€ 0.00	€ 0.19	€ 0.00	**€ 0.22**	**10.8%**
FAETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.11	€ 0.00	**€ 0.12**	**5.6%**
GWP100a	€ 0.02	€ 0.01	€ 0.19	€ 0.00	€ 0.02	€ 0.61	€ 0.00	**€ 0.86**	**41.9%**
HTP	€ 0.01	€ 0.00	€ 0.04	€ 0.00	€ 0.00	€ 0.13	€ 0.00	**€ 0.18**	**8.9%**
MAETP	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.21	€ 0.00	**€ 0.22**	**10.8%**
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**0.3%**
TETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ 0.06**	€ 0.01	**€ 0.30**	**€ 0.01**	**€ 0.04**	**€ 1.63**	**€ 0.00**	**€ 2.05**	**100.0%**
	3.0%	0.6%	**14.5%**	**0.3%**	**1.9%**	**79.6%**	**0.2%**	**100%**	

Table C.7: Environmental impacts of the C2CA2 recycling phase

C2CA2	**Excavator**	**Jaw crusher**	**Impact crusher**	**Horizontal screen**	**ADR**	**HAS**	**Conveyors**	**Total**	
ADP-minerals	4.97E-09	2.32E-07	5.76E-06	1.22E-07	7.42E-07	1.37E-07	7.14E-08		
ADP-fossil	5.03E-03	6.27E-04	4.56E-02	9.68E-04	5.88E-03	1.32E-01	5.66E-04		
AP	5.68E-03	1.43E-04	1.55E-02	3.29E-04	2.00E-03	1.49E-01	1.93E-04		
EP	1.32E-03	7.05E-04	3.55E-03	7.53E-05	4.58E-04	3.45E-02	4.41E-05		
FAETP	7.59E-02	2.51E-01	1.75E-02	3.71E-04	2.25E-03	1.99E+00	2.17E-04		
GWP100a	7.59E-01	2.61E-02	6.22E+00	1.32E-01	8.01E-01	1.99E+01	7.72E-02		
HTP	9.29E-02	3.05E+00	6.47E-01	1.37E-02	8.33E-02	2.43E+00	8.02E-03		
MAETP	1.28E+02	1.35E-08	7.57E+01	1.60E+00	9.75E+00	3.36E+03	9.39E-01		
ODP	1.30E-07	3.81E-05	3.35E-07	7.10E-09	4.32E-08	3.40E-06	4.15E-09		
POCP	1.24E-04	1.29E-03	9.44E-04	2.00E-05	1.22E-04	3.24E-03	1.17E-05		
TETP	2.59E-04	1.29E-03	3.20E-02	6.79E-04	4.13E-03	6.81E-03	3.97E-04		
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.02	€ 0.00	**€ 0.03**	**0.9%**
AP	€ 0.02	€ 0.00	€ 0.06	€ 0.00	€ 0.01	€ 0.60	€ 0.00	**€ 0.69**	**20.7%**
EP	€ 0.01	€ 0.00	€ 0.03	€ 0.00	€ 0.00	€ 0.31	€ 0.00	**€ 0.36**	**10.8%**
FAETP	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.18	€ 0.00	**€ 0.19**	**5.6%**
GWP100a	€ 0.04	€ 0.01	€ 0.31	€ 0.01	€ 0.04	€ 0.99	€ 0.00	**€ 1.39**	**41.9%**
HTP	€ 0.01	€ 0.00	€ 0.06	€ 0.00	€ 0.01	€ 0.22	€ 0.00	**€ 0.30**	**8.9%**
MAETP	€ 0.01	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.34	€ 0.00	**€ 0.36**	**10.8%**
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.00	**€ 0.01**	**0.3%**
TETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ 0.10**	€ 0.02	**€ 0.48**	**€ 0.01**	**€ 0.06**	**€ 2.66**	**€ 0.01**	**€ 3.35**	**100.0%**
	3.0%	0.6%	**14.5%**	**0.3%**	**1.9%**	**76.9%**	**0.2%**	**100%**	

Table C.8: Environmental impacts of the SC1 recycling phase

SC1	**Excavator**	**Impact crusher**	**Sieve tower**	**Air separator**	**SmartLiberator**	**Horizontal screen**	**Smartrefiner**	**Coveyor belts**	**Total**	
ADP-minerals	3.66E-09	4.24E-06	5.09E-07	3.56E-07	1.19E-07	1.78E-07	3.26E-07	3.39E-07		
ADP-fossil	3.70E-03	3.36E-02	4.03E-03	2.82E-03	9.41E-04	1.41E-03	2.59E-03	2.69E-03		
AP	4.18E-03	1.14E-02	1.37E-03	9.61E-04	3.20E-04	4.80E-04	8.81E-04	9.15E-04		
EP	9.69E-04	2.62E-03	3.14E-04	2.20E-04	7.33E-05	1.10E-04	2.01E-04	2.09E-04		
FAETP	5.59E-02	1.29E-02	1.54E-03	1.08E-03	3.60E-04	5.40E-04	9.91E-04	1.03E-03		
GWP100a	5.59E-01	4.58E+00	5.50E-01	3.85E-01	1.28E-01	1.92E-01	3.53E-01	3.66E-01		
HTP	6.84E-02	4.76E-01	5.71E-02	4.00E-02	1.33E-02	2.00E-02	3.67E-02	3.81E-02		
MAETP	9.45E+01	5.57E+01	6.69E+00	4.68E+00	1.56E+00	2.34E+00	4.29E+00	4.46E+00		
ODP	9.56E-08	2.47E-07	2.96E-08	2.07E-08	6.91E-09	1.04E-08	1.90E-08	1.97E-08		
POCP	9.09E-05	6.95E-04	8.34E-05	5.84E-05	1.95E-05	2.92E-05	5.35E-05	5.56E-05		
TETP	1.90E-04	2.36E-02	2.83E-03	1.98E-03	6.61E-04	9.91E-04	1.82E-03	1.89E-03		
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**1.4%**
AP	€ 0.02	€ 0.05	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.08**	**14.1%**
EP	€ 0.01	€ 0.02	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.04**	**7.3%**
FAETP	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**1.1%**
GWP100a	€ 0.03	€ 0.23	€ 0.03	€ 0.02	€ 0.01	€ 0.01	€ 0.02	€ 0.02	**€ 0.36**	**60.9%**
HTP	€ 0.01	€ 0.04	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.07**	**11.5%**
MAETP	€ 0.01	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.02**	**3.0%**
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.4%**
TETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.3%**
Total	**€ 0.07**	**€ 0.36**	**€ 0.04**	**€ 0.03**	**€ 0.01**	**€ 0.01**	**€ 0.03**	**€ 0.03**	**€ 0.58**	**100.0%**
	12.8%	**60.9%**	**7.3%**	**5.1%**	**1.7%**	**2.6%**	**4.7%**	**4.9%**	**100%**	

Table C.9: Environmental impacts of the SC2recycling phase

SC2	**Excavator**	**Impact crusher**	**Sieve tower**	**Air separator**	**SmartLiberator**	**Horizontal screen**	**Smartrefiner**	**Coveyor belts**	**Total**	
ADP-minerals	4.02E-09	4.65E-06	5.58E-07	3.91E-07	1.30E-07	1.95E-07	3.58E-07	3.72E-07		
ADP-fossil	4.06E-03	3.69E-02	4.42E-03	3.10E-03	1.03E-03	1.55E-03	2.84E-03	2.95E-03		
AP	4.59E-03	1.25E-02	1.51E-03	1.05E-03	3.51E-04	5.27E-04	9.66E-04	1.00E-03		
EP	1.06E-03	2.87E-03	3.44E-04	2.41E-04	8.04E-05	1.21E-04	2.21E-04	2.30E-04		
FAETP	6.13E-02	1.41E-02	1.69E-03	1.19E-03	3.95E-04	5.93E-04	1.09E-03	1.13E-03		
GWP100a	6.13E-01	5.03E+00	6.03E-01	4.22E-01	1.41E-01	2.11E-01	3.87E-01	4.02E-01		
HTP	7.51E-02	5.22E-01	6.27E-02	4.39E-02	1.46E-02	2.19E-02	4.02E-02	4.18E-02		
MAETP	1.04E+02	6.11E+01	7.34E+00	5.14E+00	1.71E+00	2.57E+00	4.71E+00	4.89E+00		
ODP	1.05E-07	2.71E-07	3.25E-08	2.27E-08	7.58E-09	1.14E-08	2.08E-08	2.16E-08		
POCP	9.98E-05	7.62E-04	9.15E-05	6.40E-05	2.13E-05	3.20E-05	5.87E-05	6.10E-05		
TETP	2.09E-04	2.59E-02	3.11E-03	2.17E-03	7.25E-04	1.09E-03	1.99E-03	2.07E-03		
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**1.4%**
AP	€ 0.02	€ 0.05	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.09**	**14.1%**
EP	€ 0.01	€ 0.03	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.05**	**7.3%**
FAETP	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**1.1%**
GWP100a	€ 0.03	€ 0.25	€ 0.03	€ 0.02	€ 0.01	€ 0.01	€ 0.02	€ 0.02	**€ 0.39**	**60.9%**
HTP	€ 0.01	€ 0.05	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.07**	**11.5%**
MAETP	€ 0.01	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.02**	**3.0%**
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.4%**
TETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.3%**
Total	**€ 0.08**	**€ 0.39**	**€ 0.05**	**€ 0.03**	**€ 0.01**	**€ 0.02**	**€ 0.03**	**€ 0.03**	**€ 0.64**	**100.0%**
	12.8%	**60.9%**	**7.3%**	**5.1%**	**1.7%**	**2.6%**	**4.7%**	**4.9%**	**100%**	

Transports

Table C.10: Environmental impacts of transports in the TC scenario

TC	**Primary gravel**	**Primary sand**	**CEM III**	**EoL concrete**	**TRCA**	**L-RFA**	**Total**	
Tw$_i$ [tkm]	**43.78**	**71.38**	**29.75**	**54.73**	**43.78**	**10.95**	**254.38**	
ADP-minerals	3.11E-08	5.07E-08	2.11E-08	3.89E-08	3.11E-08	7.78E-09		
ADP-fossil	2.92E-02	4.76E-02	1.99E-02	3.65E-02	2.92E-02	7.31E-03		
AP	1.28E-02	2.09E-02	8.73E-03	1.61E-02	1.28E-02	3.21E-03		
EP	2.83E-03	4.61E-03	1.92E-03	3.54E-03	2.83E-03	7.07E-04		
FAETP	5.49E-01	8.95E-01	3.73E-01	6.87E-01	5.49E-01	1.37E-01		
GWP100a	3.94E+00	6.42E+00	2.68E+00	4.92E+00	3.94E+00	9.84E-01		
HTP	1.72E+00	2.81E+00	1.17E+00	2.16E+00	1.72E+00	4.31E-01		
MAETP	1.16E+03	1.88E+03	7.85E+02	1.44E+03	1.16E+03	2.89E+02		
ODP	7.52E-07	1.23E-06	5.11E-07	9.39E-07	7.52E-07	1.88E-07		
POCP	5.04E-04	8.21E-04	3.42E-04	6.30E-04	5.04E-04	1.26E-04		
TETP	5.24E-03	8.54E-03	3.56E-03	6.55E-03	5.24E-03	1.31E-03		
ADP-minerals	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ 0.00	€ 0.01	€ 0.00	€ 0.01	€ 0.00	€ 0.02	**€ 0.04**	**0.8%**
AP	€ 0.05	€ 0.08	€ 0.03	€ 0.06	€ 0.01	€ 0.25	**€ 0.49**	**8.6%**
EP	€ 0.03	€ 0.04	€ 0.02	€ 0.03	€ 0.01	€ 0.12	**€ 0.24**	**4.2%**
FAETP	€ 0.05	€ 0.08	€ 0.03	€ 0.06	€ 0.01	€ 0.24	**€ 0.48**	**8.2%**
GWP100a	€ 0.20	€ 0.32	€ 0.13	€ 0.25	€ 0.05	€ 0.95	**€ 1.89**	**32.8%**
HTP	€ 0.16	€ 0.25	€ 0.11	€ 0.19	€ 0.04	€ 0.75	**€ 1.49**	**25.9%**
MAETP	€ 0.12	€ 0.19	€ 0.08	€ 0.14	€ 0.03	€ 0.56	**€ 1.11**	**19.3%**
ODP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**0.2%**
TETP	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ 0.60**	**€ 0.98**	**€ 0.41**	**€ 0.75**	**€ 0.15**	**€ 2.89**	**€ 5.77**	**100.0%**
	10%	**17%**	**7%**	**13%**	**3%**	**50%**	**100%**	

Table C.11: Environmental impacts of transports in the C2CA scenarios

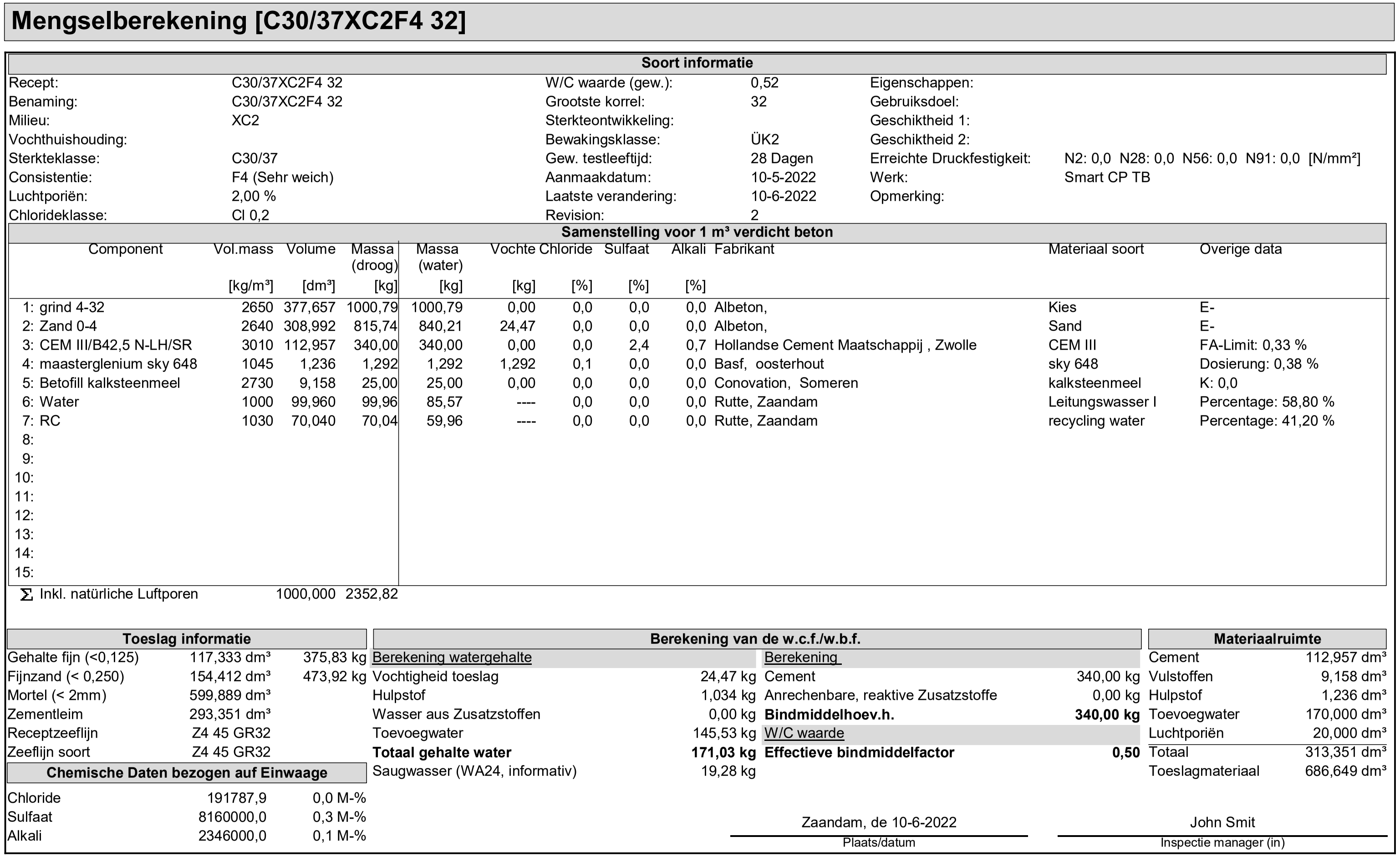
C2CA1	**Primary gravel**	**Primary sand**	**CEMIII/A**	**IRCA**	**IRFA**	**RCP**	**L-RCA**	**Total**	
Tw$_i$ [tkm]		**28.55**	**29.75**	**87.57**	**43.79**	**11.68**	**62.55**	**263.88**	
ADP-minerals		2.03E-08	2.11E-08	6.22E-08	3.11E-08	8.30E-09	4.44488E-08		
ADP-fossil		1.91E-02	1.99E-02	5.84E-02	2.92E-02	7.79E-03	0.041749746		
AP		8.38E-03	8.73E-03	2.57E-02	1.28E-02	3.43E-03	0.018349654		
EP		1.84E-03	1.92E-03	5.66E-03	2.83E-03	7.54E-04	0.00404121		
FAETP		3.58E-01	3.73E-01	1.10E+00	5.49E-01	1.46E-01	0.784695589		
GWP100a		2.57E+00	2.68E+00	7.87E+00	3.94E+00	1.05E+00	5.624921923		
HTP		1.12E+00	1.17E+00	3.45E+00	1.72E+00	4.60E-01	2.463929009		
MAETP		7.54E+02	7.85E+02	2.31E+03	1.16E+03	3.08E+02	1651.100588		
ODP		4.90E-07	5.11E-07	1.50E-06	7.52E-07	2.00E-07	1.07362E-06		
POCP		3.28E-04	3.42E-04	1.01E-03	5.04E-04	1.34E-04	0.000719568		
TETP		3.41E-03	3.56E-03	1.05E-02	5.24E-03	1.40E-03	0.00748004		
ADP-minerals	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ -	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.01	**€ 0.03**	**0.8%**
AP	€ -	€ 0.03	€ 0.03	€ 0.10	€ 0.05	€ 0.01	€ 0.07	**€ 0.31**	**8.6%**
EP	€ -	€ 0.02	€ 0.02	€ 0.05	€ 0.03	€ 0.01	€ 0.04	**€ 0.15**	**4.2%**
FAETP	€ -	€ 0.03	€ 0.03	€ 0.10	€ 0.05	€ 0.01	€ 0.07	**€ 0.30**	**8.2%**
GWP100a	€ -	€ 0.13	€ 0.13	€ 0.39	€ 0.20	€ 0.05	€ 0.28	**€ 1.19**	**32.8%**
HTP	€ -	€ 0.10	€ 0.11	€ 0.31	€ 0.16	€ 0.04	€ 0.22	**€ 0.94**	**25.9%**
MAETP	€ -	€ 0.08	€ 0.08	€ 0.23	€ 0.12	€ 0.03	€ 0.17	**€ 0.70**	**19.3%**
ODP	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**0.2%**
TETP	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ -**	**€ 0.39**	**€ 0.41**	**€ 1.20**	**€ 0.60**	**€ 0.16**	**€ 0.86**	**€ 3.62**	**100.0%**
		11%	**11%**	**33%**	**17%**	**4%**	**24%**	**100%**	
C2CA2	**Primary gravel**	**Primary sand**	**CEMIII/A**	**IRCA**	**IRFA**	**RCP**	**L-RCA**	**Total**	
Tw$_i$ [tkm]			**23.80**	**142.75**	**71.37**	**19.03**	**101.96**	**358.92**	
ADP-minerals			1.69E-08	1.01E-07	5.07E-08	1.35E-08	7.24558E-08		
ADP-fossil			1.59E-02	9.53E-02	4.76E-02	1.27E-02	0.06805609		
AP			6.98E-03	4.19E-02	2.09E-02	5.58E-03	0.029911696		
EP			1.54E-03	9.22E-03	4.61E-03	1.23E-03	0.006587561		
FAETP			2.99E-01	1.79E+00	8.95E-01	2.39E-01	1.27912908		
GWP100a			2.14E+00	1.28E+01	6.42E+00	1.71E+00	9.169162295		
HTP			9.38E-01	5.62E+00	2.81E+00	7.50E-01	4.016440633		
MAETP			6.28E+02	3.77E+03	1.88E+03	5.02E+02	2691.452338		
ODP			4.09E-07	2.45E-06	1.23E-06	3.27E-07	1.7501E-06		
POCP			2.74E-04	1.64E-03	8.21E-04	2.19E-04	0.001172964		
TETP			2.85E-03	1.71E-02	8.54E-03	2.28E-03	0.012193182		
ADP-minerals	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ -	€ -	€ 0.00	€ 0.02	€ 0.01	€ 0.00	€ 0.01	**€ 0.04**	**0.8%**
AP	€ -	€ -	€ 0.03	€ 0.17	€ 0.08	€ 0.02	€ 0.12	**€ 0.42**	**8.6%**
EP	€ -	€ -	€ 0.01	€ 0.08	€ 0.04	€ 0.01	€ 0.06	**€ 0.21**	**4.2%**
FAETP	€ -	€ -	€ 0.03	€ 0.16	€ 0.08	€ 0.02	€ 0.12	**€ 0.41**	**8.2%**
GWP100a	€ -	€ -	€ 0.11	€ 0.64	€ 0.32	€ 0.09	€ 0.46	**€ 1.61**	**32.8%**
HTP	€ -	€ -	€ 0.08	€ 0.51	€ 0.25	€ 0.07	€ 0.36	**€ 1.27**	**25.9%**
MAETP	€ -	€ -	€ 0.06	€ 0.38	€ 0.19	€ 0.05	€ 0.27	**€ 0.95**	**19.3%**
ODP	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**0.2%**
TETP	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ -**	**€ -**	**€ 0.33**	**€ 1.96**	**€ 0.98**	**€ 0.26**	**€ 1.40**	**€ 4.92**	**100.0%**
			7%	**40%**	**20%**	**5%**	**28%**	**100%**	

Table C.12: Environmental impacts of transports in the C2CA scenarios

SC1	**Primary gravel**	**Primary sand**	**CEMIII/A**	**IRCA**	**IRFA**	**RCP**	**L-RFA**	**Total**	
Tw$_i$ [tkm]		**28.55**	**29.75**	**87.57**	**65.06**	**22.51**	**75.06**	**308.50**	
ADP-minerals		2.03E-08	2.11E-08	6.22E-08	4.62E-08	1.60E-08	5.3338E-08		
ADP-fossil		1.91E-02	1.99E-02	5.84E-02	4.34E-02	1.50E-02	0.050099194		
AP		8.38E-03	8.73E-03	2.57E-02	1.91E-02	6.60E-03	0.022019365		
EP		1.84E-03	1.92E-03	5.66E-03	4.20E-03	1.45E-03	0.004849404		
FAETP		3.58E-01	3.73E-01	1.10E+00	8.16E-01	2.82E-01	0.941625297		
GWP100a		2.57E+00	2.68E+00	7.87E+00	5.85E+00	2.02E+00	6.749838862		
HTP		1.12E+00	1.17E+00	3.45E+00	2.56E+00	8.87E-01	2.956685267		
MAETP		7.54E+02	7.85E+02	2.31E+03	1.72E+03	5.94E+02	1981.300909		
ODP		4.90E-07	5.11E-07	1.50E-06	1.12E-06	3.86E-07	1.28833E-06		
POCP		3.28E-04	3.42E-04	1.01E-03	7.48E-04	2.59E-04	0.000863473		
TETP		3.41E-03	3.56E-03	1.05E-02	7.78E-03	2.69E-03	0.008975958		
ADP-minerals	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ -	€ 0.00	€ 0.00	€ 0.01	€ 0.01	€ 0.00	€ 0.01	**€ 0.03**	**0.8%**
AP	€ -	€ 0.03	€ 0.03	€ 0.10	€ 0.08	€ 0.03	€ 0.09	**€ 0.36**	**8.6%**
EP	€ -	€ 0.02	€ 0.02	€ 0.05	€ 0.04	€ 0.01	€ 0.04	**€ 0.18**	**4.2%**
FAETP	€ -	€ 0.03	€ 0.03	€ 0.10	€ 0.07	€ 0.03	€ 0.08	**€ 0.35**	**8.2%**
GWP100a	€ -	€ 0.13	€ 0.13	€ 0.39	€ 0.29	€ 0.10	€ 0.34	**€ 1.39**	**32.8%**
HTP	€ -	€ 0.10	€ 0.11	€ 0.31	€ 0.23	€ 0.08	€ 0.27	**€ 1.09**	**25.9%**
MAETP	€ -	€ 0.08	€ 0.08	€ 0.23	€ 0.17	€ 0.06	€ 0.20	**€ 0.81**	**19.3%**
ODP	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**0.2%**
TETP	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ -**	**€ 0.39**	**€ 0.41**	**€ 1.20**	**€ 0.89**	**€ 0.31**	**€ 1.03**	**€ 4.23**	**100.0%**
		9%	**10%**	**28%**	**21%**	**7%**	**24%**	**100%**	
SC2	**Primary gravel**	**Primary sand**	**CEMIII/A**	**IRCA**	**IRFA**	**RCP**	**L-RFA**	**Total**	
Tw$_i$ [tkm]			**23.80**	**96.08**	**71.38**	**24.70**	**82.35**	**298.31**	
ADP-minerals			1.69E-08	6.83E-08	5.07E-08	1.76E-08	5.85215E-08		
ADP-fossil			1.59E-02	6.41E-02	4.76E-02	1.65E-02	0.054967905		
AP			6.98E-03	2.82E-02	2.09E-02	7.25E-03	0.024159238		
EP			1.54E-03	6.21E-03	4.61E-03	1.60E-03	0.005320676		
FAETP			2.99E-01	1.21E+00	8.95E-01	3.10E-01	1.033133777		
GWP100a			2.14E+00	8.64E+00	6.42E+00	2.22E+00	7.405797762		
HTP			9.38E-01	3.78E+00	2.81E+00	9.73E-01	3.244020129		
MAETP			6.28E+02	2.54E+03	1.88E+03	6.52E+02	2173.846537		
ODP			4.09E-07	1.65E-06	1.23E-06	4.24E-07	1.41353E-06		
POCP			2.74E-04	1.11E-03	8.21E-04	2.84E-04	0.000947386		
TETP			2.85E-03	1.15E-02	8.54E-03	2.95E-03	0.009848254		
ADP-minerals	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
ADP-fossil	€ -	€ -	€ 0.00	€ 0.01	€ 0.01	€ 0.00	€ 0.01	**€ 0.03**	**0.8%**
AP	€ -	€ -	€ 0.03	€ 0.11	€ 0.08	€ 0.03	€ 0.10	**€ 0.35**	**8.6%**
EP	€ -	€ -	€ 0.01	€ 0.06	€ 0.04	€ 0.01	€ 0.05	**€ 0.17**	**4.2%**
FAETP	€ -	€ -	€ 0.03	€ 0.11	€ 0.08	€ 0.03	€ 0.09	**€ 0.34**	**8.2%**
GWP100a	€ -	€ -	€ 0.11	€ 0.43	€ 0.32	€ 0.11	€ 0.37	**€ 1.34**	**32.8%**
HTP	€ -	€ -	€ 0.08	€ 0.34	€ 0.25	€ 0.09	€ 0.29	**€ 1.06**	**25.9%**
MAETP	€ -	€ -	€ 0.06	€ 0.25	€ 0.19	€ 0.07	€ 0.22	**€ 0.79**	**19.3%**
ODP	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.0%**
POCP	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.01**	**0.2%**
TETP	€ -	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	**€ 0.00**	**0.1%**
Total	**€ -**	**€ -**	**€ 0.33**	**€ 1.32**	**€ 0.98**	**€ 0.34**	**€ 1.13**	**€ 4.09**	**100.0%**
			8%	**32%**	**24%**	**8%**	**28%**	**100%**	

D

Reference concrete recipe



Mengselberekening [C30/37XC2F4 32]

Soort informatie

Recept:	C30/37XC2F4 32	W/C waarde (gew.):	0,52	Eigenschappen:	
Benaming:	C30/37XC2F4 32	Grootste korrel:	32	Gebruiksdoel:	
Milieu:	XC2	Sterkteontwikkeling:		Geschiktheid 1:	
Vochthuishouding:		Bewakingsklasse:	ÜK2	Geschiktheid 2:	
Sterkteklasse:	C30/37	Gew. testleeftijd:	28 Dagen	Erreichte Druckfestigkeit:	N2: 0,0 N28: 0,0 N56: 0,0 N91: 0,0 [N/mm²]
Consistentie:	F4 (Sehr weich)	Aanmaakdatum:	10-5-2022	Werk:	Smart CP TB
Luchtporiën:	2,00 %	Laatste verandering:	10-6-2022	Opmerking:	
Chlorideklasse:	Cl 0,2	Revision:	2		

Samenstelling voor 1 m³ verdicht beton

Component	Vol.mass [kg/m³]	Volume [dm³]	Massa (droog) [kg]	Massa (water) [kg]	Vochte [kg]	Chloride [%]	Sulfaat [%]	Alkali [%]	Fabrikant	Materiaal soort	Overige data
1: grind 4-32	2650	377,657	1000,79	1000,79	0,00	0,0	0,0	0,0	Albeton,	Kies	E-
2: Zand 0-4	2640	308,992	815,74	840,21	24,47	0,0	0,0	0,0	Albeton,	Sand	E-
3: CEM III/B42,5 N-LH/SR	3010	112,957	340,00	340,00	0,00	0,0	2,4	0,7	Hollandse Cement Maatschappij , Zwolle	CEM III	FA-Limit: 0,33 %
4: maasterglenium sky 648	1045	1,236	1,292	1,292	1,292	0,1	0,0	0,0	Basf, oosterhout	sky 648	Dosierung: 0,38 %
5: Betofill kalksteenmeel	2730	9,158	25,00	25,00	0,00	0,0	0,0	0,0	Conovation, Someren	kalksteenmeel	K: 0,0
6: Water	1000	99,960	99,96	85,57	----	0,0	0,0	0,0	Rutte, Zaandam	Leitungswasser l	Percentage: 58,80 %
7: RC	1030	70,040	70,04	59,96	----	0,0	0,0	0,0	Rutte, Zaandam	recycling water	Percentage: 41,20 %
8:											
9:											
10:											
11:											
12:											
13:											
14:											
15:											
Σ Inkl. natürliche Luftporen		1000,000	2352,82								

Toeslag informatie

Gehalte fijn (<0,125)	117,333 dm³	375,83 kg
Fijnzand (< 0,250)	154,412 dm³	473,92 kg
Mortel (< 2mm)	599,889 dm³	
Zementleim	293,351 dm³	
Receptzeeflijn	Z4 45 GR32	
Zeeflijn soort	Z4 45 GR32	

Chemische Daten bezogen auf Einwaage

Chloride	191787,9	0,0 M-%
Sulfaat	8160000,0	0,3 M-%
Alkali	2346000,0	0,1 M-%

Berekening van de w.c.f./w.b.f.

Berekening watergehalte		Berekening	
Vochtigheid toeslag	24,47 kg	Cement	340,00 kg
Hulpstof	1,034 kg	Anrechenbare, reaktive Zusatzstoffe	0,00 kg
Wasser aus Zusatzstoffen	0,00 kg	**Bindmiddelhoev.h.**	**340,00 kg**
Toevoegwater	145,53 kg	W/C waarde	
Totaal gehalte water	**171,03 kg**	**Effectieve bindmiddelfactor**	**0,50**
Saugwasser (WA24, informativ)	19,28 kg		

Materiaalruimte

Cement	112,957 dm³
Vulstoffen	9,158 dm³
Hulpstof	1,236 dm³
Toevoegwater	170,000 dm³
Luchtporiën	20,000 dm³
Totaal	313,351 dm³
Toeslagmateriaal	686,649 dm³

Zaandam, de 10-6-2022
Plaats/datum

John Smit
Inspectie manager (in)

Figure D.1: Reference concrete mix from Rutte Groep (2022)