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Sustainable Building

A Case Study on Concrete Recycling in France

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Abstract

This case-study paper focuses on concrete recycling in France as a means of understanding circular-economy transitions in the building-materials sector. The EU, including France, produces large volumes of construction and demolition waste (CDW) per year and aims to increase the re-use of these materials, reducing landfilling and negative environmental impacts. Recycling concrete is seen as a way to contribute to these objectives by ensuring that a portion of this waste is turned into a product with value. Currently, France does not recycle CDW as much as some other Member States. This case study paper carries out a scenario analysis comparing two future scenarios for 2030, providing insights into important environmental and economic impacts of an increased concrete recycling rate in France.

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List of Abbreviations

BAU	Business as usual
CDW	Construction and demolition waste
EEA	European Environmental Agency
EoW	End of waste
EU	European Union
LCA	Life-cycle analysis
MJ	Megajoule
mm	Millimetre
Mtonnes	Million tonnes
RCA	Recycled concrete aggregates
RMC	Ready-mix concrete

Executive Summary

Concrete is the second most widely used material in the world after water, with twice the amount of concrete used annually compared to all other construction materials combined (The Cement Sustainability Initiative, 2009). While lauded for its versatility, durability, and strength in construction use, concrete poses environmental challenges regarding materials used. Portland cement, the binding component of concrete, is the energy-intensive and carbon-producing aspect of concrete manufacturing, requiring approximately 4,882 mega joules per tonne for production (Struble & Godfrey, 2004) and releasing nearly 1 tonne of carbon dioxide for every tonne of cement produced, resulting in approximately 6-7% of global CO_2 emissions (Imbabi, Carrigan, & Mckenna, 2012; Meyer, 2009). Aggregates are the largest concrete component, contributing between 60 to 75% of its volume (DPD Concrete Team, n.d.), and are predominantly sourced via quarrying for raw materials. In 2015, the total production of aggregates in the EU-28 and European Free Trade Association (EFTA) countries was 2.66 billion tonnes, including 277 million tonnes of recycled, re-used and manufactured aggregates, of which around 45% was used for different concrete applications (UEPG, n.d.(a)).

Other components of concrete's life cycle contribute to environmental costs as well. For example, transportation of materials adds significant carbon emissions. Cement production is forecasted to grow significantly, particularly in developing countries as modernisation and growth continues. In 2016 alone, global production of cement alone was 4.1 billion metric tonnes (Statista, n.d.).

Accordingly, concrete production is associated with a significant amount of pressure on the global environment. Making the process more sustainable would help to relieve some of this pressure, and recycling concrete into recycled concrete aggregates (RCA) is regarded as a possible way to do so. RCA can also be used for the production of new concrete, thereby partially replacing quarried aggregates in that particular application.

This case study, which includes a numerical analysis, was conducted on concrete recycling in France to gain a better insight into this promising method of processing the huge amounts of construction and demolition waste (CDW) that are generated in the EU each year. France was chosen based on the fact that it produces a large amount of CDW (including concrete), which is mainly used for backfilling operations and recycled as aggregates for road construction (Bougrain, Moisson, & Belaïd, 2017).

Furthermore, the French concrete sector, including the cement and aggregates industries, is one of the largest concrete sectors in Europe. The scope was further limited to ready-mix concrete because it is by far the most popular type of concrete.

The numerical analysis carried out for this case study, which was based on French data and compares a business-as-usual scenario to a circular economy scenario, provides an indication of associated environmental impacts. The results show that increasing the amount of RCA used in ready-mix concrete would lead to minor improvements in human health and environmental impacts.

Quantifying the economic and social impacts of increased use of RCA in France is more difficult due to the lack of robust data related to commodity prices and material flows specific to RCA at the time of this writing. This lack of robust data can be linked to the variability of the specific regional and local circumstances when it comes to the production of concrete. Overall, the employment impacts of a shift to increased production of recycled concrete can be expected to be minor, as both the required skill set and the location of jobs would remain largely unchanged. Aggregates, whether recycled or not, are typically not transported long distances due to their weight.

Barriers and enabling factors play a key role in increasing the demand for RCA. On the one hand, barriers that were identified for France, which generally are also relevant for other Member States, include limited information on the pricing of CDW recycled materials, little trust in the quality of CDW recycled materials and lack of clarity on liability related to CDW recycled materials. On the other hand, enabling factors that were deemed critical are European and national commitment and improved CDW management.

To better understand policy options in both France and the EU, several potential policies for increasing material re-use for recycled concrete were identified from different Member States. They deal with the implementation of end-of-waste criteria for waste-derived aggregates, landfill restrictions and taxes, and the taxation of quarried aggregates.

Though using recycled concrete in new concrete applications could help close the resource loop for that application, for the bigger picture it is important to reflect upon the total demand for aggregates. If total demand remains unchanged, then even with increased concrete recycling rates, there would be no changes in the consumption of quarried aggregates as they would be shifted to other applications. Even with a 100% CDW recycling rate, only 12 to 20% of the total demand for aggregates would be covered (UEPG, 2017a). Future research into how aggregates, both quarried and recycled, flow through the European economy would help answer this question.

1 :: Introduction

The EU-funded research project, CIRCULAR IMPACTS, investigates the macroeconomic and societal impacts of a Europe-wide transition to a circular economy. As part of this work, four case studies explore specific circular processes with market potential for greater adoption and significant impact.

The European Commission identifies construction and demolition waste (CDW) as one of the "heaviest and most voluminous waste streams generated", as it is responsible for 25%-30% of all waste generated in the EU (European Commission, 2016a). Directive 2008/98/EC, also known as the Waste Framework Directive, describes the basic concepts and definitions related to waste management. Article 11.2 introduces a 2020 target for Member States to prepare 70% (by weight) of all non-hazardous CDW for re-use, recycling and other recovery, excluding natural occurring material as defined in category 17 05 04 of the European List of Waste (European Commission, 2016b).[1]

In France, around 300 million tonnes of Construction and Demolition Waste (CDW) are produced each year (IREX, n.d., (a)), which is predominantly used for backfilling operations and recycled as aggregates for road construction (Bougrain, Moisson, & Belaïd, 2017). Overall CDW recycling and material-recovery rates differ greatly amongst Member States, from less than 10% to more than 90% (European Commission, 2016c).

Table 1 shows the extent to which unpolluted soils and stones made up by far the largest part of the inert CDW waste stream in France in 2008. The recovery of unpolluted soils and stones is not included in the 70% recovery target as set by the Waste Framework Directive. Concrete is also a large contributor to the total amount of generated inert CDW and will be included in the recovery target. Using recycled concrete in new concrete applications would fulfil recycling obligations as laid down in the Waste Framework Directive.

Based on the scale of the circular-economy opportunity and the fact that France is not yet a front-runner amongst Member States on CDW recycling, the project team decided to take a closer look at concrete recycling in France and identify potential policy options from other Member States that could be applied both in France and elsewhere.

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[1] The category "natural occurring material" is defined as soil and stones (European Commission, 2000); it excludes soil and stones containing dangerous substances.

Table 1. Composition of inert CDW in France (2008)

Waste type	Total quantity of waste generated (million tonnes)
Concrete	17.84
Bricks, tiles, ceramic and slate	2.87
Glass	0.10
Bituminous mixtures containing no tar	9.30
Unpolluted soil and stones	175.11
Other materials from roadway demolition	11.82
Non polluted track ballast	0.97
Non polluted dredging spoil	2.60
Other inert wastes	1.18
Mixed inert wastes	17.09
Total inert waste	238.89

Source: Reproduced from http://ec.europa.eu/environment/waste/studies/deliverables/CDW_France_Factsheet_Final.pdf

This case study paper follows the stepwise approach developed by Smits and Woltjer in the CIRCULAR IMPACTS project (Smits & Woltjer, 2017). Therein, the following steps were laid down:

- Step 1: Defining the baseline
- Step 2: Defining the new business case
- Step 3: Changes in the key sector
- Step 4: Expected effects on other parts of the economy
- Step 5: The impact on society
- Step 6: Are alternatives available?
- Step 7: Policy options
- Step 8: Overall conclusions.

In order to come to well-informed conclusions, the economic, social and environmental footprint of producing concrete, with and without using recycled concrete aggregates (RCA), was researched. The associated data is easily traceable, to ensure optimum transparency of the results.

An expert workshop entitled 'Building materials – Progressing towards a more circular economy'[2] held for this case study took place on the 7th of December 2017 in Brussels. Workshop participants discussed the opportunities for increasing concrete recycling along with its expected economic, social and environmental impacts. Participating experts provided feedback on a draft version of this case-study paper, while also stating their views and exchanging valuable knowledge on the topic. The project team kept in touch with these experts and revised the case study paper based on their input, including the key data and assumptions of our scenario analysis for this case study.

2 :: Step 1: Defining the Baseline

In this section, a baseline is defined that identifies the role of concrete in Europe and the associated economic, social and environmental impact thereof. The traditional process for producing concrete using quarried aggregates is described, along with the most commonly used types of concrete.

2.1 The role of concrete in Europe

Concrete has been around for thousands of years, albeit in different compositions. The ancient Romans widely used it as a building material, something the Colosseum in Rome is an iconic remnant of. Their concrete was similar to the one which is in widespread use today.

Currently, concrete is the most frequently used building material. It is used in buildings, bridges, tunnels and many more types of structures. It is hailed for its strength and durability, while also being versatile, affordable and requiring little maintenance (The Cement Sustainability Initiative, n.d.). In 2006, around 30 billion tonnes of concrete were consumed worldwide, while in 1950, this number was still at 2 billion tonnes (The Cement Sustainability Initiative, 2009).

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[2] For more information, please visit https://www.ceps.eu/events/building-materials-progressing-towards-more-circular-economy

2.1.1 The environmental, economic and social footprint of concrete

Environmental key facts

Most of the carbon dioxide released in concrete production comes from the cement production (Collins, 2013), while the course aggregates contribute 13-20% of the carbon emissions for concrete (Nazari & Sanjayan, 2016). The production process of one tonne of Portland cement requires approximately 4,882 megajoules of energy (Struble & Godfrey, 2004), and releases nearly 1 tonne of carbon dioxide. Overall, concrete production contributes 6-7% of global carbon dioxide emissions (Imbabi, Carrigan, & Mckenna, 2012; Meyer, 2009). The major component of concrete is aggregates, most of which are raw materials extracted via quarrying. In 2015, over 2.38 billion tonnes of quarried aggregates were extracted in the EU-28 and European Free Trade Association (EFTA) countries (UEPG, n.d.(a)). Transportation of these materials contributes significant carbon emissions. Concrete sludge, which is waste water produced during the construction and demolition of concrete, is extremely hazardous due to its high alkalinity (Aggregates Business Europe, 2011).

Economic key facts

In 2012, the value added by the concrete sector (including the cement industry) in the EU-28 was €20 billion, with an additional €36 billion of indirect value. The cement industry alone provided a gross value added of €4.5 billion in 2014 (CEMBUREAU, n.d.).

Table 2. Value added by concrete sector (including cement industry) in the EU-28

	Data	Year
Direct added value	€20 billion	2012
Direct & indirect value	€56 billion	2012

Source: Based on https://cembureau.eu/cement-101/key-facts-figures/

On average, cement plants cost €150 million to build, equivalent to about three years of a plant's revenue. The average cement plant will annually produce around 1 million tonnes of cement (CEMBUREAU, n.d.).

Social key facts

In 2012, the concrete sector (including the cement industry) generated 384,000 direct jobs, thereby creating 696,000 indirect jobs in the EU-28. In 2015, the cement industry alone provided over 38,000 direct jobs.

Table 3. Jobs by concrete sector (including cement industry) in the EU-28

	Data	Year
Direct jobs created	384,000	2012
Direct & indirect jobs created	1.08 million	2012

Source: Based on https://cembureau.eu/cement-101/key-facts-figures/

2.2 Producing concrete with quarried aggregates

Concrete is produced with the following ingredients: fine and course aggregates, cement, water and air. These materials are mixed together to form a malleable paste which then hardens over time, forming a rock-like consistency. Typically, the mix consists of the following components (% figures given are % of volume):

- Fine and coarse aggregates (60-75%)
- Cement, including water (around 25-40%)
- Air (0.5-2%) (DPD Concrete Team, n.d.)

The percentages differ by concrete type, but fine and coarse aggregates always make up the majority of the mix. Generally, coarse aggregates come in the form of gravels or crushed stone (particles larger than 4 mm) or a combination thereof, while fine aggregates consist of natural sand or crushed stone (particles smaller than 4 mm).[3] These aggregates are typically obtained from quarries.

Cement is made from clinker and forms the binder for the aggregates, of which Portland cement is by far the most common one. Clinker is produced from raw materials (often limestone and clay), by heating them in a kiln to around 1,400 degrees Celsius. After cooling, gypsum is added and in some cases, other additions such as coal fly ash as well. The clinker, gypsum and any additional additives are then ground to a fine powder in a cement mill, yielding the final product (Eurostat, 2009). The manufacturing process is

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[3] As discussed during the expert workshop on 7 December 2017.

extremely energy intensive and is responsible for around 6-7% of global CO_2 emissions (Imbabi, Carrigan, & Mckenna, 2012; Meyer, 2009). Sixty percent of these CO_2 emissions are the result of processing the limestone, whereas the other 40% are linked to the fuel burned in the kiln (The Concrete Initiative, 2015). Portland cement is hydraulic, meaning it requires water for the chemical reaction to take place. The chemical process is irreversible, meaning that recycling cement into new cement for re-use is not possible.

For the production process, the correct ratio of water to cement is crucial, as it affects the structural performance of the concrete. This ratio (also known as the w/c ratio) should be about 0.30 (Chen et al., 2010), provided that there are no external water sources for hydration (Somayaji, 2000). The quality of the water is important as well: it should be suitable for human consumption if it is used in the production of concrete, though in some instances, non-potable water can be used as well (Kucche, Jamkar, & Sadgir, 2015). Another important factor in the production of cement is the air entrainment. Concrete that is exposed to freezing and thawing environments needs a certain amount of air in order to release the pressure of the frozen water, which expands and pressurizes the concrete (Portland Cement Association, 1998).

2.2.1 Ready-mix concrete

Many types of concrete exist, each with specific performance properties that are in line with its specific use requirements. There are also different ways of ensuring that the concrete is delivered to the users, which again is determined case-by-case on what is most effective.

Some concrete is created by mixing the contents of cement packets with aggregates and water on-site in a concrete mixer, to then be used for the desired application. However, since there are not quality controls, this is not permitted whenever a strength requirement is needed. Pre-casting concrete is also an option, meaning that the concrete is mixed, poured and cured in a controlled environment under the supervision of factory personnel. The end product is then brought to the designated site and installed.

Ready-mix concrete (RMC), is produced in concrete plants, which are also known as batch plants. Here, all the final ingredients of the concrete are mixed, including the water. After the batching process, the RMC should be transported and poured at the designated site within 30 to 45 minutes. Transit mixers are used for transport; the truck's rotating drum postpones the curing process. Even though the time constraint poses a challenge, the batching process can be run with higher precision than mixing on-site.

In 1967, ready-mix concrete only accounted for 10% of the total cement consumption in the European concrete sector. Currently, this number is at 65%, with more than 350 million cubic metres being produced annually (ERMCO, n.d.). Therefore, this case study focuses on RMC.

3 :: Step 2: Defining the New Business Case

With the baseline established, the new business case can be introduced: increased recycling of concrete for use as aggregates in new concrete. It should be noted that this business case is not entirely new, as the European aggregates industry has been recycling aggregates for many years, with an increasing amount becoming available to the market over time. This section describes the benefits of recycling concrete and in order to provide a policy context, analyses relevant European policy. The process of creating concrete with recycled concrete aggregates is also explored and the possible quality concerns of using RCA in new concrete are highlighted.

3.1 The benefits of concrete recycling

Achieving higher rates of resource efficiency as a way to address the earth's limited supply of raw materials has gained momentum globally, resulting in an increase in research performed on the potential of material extraction via recycling. In addition to the depletion of raw materials, there are environmental concerns regarding the construction and demolition waste (CDW) produced from the construction sector. As explained in the introduction, the construction sector generates a large amount of CDW, for which concrete is partly responsible. Approximately 850 million tonnes of CDW waste are generated in the EU per year, which represents 31% of total waste generation (Fischer & Werge, 2009).

Contrary to popular belief, concrete can be recycled into a high-quality product. Recycled concrete aggregates have the potential to replace quarried aggregates in concrete mixtures. Several experimental building constructions have been built in Germany, Spain, Switzerland, and Australia, using RCA as aggregate (The Cement Sustainability Initiative, 2009).

The price factor plays a decisive role in the increased uptake of recycled concrete aggregates in structural concrete applications. Currently, much of the potential value of RCA is not captured. If quarried aggregates become more expensive than RCA, there will be a financial incentive to increase the latter's uptake, also in structural applications such as buildings, bridges and tunnels. Regarding RCA's potential applications, the European Aggregates Association (UEPG) states that the use of recycled aggregates should be promoted only where "economically, environmentally, and technically feasible respecting the given technical standards (UEPG, n.d., (b))."

The EU has acknowledged the benefits of recycling construction and demolition waste (including concrete) and wants to ensure that more of its value is recovered. To this end, it has created several policies, such as the Waste Framework Directive and the EU Construction and Demolition Waste Protocol. France has implemented policies that address the issue as well.

3.2 Relevant European and national policy

3.2.1 The European Waste Framework Directive

The Waste Framework Directive was implemented in 2008 and captures the basic concepts and definitions related to waste management, such as definitions of waste, recycling and recovery. It also established the “polluter pays principle” and introduced “extended producer responsibility”.

Member States are supposed to apply as a priority order the following waste management hierarchy: prevention (non-waste); preparing for re-use; recycling; recovery; and disposal. As already mentioned in the introduction, it also lays down the target for them to prepare 70% (by weight) of all non-hazardous CDW for re-use, recycling and other recovery, to be achieved by 2020 (European Commission, 2016b). France adopted the framework described in the Waste Framework Directive to promote the circular economy (Bougrain, Moisson, & Belaïd, 2017).

Furthermore, Articles 6.1 and 6.2 of the Directive state that waste ceases to be waste after undergoing a recovery (including recycling) operation while also complying with pre-defined criteria. The latter are referred to as end-of-waste (EoW) criteria and must be developed in line with the following:

- The substance or object is commonly used for specific purposes
- There is an existing market or demand for the substance or object
- The use is lawful (substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products)
- The use will not lead to overall adverse environmental or human-health impacts.

The Joint Research Centre has developed a methodology to develop EoW criteria, which up until now have been laid down for iron, steel and aluminium scrap, glass cullet and copper scrap (European Commission, 2016d).

In January 2018, the Waste Framework Directive was revised, as part of a series of new measures that were adopted in light of the Circular Economy Action Plan. Member States were now urged to take measures to "[...] promote sorting systems for construction and demolition waste for at least the following: wood, aggregates, metal, glass and plaster" and to "reduce waste generation in processes related to industrial production, extraction of minerals and construction and demolition, taking into account best available techniques" (European Commission, 2015).

3.2.2 The EU Construction and Demolition Waste Management Protocol

In 2016, the European Commission launched the EU Construction and Demolition Waste Management Protocol, which is part of the Circular Economy Package and fits within the Construction 2020 strategy. The non-binding guidelines as laid down in the Protocol are a proposal to the industry and have the goal to strengthen the confidence in CDW management. This is to be achieved by:

- Improved waste identification, source separation and collection
- Improved waste logistics
- Improved waste processing
- Quality management
- Appropriate policy and framework conditions (European Commission, 2016e).

A lack of confidence in the quality of CDW recycled materials is often perceived as a barrier to increasing recycling rates. This lack of confidence also applies to RCA.

3.3 The French Energy Transition for Green Growth Act

In France, the Energy Transition for Green Growth Act was established on 17 August 2015. The goal is to make France "[...] an exemplary nation in terms of reducing its greenhouse gas emissions, diversifying its energy model and increasing the deployment of renewable energy sources" (Ministère de l'Environnement, de l'Énergie et de la Mer, 2016). Article 70 sets a non-binding objective to recover 70% of construction waste by 2020 (Legifrance, 2015).

Article 79 obligates the French government and the local authorities to recover at least 70% of the public works waste generated by their construction and road maintenance works from now on to 2020. Aditionally, it states that from 2017 on, at least 50% by mass of all materials used for road construction sites should be derived from recovered waste annually. With respect to road maintenance, at least 10% by weight of the materials used in surface layers and at least 20% in the base layers should be from recovered waste. From 2020 onward, these figures are set at 60%, 20% and 30%, respectively (Legifrance, 2015).

3.4 Producing concrete with recycled aggregates

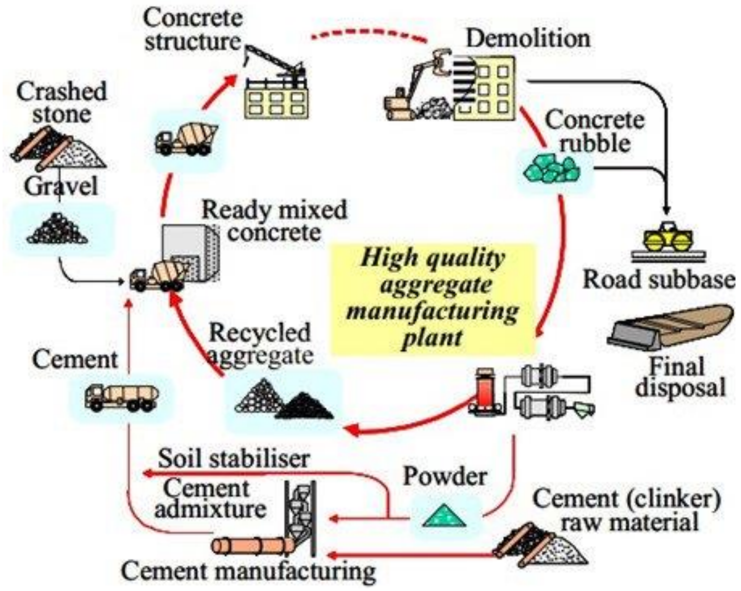
Concrete can be recycled from:

- Construction and Demolition Waste (CDW)
- Returned concrete from ready-mix trucks which is fresh (wet)
- Production waste at a pre-cast production facility (The Cement Sustainability Initiative, 2009).

Out of these three options, CDW is most often targeted. However, it is also the most challenging one because the concrete is often mixed with other materials. Only uncontaminated CDW can be recycled and crushing is the most often used method to remove unwanted materials and ensure the quality of the RCA (The Cement Sustainability Initiative, 2009).

Figure 1 shows the process of recycling concrete from CDW. The recycled end product consists of two main components; one of them being the cement, which cannot be recycled and always requires the use of new raw materials, and RCA, which are yielded from the demolition of concrete structures. Part of the latter becomes concrete rubble for road construction, the rest is transported to an aggregate manufacturing plant. Here it is recycled into RCA, which is then used for the production of concrete (The Constructor, n.d.). The production of concrete with recycled aggregates still requires the use of new cement, so its impact on lowering greenhouse gas emissions is limited. Moreover, in some cases, concrete with RCA requires an increased amount of cement (The Cement Sustainability Initiative, 2009).

Figure 1. Process of recycling concrete from CDW



Source: Reproduced from https://theconstructor.org/concrete/concrete-recycling/755/

If recycled concrete aggregates are used in concrete at all, it is mainly in ready-mix concrete as a substitute for the use of quarried aggregates (The Cement Sustainability Initiative, 2009). This reduces the need for quarrying and landfilling amongst others. Therefore, this case study focuses on the use of RCA for the production of ready-mix concrete. Additional uses have been limited, but according to various national practices (e.g. the OFRIR project)[4] RCA are mainly used as aggregates in granular base or sub-base applications, whereby its full potential and thus value is not reached.

However, recycled concrete aggregates cannot fully substitute the need for quarried aggregates, as the quality of the concrete is affected, depending on the percentage used. Opinions on what percentage is allowable in various applications differ significantly. In addition, according to the UEPG publication ‘Life Cycle of Aggregates - A resource efficient industry’, it is not possible for RCA to completely replace natural aggregates; even with a 100% CDW recycling rate, only 12-20% of the total demand for aggregates would be covered (UEPG, 2017a). In a 2030 forecasting study, PIPAME also mentions that there is not enough CDW in France to recycle to cover total demand (PIPAME, 2016).

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[4] For more information, please visit http://ofrir2.ifsttar.fr/en/accueil/

3.4.1 Quality concerns

Impact of RCA on concrete performance

A primary concern about using recycled concrete aggregates mainly relates to the quality of the concrete. The maximum allowable percentage of RCA that can be used in concrete for new construction varies amongst countries, ranging from 10% in the United States to up to 30% in Australia (The Cement Sustainability Initiative, 2009). For France, up to 15% is considered safe to use.[5] However, preliminary research has indicated that larger amounts of RCA could be used without sacrificing quality and safety of the concrete. The elastic modulus, or tensile stress to strain ratio, is affected by the percentage of replacement. If the percentage of replacement does not exceed 50%, the elastic modulus will change only slightly (Lopez Gayarre et al., 2009). Though newer research indicates there is potential to safely use higher percentages of RCA in construction, they are still rarely considered for higher-quality product applications such as for structural concrete.

RCA are generally produced by a two-stage crushing, combined with screening and removal of contaminants such as reinforcement, paper, wood, plastics, and gypsum via magnetic separation, water cleaning, and air-sifting. Small amounts of mortar and cement paste from the original concrete remains attached to stone particles in recycled aggregate post production. This affects some properties of RCA compared to quarried aggregates, leading to concerns about the quality of RCA. The density of RCA is up to 10% less than the density of quarried aggregates (Hansen, 1992; Poon & Lam, 2008; Sanchez de Juan & Gutierrez, 2004). Water absorption of RCA is significantly higher compared to quarried aggregates, with coarse RCA ranging from 3.5% (Rahal., 2007; Lopez Gayarre et al., 2009) to 9.2% (Xiao, Li, & Zhang, 2005) and fine RCA ranging from 5.5% (Yang, 2008) to 13% (Evangelista & de Brito, 2007) compared to quarried aggregates which typically range from 0.5% to 1.0%.

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[5] The maximum allowed amount of recycled concrete aggregates is 15% of the total aggregates in a concrete mixture, according to European standard NF EN 206/CN.

Table 4. Comparison of concrete made with RCA versus quarried aggregates

Property	RCA compared to quarried aggregates	References
Compressive strength	Decreased up to 25%	Ajdukiewicz and Kliszczewicz (2002) Batayneh et al. (2007) Hansen (1992) Poon et al. (2004) Rahal (2007) Sanchez de Juan and Gutierrez (2004) Yang et al. (2008)
Slitting and flexural tensile strength	Decreased up to 10%	Ajdukiewicz and Kliszczewicz (2002) Batayneh et al. (2007) Hansen (1992) Malesev et al. (2007) Yang et al. (2008)
Modulus of elasticity	Decreased up to 45%	Ajdukiewicz and Kliszczewicz (2002) Rahal (2007) Sanchez de Juan and Gutierrez (2004) Xiao et al. (2005) Yang et al. (2008)
Drying shrinkage	Increased up to 50%	Domingo-Cabo et al. (2009) Gómez-Soberón (2002a) Hansen (1992) Li (2008)
Creep	Increased up to 50%	Domingo-Cabo et al. (2009) Gómez-Soberón (2002b) Hansen (1992)
Water absorption	Increased up to 50%	Li (2008) Malesev et al. (2007)
Freezing and thawing resistance	Decreased	Salem et al. (2003) Zaharieva et al. (2004)
Carbonation	Similar	Levy and Helene (2004) Otsuki et al. (2003)
Chloride penetration	Similar or slightly increased	Ann et al. (2008) Olorunsogo and Padayachee (2002) Otsuki et al. (2003)

Source: Based on https://www.researchgate.net/publication/261667813_Use_of_recycled_concrete_aggregate_in_concrete_A_review

The comparisons in Table 4 represent the upper bounds of all the referenced data. These comparisons have a wide range because the quality of RCA depends on the quality of the waste concrete used for its production.

Potential soil and groundwater contamination due to the use of RCA

Several studies from the UK and Switzerland have generally shown no indication of differences in contamination potential from construction using RCA versus quarried aggregates (The Cement Sustainability Initiative, 2009). Some countries have put policy measures in place to address potential of soil and groundwater contamination from heavy metals based on the quality and exposure of the first life-cycle concrete. For example, Japan monitors soil contamination of hexavalent-chromium and lead that originates from the cement in RCA (Dosho, 2007). Switzerland requires groundwater protection measures, and prohibits filtration and drainage beds in construction from using RCA and other recycled demolition materials. Areas that use de-icing material risk salt contamination that could contribute to earlier deterioration of construction using RCA (The Cement Sustainability Initiative, 2009).

Carbonation

Carbonation is the process by which concrete absorbs carbon from the atmosphere over its lifetime. While cement cannot be recycled, some of the calcium hydroxide ($Ca(OH)_2$) that forms during the curing process will ionise with water throughout the lifetime of the concrete, forming a highly alkaline solution. Carbon dioxide (CO_2) will combine with water to form a weak carbonic acid, some of which ionises into carbonate ions (Collins, 2013). The calcium and the carbonate will precipitate out, while the hydrogen and hydroxide ions neutralise into water (Lagerblad, 2005). However, carbonation leads to the corrosion of steel reinforcement and shrinkage, so it is not necessarily a desirable phenomenon (Understanding Cement, n.d.).

The degree of carbonation is greatly dependent on the type of concrete recycled, surface area exposure, as well as the how the RCA are used in their second life (Collins, 2013; Wijayasundara, Mendis, & Ngo, 2017). Higher amounts of carbonation can take place with smaller RCA due to the higher surface area to volume ratio (Collins, 2013; Wijayasundara, Mendis, & Ngo, 2017), and the size of RCA is dependent on use (Collins, 2013). This process helps alleviate some of the atmospheric carbon produced from cement, with some observed carbonation ranging from 17% to 65% from the life cycle of the concrete. However, it is important to note that this is a gradual process without a large immediate impact and does not change the carbon production of the new concrete required to use RCA, nor the fact that quarried aggregates are needed for concrete production (Collins, 2013; Wijayasundara, Mendis, & Ngo, 2017).

4 :: Step 3: Changes in the Key Sector in France

In this section, the impacts of the new business case on the French concrete sector are examined. By using key data and assumptions, two scenarios will be worked out: a business as usual scenario and a circular scenario, each with 2030 as the end year. These two scenarios will be compared and the main difference in their impacts described.

4.1 The concrete sector

According to the concrete industry federation in France, there are 800 concrete production sites, combined sales of €2.5 billion, 21 million tonnes of concrete goods and 20,000 direct jobs involved in the French concrete sector (INTERMAT, n.d.). In 2016, France produced 36.3 million cubic metres of ready-mix concrete, making it a Member State with one of the highest outputs in the EU (along with Germany). Furthermore, 503 French companies were active in this market (UNICEM, 2018a).

Table 5. Economic key data of ready-mix concrete (RMC) production in France

	2013	2014	2015	2016
Net sales of RMC (millions of €)	3,959	3,770	3,517	3,647
Number of businesses for RMC	538	523	516	503

Source: Based on http://www.unicem.fr/wp-content/uploads/depliant-bpe-chiffres-2016.pdf

The French concrete sector is mainly made up of two other industries that provide the most important ingredients for concrete: the cement and aggregates industries.

4.1.1 Cement industry

The following companies produced cement in France in 2016. The number of industrial sites for each company is indicated in parentheses:

- Ciments Calcia/Heidelberg Cement Group (10)
- Eqiom (7)
- Kerneos (3)
- Lafarge Ciments (14)[6]
- Vicat (7) (Infociments, 2017).

Table 6. French cement production and consumption figures in thousands of tonnes[7]

	2012	2013	2014	2015	2016
Clinker production	14,178	13,778	13,146	12,513	12,528
Cement production	18,018	17,469	16,426	15,597	15,934
Cement consumption	19,973	19,217	18,165	17,170	17,429
Consumption – in kg/habitant[8]	327	314	297	276	269

Source: Based on http://www.infociments.fr/publications/industrie-cimentiere/statistiques/st-g08-2012 and http://www.infociments.fr/publications/industrie-cimentiere/statistiques/st-g08-2017

Table 6 shows that from 2012 to 2015, cement consumption has continually decreased, and therefore, cement and clinker production have decreased as well.

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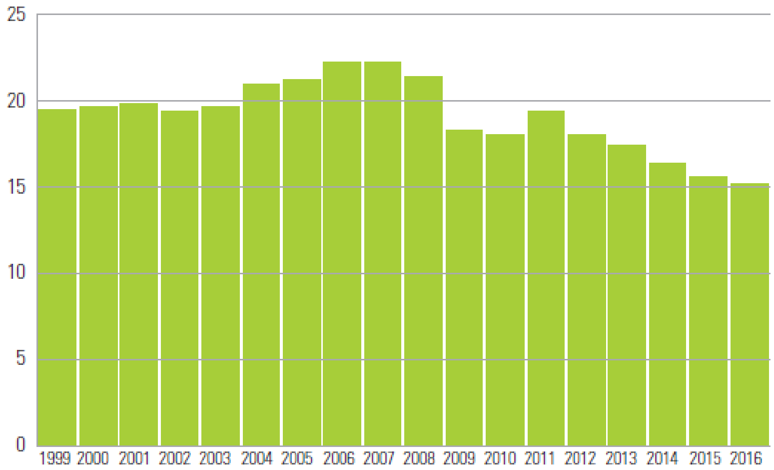
[6] Lafarge merged with the Swiss-based company Holcim on 14 July 2015. From that point on, they were called LafargeHolcim.

[7] Metropolitan France

[8] Cement and geotechnical binders

Figure 2. Cement production in millions of tonnes



Source: Reproduced from:
http://www.infociments.fr/publications/industrie-cimentiere/statistiques/st-g08-2017

Figure 2 demonstrates that up until the financial crisis in 2008, the production of cement was steadily growing. After 2008, however, it shrank considerably, as a result of less building activity in France and Europe generally.

Table 7. Economic key data of cement and ready-mix concrete (RMC) production in France

	2012	2013	2014	2015
Net sales of cement (millions of €)	2,350	2,310	2,150	2,120*
Investments by cement industry (millions of €)	144	120	120	110*
Number of employees for cement[9]	4,909	4,873	4,814	4,711

* Estimation

Source: Reproduced from http://www.infociments.fr/publications/industrie-cimentiere/statistiques/st-g08-2015

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[9] Including the associations SFIC, ATILH and CIMbeton

Net sales, investments and the number of employees slowed down after 2012 due to the aftermath of the financial crisis in 2008. The trend is even stronger for the years 2014 and 2015, though the figures for 2015 remain estimates. However, despite this current trend, concrete usage is still expected to be higher in 2050 than it is now (International Energy Agency, 2009).

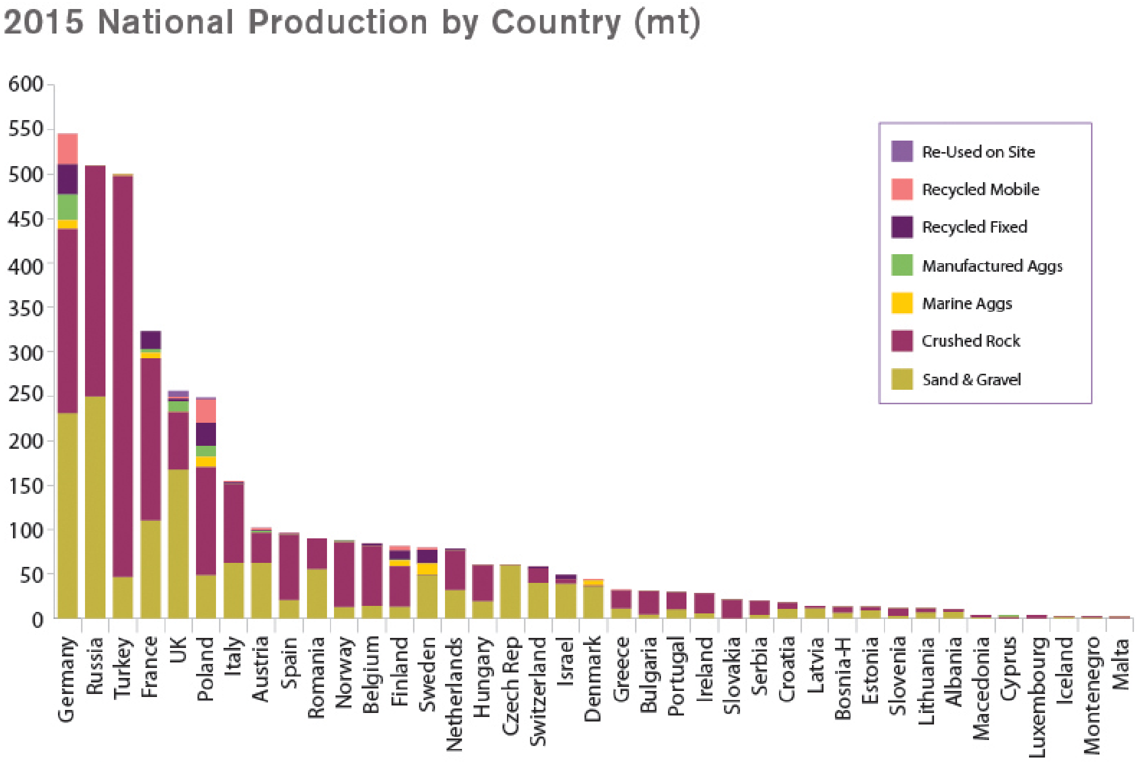
Because the production of concrete with recycled concrete aggregates always requires new cement, the French cement industry will not be heavily affected by an increased use of RCA, as the demand for their product is not affected. Accordingly, only the aggregates industry is relevant for this case-study analysis, because RCA are able to replace quarried aggregates.

4.1.2 Aggregates industry

Aggregates are the most quarried material globally, with demand expected to rise 5.2% annually to 51.7 billion metric tonnes in 2019 (Green, 2016). Their extraction from quarries, if not well managed, results in negative environmental impacts such as landscape destruction and discharge of contaminants (Quality Planning, n.d.). On the other hand, the rehabilitation of quarries can lead to the establishment of habitats of high biological value (UEPG, n.d., (c)).

France is one of the largest aggregates producers in Europe, behind only Germany, Russia and Turkey. Figure 3 provides an overview for 2015.

Figure 3. National aggregates production per country



Source: Reproduced from:
http://www.uepg.eu/uploads/images/statistics-graphs/UEPG-figure1_2016-17-04.jpg

In 2015, France produced around 328 million tonnes of aggregates. As illustrated in Figure 3, recycled aggregates accounted for a small portion of the national production: only 25.3 million tonnes, which was 8% of the total aggregates production (UNICEM, 2017). Crushed rock and sand and gravel made up the largest share of the output. Consumption of aggregates at the beginning of 2016 was down 3.5% as compared to 2015 (Aggregates Business Europe, 2016). Aggregates re-used on site and the recycled mobile aggregates production in France were not included in Figure 3, due to a lack of data. In total, France produced 330.1 million tonnes of aggregates in 2016, which demonstrated a growth rate of 0.8% in relation to the previous year (UNICEM, 2018b).

Generally, aggregates are not transported over long distances. It is not economically attractive to do so because they are relatively inexpensive and extremely heavy. As a result, the aggregates market worldwide is still very much fragmented (LafargeHolcim, n.d., (a)). In France, one tonne of aggregates costs around €6 to €10 and one cubic metre weighs around two tonnes. Transport constitutes the largest part of the price and the transport costs increase quickly with distance (UNPG, n.d.). Accordingly, the EU Construction and Demolition Waste Management Protocol encourages the recycling of CDW in densely populated areas, because it is here that supply and demand come together (Ecorys, 2016). However, ready-mix plants located in urban areas often do not have space to store different types of aggregates.

Despite the high cost of transport, France exported around 9 million tonnes of aggregates in 2016 to amongst others Switzerland, Germany, the Netherlands and the U.K., and imported around 10.7 million tonnes amongst others from Belgium, Spain, Germany, the U.K. and Norway (UNICEM, 2017). Table 8 shows that the three most important French regions were Auvergne Rhône-Alpes, Nouvelle-Aquitaine and Grand Est, with a combined production of 124 million tonnes of aggregates. Île-de-France, being the region wherein Paris is located, was the biggest producer of recycled aggregates, with 4.8 million tonnes.

Table 8. French regional production of aggregates in 2016 in millions of tonnes

Region	Recycled aggregates	All aggregates	% change in production (all aggregates, 2015 to 2016)
Auvergne-Rhône Alpes	3.8	46.3	1.8%
Nouvelle-Aquitaine	1.2	39.2	-6.6%
Grand Est	4.3	38.5	5.8%
Occitanie	1.8	36.7	-2.7%
Pays de la Loire	0.5	32.6	0.0%
Provence	3.4	24.1	-1.6%
Bretagne	0.2	22.8	-2.6%
Bourgogne Franche-Comté	0.3	22.3	5.7%
Hauts-de-France	3.7	21.1	6.0%
Normandie	1.1	20.5	6.8%
Île-de-France	4.8	13.0	3.2%
Centre-Val de Loire	0.6	11.0	1.9%
Corse	0	2.0	-4.8%
Total	**25.7**	**330.1**	

Source: Based on http://www.unicem.fr/wp-content/uploads/depliant-unpg-chiffres-2016.pdf

The total turnover of the French aggregates industry (excluding taxes) for 2016 was around €3.45 billion, which represented a 1% increase above the 2015 figure (UNICEM, 2018b).

4.2 Scenario building

For this case study, the authors conducted a numerical analysis of future scenarios regarding the use of RCA in new concrete. This is not a formal proposal of what specific aims the French government should pursue, but rather an exercise to gain insight into the dynamics of the processes involved. This subsection describes the development of the two scenarios: a “business as usual” scenario and a “circular” scenario. The results and the differences between scenario outcomes were used as bases for identifying likely environmental impacts as well as possible economic and social impacts. The analysis is described here, along with some of the key data and assumptions. The technical-documentation section (see Section 10) provides an overview of the numerical analysis and explains the rationale behind it, step by step.

4.2.1 Key data and assumptions

In order to do the scenario building, key data were collected for France on several issues and several assumptions were made. Unless specified differently, the data and assumptions relate to 2016.

Table 9 provides an on overview of the key data for France and Table 10 discloses what assumptions were made.

Table 9. Key data for France

Data	Value	Source
Country population 2016	64,720,690	Worldometers[10]
Total 2016 production of aggregates	330 million tonnes	UNICEM[11]
Total 2016 production of aggregates from concrete waste	21 million tonnes	UNICEM[12]
Total 2016 ready-mix concrete production	36.3 million cubic metres	UNICEM[13]

Source: Authors' own elaboration

Table 10. Assumptions used for the scenarios

Assumption	Basis for the assumption
The French population will have reached 67,894,270 by 2030.	Calculation by Worldometers.[14]
Aggregate production and consumption grows at the same rate as the population, as does the amount of concrete waste and the ready-mix concrete production.	The population growth rates were based on factual data. The assumption was made that this number corresponds with the growth rate of the aggregate production and consumption, and the ready-mix concrete production, implying constant per-capita consumption of these materials during the period.
All produced aggregates are consumed, i.e. there is a balance between import and export.	Based on past production statistics and expert feedback.
Each concrete mixture using RCA contained on average 15% of RCA (measured as a percentage of the total aggregates in the mixture by weight).	The maximum allowed amount of recycled concrete aggregates is 15% of the total aggregates in a structural concrete mixture, according to French standard NF EN 206/CN.

Source: Authors' own elaboration

The analysis takes into account the 1.8% weight difference of the aggregates (for a given volume of concrete) in the two concrete mixtures (one with no RCA; one with 15% RCA). The specific quantities of cement and aggregates per cubic metre were included in the scenario modelling.

4.2.2 Comparing the two scenarios

The business as usual (BAU) scenario was created to simulate a situation where the French government and the EU do not put extra effort into promoting the use of RCA by 2030. The circular scenario was established to simulate the French government and the EU from 2016 on more actively stimulating the uptake of RCA by e.g. implementing policies aimed at pushing French construction companies to use CDW recycled materials. The variables used in the different scenarios are noted in Table 11.

Table 11. Scenario variables

Scenario variable	BAU scenario	Circular scenario
% of RCA that is used in ready-mix concrete	12%	25%[15]
Avg. % of RCA in concrete mixture	15%	15%[16]

Source: Authors' own elaboration. Footnotes provide an explanation showing why each scenario variable was chosen.

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[10] Data reference: http://www.worldometers.info/world-population/france-population/

[11] Data reference: http://www.unicem.fr/wp-content/uploads/depliant-unpg-chiffres-2016.pdf

[12] Data reference: http://www.unicem.fr/wp-content/uploads/depliant-unpg-chiffres-2016.pdf

[13] Data reference: http://www.unicem.fr/wp-content/uploads/depliant-bpe-chiffres-2016.pdf

[14] Data reference: http://www.worldometers.info/world-population/france-population/

[15] Presently, 25% of quarried aggregates are used in ready-mix concrete. For the circular scenario, we assumed that same percentage uptake would be achieved for RCA as well. For our business-as-usual scenario, we assumed that the percentage of RCA produced that would wind up in ready-mix concrete would be just half as high (12%).

[16] According to current regulations, the maximum percentage of RCA allowed in structural concrete mixtures is 15%. For both scenarios, we assumed that 15% of the aggregates used for recycled concrete would be RCA, with 85% quarried aggregates. While future regulations may allow higher percentages of RCA, we expect the average percentage RCA to remain closer to these modest levels.

Table 12 shows the characteristics of the ready-mix concrete mixture with 15% RCA, as used in the numerical analysis.

Table 12. Characteristics of the ready-mix concrete mixture with 15% RCA (as used in the numerical analysis; includes transport distances)

Material	Weight (kg/m³)	Transport distance (km)
Natural sand	704	30
Recycled sand	–	10
Natural course aggregates	799	30
Recycled coarse aggregates	213	10
Natural fine aggregates	83	30
Recycled fine aggregates	29	10
Cement (CEM 1)	350	125
Water	191	–
Additives	1	165

Source: Based on https://www.sciencedirect.com/science/article/pii/S2352710215300462

Environmental impacts

Recent research on the life-cycle impacts of both recycled and non-recycled concrete has been carried out for the French context (Serres, Braymand, & Feugeas, 2016). The results of this thorough life-cycle analysis generated environmental-impact indicators in the following three categories:

- **Human health**: ‘global warming’, ‘ozone layer depletion’, ‘photochemical oxidation’, ‘air pollution’ and ‘water pollution’
- **Ecosystem quality**: ‘acidification’ and ‘eutrophication’
- **Resources**: ‘abiotic depletion’, ‘consumption of energetic resources’ and ‘water consumption

The life-cycle analysis results that were calculated for one tonne of concrete (Serres, Braymand, & Feugeas, 2016) were multiplied by the amount of concrete of various types expected in the two 2030 scenarios. An overview of the results of the numerical analysis can be found in Table 13. As can be seen in Table 13, the environmental impact indicators are all lower in the circular scenario (with a percent change on the order of 2% for most indicators). The one environmental indicator that showed a negative change in the circular scenario was the measure 'Acidification'. As pointed out by the authors of the study, the increased acidification with RCA could be due to the use of additives as a way to compensate for the increased amounts of RCA in the concrete mixture.[17]

Based on these LCA results, it can be concluded that the circular scenario would not affect human health and resource use as much in a negative way as the BAU scenario. For ecosystem quality, the outcome remains inconclusive. The extent of the environmental benefits are closely linked to the transport distances of the aggregates; it is important to note that the transport distances in the LCA study were shorter for RCA.

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[17] Please see Section 10 (technical documentation) for more information.

Table 13. Results of the numerical analysis for environmental impacts

Envr. impact indicator	Units	BAU scenario	Circular scenario	% Diff
Consumption of energetic resources	10^3 MJ	79,906,782	78,193,343	**–2.14%**
Abiotic depletion	kg eq Sb	61,131,038	59,703,172	**–2.34%**
Water consumption	10^5 L	293,704,140	290,118,611	**–1.22%**
Global warming	10^2 kg eq CO2	167,165,607	165,103,134	**–1.23%**
Acidification	kg eq SO2	33,392,052	34,090,120	**2.09%**
Eutrophication	kg eq PO4^3–	8,230,866	8,072,214	**–1.93%**
Air pollution	10^5 m3	280,523,225	273,796,391	**–2.40%**
Water pollution	10^3 m3	126,772,895	124,678,692	**–1.65%**
Ozone layer depletion	10^–5 kg CFC eq R11	107,030,573	104,587,336	**–2.28%**
Photochemical oxidation	kg eq C2H4	4,862,362	4,767,171	**–1.96%**

Source: See Section 10 (technical documentation)

Economic impacts

With the BAU scenario, the total weight of RCA would be 2.6 million tonnes, whereas with the circular scenario this would be 5.5 million tonnes. The difference of 2.9 million tonnes is equivalent to the aggregates needed to build around 10.000 houses.[18] Though the circular scenario approximately doubles the amount of RCA used for recycled concrete, the additional 2.9 tonnes of RCA diverts just under 1% of total aggregate production from being used in concrete.

Still, in both scenarios, more than 60 million tonnes of quarried aggregates would be used to produce around 90 million tonnes of ready-mix concrete. Increasing the average percentage of RCA in the concrete mixture does not do anything to mitigate the environmental impacts, but only distributes them over a smaller amount of ready-mix concrete containing RCA.

Determining the economic impacts due to an increased use of recycled concrete aggregates is challenging, because these are very closely related to regional and local circumstances.[19] Aggregates are heavy and do not contain a lot of value. Economically, it does not make sense to transport them over long distances: in France, 90% of CDW travels less than 50 kilometres (Deloitte et al., 2015a). This means that the import and export of aggregates does not play a major role in either scenario.

Moreover, information on the pricing of quarried aggregates versus RCA in France is not readily available, and even if it were for some regions, such price information would have a limited geographical scope because it would be highly dependent on regional and local demand and supply. Where there are many quarries producing aggregates, the price is lower, whereas if there is little opportunity for quarrying, the price is higher. This also correlates with the demand: if there is high demand, the price rises. Accordingly, it is still not clear whether using RCA instead of quarried aggregates always makes sense financially. Transport is also critically important in this regard, as increased transport distances quickly increase the price.

It is clear that with the new business case, the economic impacts would mainly occur at the beginning of RCA’s life cycle. After the latter are mixed in a batch plant, they basically go through the same process as quarried aggregates do. As part of the economic transitioning involved in the circular scenario, significant investments would be needed to pay for the new machinery that would be used to clean up and process concrete waste.

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[18] Assuming that one individual house requires around 300 tonnes of aggregates to be built (GSM, n.d.).

[19] Based on expert feedback.

Social impacts

As with the economic impacts, identifying social impacts as a result of an increased use of RCA is extremely difficult because the exact nature of social impacts are strongly intertwined with regional and local circumstances.[20]

As with the economic impacts, the social impacts predominantly take place at the beginning of RCA's life cycle. To the extent that increased use of RCA reduces the demand for quarried aggregates, the quarrying for aggregates will partially be substituted by the separation and preparing of concrete waste during demolition works for the production of RCA. Accordingly, the nature of the required skill set to perform such actions would not differ greatly in either scenario and retraining of employees would be a feasible option.

Furthermore, due to the extremely short distances between suppliers and buyers in the aggregates sector, any jobs that would be lost or gained would remain regional and local in nature.

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[20] Based on expert feedback.

5 :: Step 4: Expected Effects on Other Parts of the French Economy

The expected effects of the two scenarios on other parts of the French economy, besides the aggregates industry, are also important to take into account. The construction sector plays a significant role in this regard.

5.1 Total demand for aggregates

Before looking at how the French construction sector will be affected, there is a key issue that requires some thought. Recycled concrete aggregates are frequently described as being able to save natural resources. Instead of quarrying for aggregates, CDW is recycled and used in different ways, ranging from road construction to structural applications. However, the bigger picture is often not addressed, which is closely related to the way aggregates are used and the total demand for them. The question that arises is whether and to what extent putting RCA into higher-value uses helps to relieve the environmental footprint of the aggregates sector overall. For example, by increasingly using RCA in structural applications, would that mean that as a result more quarried aggregates would be used to build roads? If the total demand for aggregates does not decrease, then this very well might be the case.

Here it is crucial to identify how RCA, compared to quarried aggregates, flow through the economy by means of material flow analysis. Unfortunately, detailed information on this issue was not available for France at the time this case study was being conducted. Future research on this issue would be of value, as it could provide insight on how an increased use of RCA would change the overall use of aggregates.

5.2 Construction sector

The French construction sector is one of the largest in Europe, having a total construction output of 200 billion euros in 2014 (Building Radar, 2015). Furthermore, it contributed to 4.9% of the French GDP and employed around 1.5 million people (Atradius, 2016). Nevertheless, construction companies were hit hard by the financial crisis, which resulted in a 19.5% production drop in the sector between 2008 and 2015. The majority of construction companies are classified as SMEs, with 95% of them employing around 1-10 people. There are about 200 companies employing around 200 people (Atradius, 2016). At present, it is difficult for construction companies to be profitable. However, the outlook for the sector in the coming years is positive, with 3.1% market growth in 2018 and 2.9% market growth in 2019 expected (European Commission, 2017).

Aggregates are crucial for the construction sector:

- Building an individual house requires 100 to 300 tonnes of aggregates
- A hospital or a school requires 20,000 to 40,000 tonnes of aggregates
- One kilometre of railroad requires 10,000 tonnes of aggregates
- One kilometre of highway 30,000 tonnes of aggregates (GSM, n.d.)

Any significant changes in the value chain of aggregates would affect the French construction sector. However, since there are no relevant data available on the pricing of RCA versus quarried aggregates, it remains hard to predict how the French construction sector would be affected in both scenarios, other than that there would be an increased focus and interest in recycling.

6 :: Step 5: The Impact on French Society

Technological change can have disruptive effects on societies. To what extent could increasing the level of concrete recycling affect French society?

6.1 Possible disruptive effects

Based on the numerical analysis in this case study, the impact on French society would be limited. Recycling concrete is not a disruptive technology that, for example, changes the way people communicate with each other or significantly alters their lives. Structures will not function or look different due to the incorporation of RCA. Recycling concrete is currently already being done on a small scale and mainly for low-value applications. It still requires human labour in order to produce a high-quality product. Consequently, the employment rate will not be heavily affected in France.

7 :: Step 6: Are Alternatives Available?

The question as to whether there are any feasible alternatives to recycling concrete is important to consider. These alternatives would need to be realistic and achieve the same result: a more sustainable use of aggregates and a less resource-intensive construction sector in France.

7.1 An increased use of other building materials

The environmental footprint of concrete would be lower if its demand were to be reduced: for example, by using other building materials such as wood more often. In France, there is already an initiative on the city level that is promoting this approach. The city of Bordeaux has stated its intent to build around 25,000 square metres of wooden spaces per year for the coming 15 years (CityLab, 2017).

However, this particular option—replacing concrete with wood in a significant way—is not a viable alternative because as indicated before, the positive characteristics ascribed to concrete are the reason of its unmatched popularity, as demonstrated by Table 14. In France, concrete production remains high, especially compared to other Member States, even though it decreased steadily between 2013 and 2015. In 2015, the country produced 48 million cubic metres of concrete. Furthermore, the extensive use of wood might also lead to other environmental pressures.

For the EU as a whole, concrete production grew by 6.3 million cubic metres between 2013 and 2015, leading to the conclusion that wood or other building materials would not be able to substitute the demand for concrete in a significant way and accordingly this is not a feasible alternative.

7.2 Reusing concrete in original form

Reusing concrete in its original form is environmentally friendly because it does not require new cement or aggregates, which is where most of the CO_2 emissions originate from. This would require the old concrete to be cut up in blocks in order to be transported to a different location.

However, reusing concrete severely limits applicability, as there is no opportunity to adjust its shape or mix for the required application. This would eliminate one of concrete's most beloved characteristics: its versatility. As a result, reusing concrete in its original form occasionally might be a good alternative, but in most cases would not make sense.

Table 14. Concrete production in million cubic metres

Country	2013	2014	2015
Austria	15.0	14.3	15.0
Belgium	22.5	21.4	21.4
Czech Republic	10.0	10.0	10.0
Denmark	4.2	4.3	4.4
Finland	3.9	3.9	3.8
France	54.0	51.0	48.0
Germany	67.2	77.4	77.4
Ireland	2.8	2.8	2.8
Italy	46.6	40.0	35.0
Netherlands	11.8	11.6	13.0
Poland	32.1	33.7	34.0
Portugal	5.5	5.5	5.5
Slovakia	2.2	2.1	2.5
Spain	32.0	31.0	32.5
Sweden	–	–	–
United Kingdom	28.2	37.0	39.0

Source: Based on http://www.ermco.eu/document/ermco-statistics-2015-final-pdf/

8 :: Step 7: Policy Options

Policy measures are critically important to achieving future CDW recycling targets in France. In order to better understand what will be effective and what not, enabling factors and barriers must first be identified. Policy examples will help to see how, potentially, enabling factors can be fostered and barriers overcome. Table 15 provides an overview of enabling factors and barriers to an increased use of recycled concrete aggregates in France.

Table 15. Overview of enabling factors and barriers for an increased uptake of RCA in France

Enabling factors	Barriers
• European and national commitment • Improved CDW management	• Limited information on the pricing of CDW recycled materials • Little trust in the quality of CDW recycled materials • Lack of clarity on liability related to CDW recycled materials

Source: Authors' own elaboration based on feedback from the workshop participants and desk-based research

8.1 Enabling factors

8.1.1 European and national commitment

CDW recycling, and more specifically concrete recycling, was not prominent on the EU's political agenda until fairly recently. Since concrete is a non-hazardous building material, there was not a strong incentive to find a suitable alternative to landfilling. Additionally, there was not a pressing scarcity of resources threatening to interrupt the supply of concrete.

However, the European Commission has acknowledged that the European construction sector needs to improve its CDW management, which the former aims to achieve with the publication of the EU Construction and Demolition Waste Management Protocol in 2016. Furthermore, Member States now must adhere to the waste hierarchy described in the Waste Framework Directive, and as a result must strive for recycling, instead of the recovery or disposal of waste.[21] This will help the European Commission and Member States to carry out the Circular Economy Strategy.

Additionally, several French stakeholders have publicly expressed their interest in becoming more sustainable. LafargeHolcim, a manufacturer of building materials established in 2015 with the merger of the French company, Lafarge, and the Swiss company, Holcim, has a sustainability strategy for the period through 2030 (LafargeHolcim, n.d., (b)). On the French national level, the research project RECYBETON was funded, involving 47 partners with various expertise. The goal of this research project is to recycle all the materials of deconstructed concrete to create new concrete or hydraulic binders (IREX, n.d., (b)).

8.1.2 Improved CDW management

Increasing the transparency regarding where waste-derived aggregates originate from will help French construction companies to rely more on recycled CDW materials. This could be achieved by standardised documentation procedures. Nevertheless, excessive reporting requirements and/or permits can become a burden as well, so ensuring a suitable balance is found will be important.

The EU Construction and Demolition Waste Protocol has as an annex that provides a step-by-step checklist for companies active in the construction and demolition industry to ensure that construction materials are reused and recycled as much as possible. The various parts of the waste-management chain are covered: waste identification; source separation; collection; waste logistics; waste processing and treatment; as well as quality management and assurance (European Commission, 2016e). A key issue is improving the collection processes for these diverse wastes, including improved sorting at the demolition site.

In France, there are several examples of where efforts are being made to improve CDW management. The French Demolition Association (SNED) launched Investigo, an online platform to make it easier for companies to trace waste, while simultaneously respecting French legislation (European Commission, 2016e).

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[21] Recovery means that the waste serves a useful purpose by saving resources that otherwise would have used to fulfil a particular function. For more information, please visit http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Recovery_of_waste

8.2 Barriers

8.2.1 Limited information on the pricing of CDW recycled materials

There is inadequate information available on the pricing of CDW recycled materials (including recycled concrete aggregates) and elasticity of demand for these materials, to conduct a sophisticated economic analysis. This is true for France but also in the EU as a whole. This relates to the fact that estimations are hard to make because prices depend on local circumstances. It is clear that the transport distance play a key role here, because aggregates are very expensive to move around.

However, if recycled concrete aggregates are not clearly cheaper than quarried aggregates, it will be hard to convince the French construction companies (mainly SMEs) to use them.

8.2.2 Little trust in the quality of CDW recycled materials

Generally, there is a lack of confidence in the quality of CDW recycled materials, which poses a barrier to their use.[22] RCA are still viewed as a second-hand product and as a result are not trusted. Uncertainty also remains regarding what the potential health risks could be for people working with the materials. This closely relates to the quality of CDW management. Research undertaken in the RECYBETON project is largely aimed at clarifying some of these quality- and performance-related concerns.[23]

8.2.3 Lack of clarity on liability related to CDW recycled materials

The majority of the French construction sector is made up of SMEs. These construction companies have to work with limited resources and are not capable of dealing with major economic setbacks. As a result, they often cannot take the risk of building houses using RCA, because if anything goes wrong and there are damages to be paid for, the risks are high that these small firms could get into financial difficulties. The following question needs to be addressed: which party is responsible for structures built with recycled

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[22] As discussed during the expert workshop on 7 December 2017.

[23] By the end of 2018, the RECYBETON project will publish a scientific book that addresses concrete recycling, offering significant new data on the material science of recycled concrete as well as guidelines for users.

concrete? At the moment, there is uncertainty about liability in this regard and as long as this is not clear construction companies will be hesitant to differ from the traditional process.

8.3 Policies for consideration

Policies established by some Member States aim to overcome the barriers above and to decrease landfilling of CDW. Potential policies for consideration are: implementing end-of-waste criteria; landfill restrictions and taxes; and taxes on quarried aggregates. When considering implementation of such policies within additional Member States, knowledge exchange is of central importance, as is an understanding of the specific applicability of the policy in each Member State context. Determining the specific applicability of the following policies to the French context is outside the scope of this case study.

8.3.1 Implementation of end-of-waste criteria for waste-derived aggregates

EoW criteria, which specify when waste ceases to be waste and becomes a product (or secondary raw materials), could play an important role in the promotion of concrete recycling (European Commission, 2016d). Their implementation provides all parties involved in clarity with when RCA are waste and when not and will help to reduce the administrative burden associated with the waste status (Cuperus & Broere, 2017). As indicated before, the European Commission is now in the process of laying down EoW criteria for different sorts of waste streams.

As of May 2017, only four Member States had developed EoW criteria for waste-derived aggregates; namely the UK, the Netherlands, Austria and France. France had developed them for aggregates produced from construction and public works to be used in road building, whereas the UK had implemented them for the production and use of aggregates from inert waste (Velzeboer & van Zomeren, 2017).

Currently, the European Commission considers waste-derived aggregates as possible candidates for the development of EoW criteria (Hjelmar et al., 2013). This would be a step in the right direction, as it would make the wider use of RCA significantly easier. Additionally, cross-border transport would become less of an issue, due to the comparable legal frameworks of Member States.

8.3.2 Landfill restrictions and taxes

France is one of the only Member States that does not tax the landfilling of inert waste (Deloitte et al., 2015a). Furthermore, the landfill tax (TGAP) is currently low and it is agreed upon that even with a moderate increase, it would still not be an effective deterrent.

In the Netherlands, by comparison, limited resources and land availability combined with high population density and groundwater levels naturally restrict the Dutch from quarrying and landfilling, and also reduce the potential for illegal dumping. The Netherlands began implementing waste legislation in 1972, leading to the adoption of a 'waste hierarchy' in 1979. This eventually led to waste legislation enacted in 1994 that currently bans landfilling for 45 types of waste, including mineral CDW and mixed CDW. Additionally, recycled CDW must comply with a Soil Quality Decree, which prioritises the safe removal of asbestos and safe removal, disposal, and storage of materials such as asphalt, hazardous waste, and gypsum, as well as enforcing chemical limits regarding leaching potential (Cuperus & Broere, 2017).

It should be noted that the Dutch economy is open to the import and export of hazardous and tradable waste. This greatly contributes to the high success rate of recycling of CDW in the Netherlands, as this allows materials to be processed in locations with greater capabilities for recycling (Baldè, 2016).

According to the EU Construction and Demolition Waste Management Protocol, landfill restrictions are a prerequisite for creating a market for CDW recycled materials, but should be supplemented by additional measures (European Commission, 2016e). Landfill taxes are an instrument that can ensure that landfilling is no longer the least expensive option for how to deal with CDW; however, the tax structure and levels should fit the local situation and the specificities of the wastes involved (European Commission, 2016e).

8.3.3 Taxing quarried aggregates

In 2002, the UK introduced a tax on the use of rock, sand and gravel, commonly referred to as the Aggregates Levy. The condition is that they need to be dug from the ground, dredged from the sea in UK waters or imported. In some cases, such as when aggregates are exported or are used for certain industrial or agricultural process, reliefs can apply and organic matter such as soil is exempted (UK government, n.d.).

The main goal of the Aggregates Levy is to achieve a market price that better reflects the environmental costs of quarrying. Additionally, it seeks to reduce demand for aggregates by making them more expensive to obtain, thereby also stimulating the use of alternative materials, such as, for example, CDW recycled materials (Söderholm, 2011). The tax rate from 1 April 2017 on was £2.00/tonne (UK government, 2017). For around a decade, the revenues were earmarked. From 2002 to 2011, around €57 million (35 million British pounds) were used by the Aggregate Levy Sustainability Fund to reduce and mitigate the environmental impacts of quarried aggregates extraction on a local scale. Budget considerations caused the fund to be abolished in 2011 (Ettlinger, 2017). In the UK, the use of quarried aggregates per unit of construction was reduced around 40% from 2000 to the years 2010-2014, which could partially be attributed to the Aggregates Levy in combination with the landfill tax which was implemented in 1997 (Ettlinger, 2017).

In Italy, the extraction of quarried aggregates in the form of sand, gravel and rock is taxed per cubic metre. The country does not apply a national tax rate, but instead takes a more decentralized approach, whereby each region has different rates at provincial and municipal level. The tax did not lower the demand for aggregates or promote recycling, which were also not the primary goals (European Commission, 2016e). The main aim was to cover the direct and indirect costs of land-use impacts due to quarrying activities (Söderholm, 2011). Therefore, the revenues go to the municipalities, who can then use these for 'compensatory investments' in areas where quarry activities take place.

A study from the European Environment Agency (EEA) on the effectiveness of environmental taxes stated that "[a] tax on aggregates, if properly designed and combined with other instruments, could have positive effects on the environmental impacts of aggregates and construction" (EEA, 2008). However, it depends on the local situation whether a tax on quarried aggregates may be an option (European Commission, 2016e).

9 :: Step 8: Overall Conclusions

The results of this case study offer a basis for policy recommendations to be made for France, but also for the EU. Both will be discussed here.

9.1 Results

Judging by the outcome of the numerical analysis, it can be concluded that, in this particular case, increasing the percentage of RCA in ready-mix concrete by 2030 to 25% could mildly reduce the environmental impacts of the French concrete sector.

The transport distances, as noted in Table 12, played a significant role in shaping the results, with the recycled materials travelling shorter distances compared to the quarried materials.

Additionally, when looking at a bigger picture that also incorporates the aggregates sector, it remains unclear if total demand for aggregates would be affected by an increased use of RCA. There is a risk that the total environmental impact of the French aggregates and concrete sectors might not be meaningfully reduced. RCA used for structural concrete could displace quarried aggregates in concrete, but those raw materials may merely be shifted to lower-value applications that RCA had previously been used for (e.g. road building).

Since there is still not much information available on the cost aspect of recycling concrete compared to quarrying for aggregates, it remains challenging to say anything regarding the potential socio-economic impacts. As mentioned before, this is mainly due to the significance of regional and local conditions. Nevertheless, as described, the recycling process will not significantly change the broader French economy or society.

9.2 Policy recommendations

Based on the results of this case study, the following policy recommendations are relevant for France and could also be considered for other EU Member States, as well as the EU as a whole:

- **Seek to capture the benefits of recycling concrete, but be realistic about its limitations.** Using recycled concrete aggregates instead of quarried aggregates has the potential to achieve environmental benefits. The distances that aggregates travel should not be increased due to recycling as this quickly increases the costs and cancels out the environmental benefits of recycling. Also, it is important to keep in mind that there is always a need for new cement (the vast bulk of concrete's CO_2 emissions) when producing concrete, even if RCA are incorporated. Quarried aggregates will always be needed to meet the total demand for aggregates. Policymaking should be based on an understanding of the net impact of shifting flows of recycled concrete from one application to another (e.g. from road beds to new concrete).

- **Keep investing in making concrete more sustainable.** There is not a single building material that comes close to the popularity of concrete. Improvements to the sustainability of concrete can have large-scale impacts as new techniques are implemented around the globe. The French research project RECYBETON provides a good example of an investment in improving the knowledge base for concrete recycling.
- **Ensure that concrete containing RCA is not regarded as an inferior product.** Introducing quality standards and labels could raise market confidence in recycled concrete. Additionally, clear end-of-waste criteria for waste-derived aggregates should be developed, not only for the purpose of building roads. This could be done on an EU level if the uniformity of Member States' regulatory frameworks would offer economic and environmental advantages. Increased public procurement of concrete containing locally available RCA could help establish its respectability in the market.
- **Define liability and keep reporting/permit requirements to a minimum.** Since the French construction sector is predominantly made up of SMEs, these businesses need to have certainty regarding who is liable for what when choosing to work with RCA. Furthermore, their small size makes it especially important to keep burdens of reporting and permitting manageable. This also relates to the implementation of end-of-waste criteria for waste-derived aggregates.
- **Consult all relevant stakeholders in the policymaking process.** The different sectors that are involved in the production and consumption of concrete, such as the cement industry, the aggregates industry and the construction sector, should all be asked to share their views before any major political decisions are made, as they have the expertise and experience to contribute to the debate. Public consultations provide a good means to collect such input.
- **Improve statistical knowledge of the market.** More detailed statistics on markets for the re-use and recycling of CDW would help guide policymakers and businesses seeking to create circular-economy opportunities that have combined economic and environmental benefits.

10 :: Technical Documentation

10.1 Measuring the different impacts

Finding comparable data on the environmental, economic and social impacts of the baseline compared to the new business case was an essential step for establishing the two scenarios and comparing them. For the environmental impacts, this was achieved, but acquiring data on the economic and social impacts turned out to be a critical challenge for the recycled-concrete case study.

10.1.1 Environmental impacts

The article 'Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment' by Nicolas Serres, Sandrine Braymand and Françoise Feugeas was used as a basis for several components of the analysis (Serres, Braymand, & Feugeas, 2016). In their study, the authors investigated the environmental performance of three concrete samples, each with different compositions but the same compressive strength, by means of a life-cycle assessment. The goal was to reach a compressive strength of C35/45. The article gives a clear description of how the life-cycle assessment was carried out, but here only the most important details will be highlighted.

The data was gathered in a unified way and both the recycled aggregates and quarried aggregates came from Alsace, France. Additionally, associated consumption was taken into account, such as transport, which is significant when it comes to concrete production.

The detailed listing of ingredients for the three samples examined in the life-cycle assessment—called 'traditional' (0% RCA), 'mixed' (56% RCA) and 'recycled' (100% RCA)—were the basis used by the CIRCULAR IMPACTS case-study team for interpolating the different material needs for concrete incorporating varying percentages of RCA. Even though the original samples in the LCA analysis were classified as precast concrete, they were applied to the case-study data on ready-mix concrete, since the same mix proportions could be realised in a batch plant.

The impact indicators were also interpolated to match the interpolated concrete samples. The indicators encompassed three damage categories:

- **Human health**: 'global warming', 'ozone layer depletion', 'photochemical oxidation', 'air pollution' and 'water pollution'

- **Ecosystem quality**: ‘acidification’ and ‘eutrophication’
- **Resources**: ‘abiotic depletion’, ‘consumption of energetic resources’ and ‘water consumption.

Furthermore, the transport distances per material were taken into account:

- Cement[24]: 125 km
- Natural sand: 30 km
- Recycled sand: 10 km
- Natural coarse gravel: 30 km
- Recycled coarse gravel: 10 km
- Natural fine gravel: 30 km
- Recycled fine gravel: 10 km
- Superplasticizer admixture: 165 km.

Short supply distances were used and the assumption was made that the “transportation distances from recycling centres correspond to road uses and are optimised for production of recycled aggregates for concrete production (Serres, Braymand, & Feugeas, 2016)”. Accordingly, the quarried aggregates travelled three times as far as the recycled concrete aggregates, with the mode of transport being a truck.

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[24] CEM 1 52.5 N CE CP2 NF to be exact, which is a type of Portland cement.

10.1.2 Numerical analysis

Scenario model: Recycling concrete in France
16.07.2018

Factual data	*Assumptions*
Scenario variab	*Calculations*

Description	Units	2016	2030		*Walk-through comments*
			BAU	Circular	
KEY DATA FOR FRANCE					
Country population	Number of people	64,720,690	67,894,270	67,894,270	*Take the population of France, …*
Growth rates					
Country population growth (as % of 2016 population)	%		104.9%	104.9%	*…compute the population growth rate, then …*
Total aggregate production & consumption (as % of 2016 production & cons	%		104.9%	104.9%	*… assuming that both concrete and aggregate consumption and production grow at the same rate as the population …*
Production and consumption of ready-mix concrete and aggregates					
Total ready-mix concrete production	million cubic metres	36	38.1	38.1	*… use the population growth rate to forecast consumption and production growth for ready-mix concrete, …*
Total production of aggregates	million tonnes	330	346	346	*… use the population growth rate to forecast consumption and production growth for aggregates, …*
Total amount of aggregates from concrete waste	million tonnes	21	22	22	*… and use the population growth rate to forecast production growth for aggregates made from concrete waste.*
Total consumption of aggregates	million tonnes	330	346	346	
Recycled concrete aggregates (RCA) production					
% of concrete waste used as RCA in ready-mix concrete	*%*		12%	25%	*Assume a % of concrete waste used as RCA in ready-mix concrete …*
Total amount of RCA used in ready-mix concrete	million tonnes		2.64	5.51	*… to estimate the total amount of RCA used in ready-mix concrete.*
KEY ATTRIBUTES FOR CONCRETE MIXTURE (READY-MIX)					
% of RCA in concrete mixture	%		15%	15%	*For the two scenarios, assume the percentages of RCA (of total amount of aggregates) in the concrete mixture …*
Attributes of concrete mixture with RCA % as specified above					*… and create an overview of the different attributes for this concrete mixture with the given % of RCA.*
Weight of RCA per cubic meter of concrete mixture	kg		242	242	
Weight of non-RCA per cubic meter of concrete mixture	kg		1,586	1,586	
Total weight of aggregates per cubic meter of concrete mixture	kg		1,827	1,827	
Weight of non-aggregate materials per cubic meter concrete mixture	kg		541	541	
Weight of a cubic meter of concrete mixture	kg		2,368	2,368	
TOTAL READY-MIX CONTAINING RCA IN FRANCE					
Total weight of RCA	million tonnes		2.6	5.5	
Total weight of quarried aggregates	million tonnes		17.3	36.1	
% of RCA of the total weight of concrete mixture	%		10%	10%	*Use the resulting % RCA (of total weight) in the concrete mixture …*
Total amount of ready-mix concrete containing RCA	million tonnes		26	54	*… and divide it by the total amount of RCA used in ready-mix concrete to find the total amount of concrete containing RCA (by weight) …*
Total amount of ready-mix concrete containing RCA	million cubic metres		10.9	22.8	*… and convert it to a volume figure (million cubic metres).*

Scenario model: Recycling concrete in France

16.07.2018

Factual data	*Assumptions*
Scenario variab	*Calculations*

Description	**Units**	**2016**	**2030**		***Walk-through comments***
			BAU	**Circular**	
NON-RCA READY-MIX CONCRETE IN FRANCE					
Total amount of ready-mix concrete containing only non-RCA aggregates	million cubic metres		27.1	15.3	*Calculate the amount of non-RCA concrete by subtracting the amount of RCA concrete from total concrete production, ...*
Total weight of aggregates per cubic meter of concrete mixture	kg		1,861	1,861	*... create an overview of the different attributes for this concrete mixture with 0% RCA, ...*
Weight of non-aggregate materials per cubic meter concrete mixture	kg		544	544	
Weight of a cubic meter of concrete mixture	kg		2,405	2,405	
Total amount of ready-mix concrete containing quarried aggregates	million tonnes		65.3	36.8	*... and use those attributes to calculate the amount of quarried aggregates in concrete using only quarried aggregates.*
Total amount of quarried aggregates used in ready-mix concrete	million tonnes		50.5	28.5	
TOTAL WEIGHTS OF AGGREGATES IN ALL FORMS OF READY-MIX IN FRANCE					
Total weight of RCA	million tonnes		2.6	5.5	*Sum the weights of all aggregates (RCA and quarried) for each scenario.*
Total weight of quarried aggregates	million tonnes		67.9	64.6	
Total weight of ready-mix concrete	million tonnes		91.2	90.7	
ENVIRONMENTAL IMPACT ANALYSIS					
Key environmental impacts (per cubic metre)	**Units**				*Based on existing LCA data, estimate the key environmental impacts are of producing one cubic metre of the concrete mixture ...*
Consumption of energetic resources	10^3 MJ		2.00	2.00	*... with the given % of RCA.*
Abiotic depletion	kg eq Sb		1.52	1.52	
Water consumption	10^5 L		7.50	7.50	
Global warming	10^2 kg eq CO2		4.27	4.27	
Acidification	kg eq SO2		0.92	0.92	
Eutrophication	kg eq PO4^3-		0.21	0.21	
Air pollution	10^5 m3		6.96	6.96	
Water pollution	10^3 m3		3.20	3.20	
Ozone layer depletion	10^-5 kg CFC eq R11		2.66	2.66	
Photochemical oxidation	kg eq C2H4		0.12	0.12	
Key environmental impacts (total RCA concrete production)	**Units**				*Use the key environmental impacts for producing one cubic metre of the concrete mixture with the given % of RCA ...*
Consumption of energetic resources	10^3 MJ		21,818,766	45,455,763	*... and multiply that by the total amount of ready-mix concrete containing RCA ...*
Abiotic depletion	kg eq Sb		16,614,988	34,614,559	*... to calculate an estimate of the total key environmental impacts.*
Water consumption	10^5 L		81,981,465	170,794,719	
Global warming	10^2 kg eq CO2		46,646,546	97,180,304	
Acidification	kg eq SO2		10,048,270	20,933,896	
Eutrophication	kg eq PO4^3-		2,259,201	4,706,669	
Air pollution	10^5 m3		76,129,412	158,602,942	
Water pollution	10^3 m3		35,026,403	72,971,673	
Ozone layer depletion	10^-5 kg CFC eq R11		29,127,486	60,682,263	
Photochemical oxidation	kg eq C2H4		1,333,651	2,778,440	

Scenario model: Recycling concrete in France

16.07.2018

Factual data	*Assumptions*
Scenario variab.	*Calculations*

Description	**Units**	**2016**	**2030**		***Walk-through comments***
			BAU	**Circular**	
ENVIRONMENTAL IMPACT ANALYSIS (concrete with quarried aggregates)					
Key environmental impacts (per cubic metre)	**Units**				*Based on existing LCA data, estimate the key environmental impacts of producing one cubic metre of the concrete mixture ...*
Consumption of energetic resources	10^3 MJ		2.14	2.14	*... with 0% of RCA.*
Abiotic depletion	kg eq Sb		1.64	1.64	
Water consumption	10^5 L		7.80	7.80	
Global warming	10^2 kg eq CO2		4.44	4.44	
Acidification	kg eq SO2		0.86	0.86	
Eutrophication	kg eq PO4^3-		0.22	0.22	
Air pollution	10^5 m3		7.53	7.53	
Water pollution	10^3 m3		3.38	3.38	
Ozone layer depletion	10^-5 kg CFC eq R11		2.87	2.87	
Photochemical oxidation	kg eq C2H4		0.13	0.13	
Key environmental impacts (concrete with quarried aggregates)	**Units**				*Use the key environmental impacts for producing one cubic metre of the concrete mixture with 0% RCA ...*
Consumption of energetic resources	10^3 MJ		58,088,016	32,737,580	*... and multiply that by the total amount of ready-mix concrete not containing any RCA ...*
Abiotic depletion	kg eq Sb		44,516,050	25,088,613	*... to calculate an estimate of the total key environmental impacts of non-RCA concrete production.*
Water consumption	10^5 L		211,722,675	119,323,891	
Global warming	10^2 kg eq CO2		120,519,061	67,922,830	
Acidification	kg eq SO2		23,343,782	13,156,224	
Eutrophication	kg eq PO4^3-		5,971,665	3,365,546	
Air pollution	10^5 m3		204,393,813	115,193,449	
Water pollution	10^3 m3		91,746,492	51,707,019	
Ozone layer depletion	10^-5 kg CFC eq R11		77,903,087	43,905,073	
Photochemical oxidation	kg eq C2H4		3,528,711	1,988,732	
Key environmental impacts (total concrete production)	**Units**				*Sum the key environmental impacts for total concrete production in France.*
Consumption of energetic resources	10^3 MJ		79,906,782	78,193,343	
Abiotic depletion	kg eq Sb		61,131,038	59,703,172	
Water consumption	10^5 L		293,704,140	290,118,611	
Global warming	10^2 kg eq CO2		167,165,607	165,103,134	
Acidification	kg eq SO2		33,392,052	34,090,120	
Eutrophication	kg eq PO4^3-		8,230,866	8,072,214	
Air pollution	10^5 m3		280,523,225	273,796,391	
Water pollution	10^3 m3		126,772,895	124,678,692	
Ozone layer depletion	10^-5 kg CFC eq R11		107,030,573	104,587,336	
Photochemical oxidation	kg eq C2H4		4,862,362	4,767,171	

Scenario model: Recycling concrete in France

16.07.2018

Factual data	*Assumptions*
Scenario variab	*Calculations*

Description	**Units**	**2016**	**2030**		***Walk-through comments***
			BAU	**Circular**	
Key environmental impacts (difference between BAU and circular scenario	**Units**		***%***	***nominal***	*Compare the difference between the BAU and circular scenarios for the environmental impacts.*
Consumption of energetic resources	10^3 MJ		*-2.14%*	*- 1,713,439*	
Abiotic depletion	kg eq Sb		*-2.34%*	*- 1,427,866*	
Water consumption	10^5 L		*-1.22%*	*- 3,585,530*	
Global warming	10^2 kg eq CO2		*-1.23%*	*- 2,062,473*	
Acidification	kg eq SO2		*2.09%*	*698,068*	
Eutrophication	kg eq PO4^3-		*-1.93%*	*- 158,652*	
Air pollution	10^5 m3		*-2.40%*	*- 6,726,835*	
Water pollution	10^3 m3		*-1.65%*	*- 2,094,203*	
Ozone layer depletion	10^-5 kg CFC eq R11		*-2.28%*	*- 2,443,237*	
Photochemical oxidation	kg eq C2H4		*-1.96%*	*- 95,191*	

10.1.3 Interpolations of life-cycle assessment data

1. Division of weight of ready-mix concrete mixtures

% RCA	**kg/m3**	Total weight of recycled aggregates	Total weight of aggregates	Total weight of non-aggregate materials	Total weight of concrete
0%	**Traditional (0% RCA of total used aggregates)**	-	**1,861**	**544**	**2,405**
10%		161	1,839	542	2,381
15%		242	1,827	541	2,368
20%		322	1,816	540	2,356
30%		484	1,794	538	2,332
40%		645	1,771	536	2,307
50%		806	1,749	535	2,283
60%	**Mixed (56% RCA of total used aggregates)**	**967**	**1,726**	**533**	**2,259**
70%		1,134	1,703	531	2,234
80%		1,301	1,681	529	2,210
90%		1,468	1,658	527	2,185
100%	**Recycled (100% RCA of total used aggregates)**	**1,635**	**1,635**	**526**	**2,161**

Source: authors' own elaboration, based on data table from https://www.sciencedirect.com/science/article/pii/S2352710215300462

2. Characteristics of ready-mix concrete mixtures

% RCA	Natural sand	Recycled sand	Natural coarse aggregates	Recycled coarse aggregates	Natural fine aggregates	Recycled fine aggregates	Cement (CEM 1)	Water	Additives	Total weight	Percentage of weight that is aggregates
0%	**685**	**-**	**1,065**	**-**	**111**	**-**	**350**	**194**	**-**	**2,405**	**77%**
10%	697	-	888	142	93	19	350	192	0		
15%	704	-	799	213	83	29	350	191	1		
20%	710	-	710	284	74	38	350	189	1		
30%	722	-	533	426	56	58	350	187	1		
40%	734	-	355	568	37	77	350	185	2		
50%	747	-	178	710	19	96	350	182	2		
60%	**759**	**-**	**-**	**852**	**-**	**115**	**350**	**180**	**3**	**2,259**	**76%**
70%	569	192	-	745	-	197	350	176	5		
80%	380	385	-	638	-	279	350	173	7		
90%	190	577	-	531	-	360	350	169	9		
100%	**- 0**	**769**	**-**	**424**	**-**	**442**	**350**	**165**	**11**	**2,161**	**76%**

Source: authors' own elaboration, based on data table from https://www.sciencedirect.com/science/article/pii/S2352710215300462

3. Environmental impact indicators of ready-mix concrete mixtures

Key environmental impacts for production of:		Consumption of energetic resources	Abiotic depletion	Water consumption	Global warming	Acidification	Eutrophication	Air pollution	Water pollution	Ozone layer depletion	Photochemical oxidation
Units		10^3 MJ	kg eq Sb	10^5 L	10^2 kg eq CO2	kg eq SO2	kg eq PO4^3-	10^5 m3	10^3 m3	10^-5 kg CFC eq R11	kg eq C2H4
Written-out units		10^3 megajoules	Kilogram of antimony equivalent	10^5 liter	Kilogram of carbon dioxide equivalent	Kilogram of sulfur dioxide equivalent	Kilogram of phosphate equivalent	10^5 cubic meter	10^3 cubic meter	10^-5 kilogram CFC equivalent R-11	Kilogram of ethylene equivalent
Type of unit		Energy	Weight	Volume	Weight	Weight	Weight	Volume	Volume	Weight	Weight
% RCA	**0%**	**2.14**	**1.64**	**7.80**	**4.44**	**0.86**	**0.22**	**7.53**	**3.38**	**2.87**	**0.13**
	10%	2.04	1.56	7.60	4.32	0.90	0.21	7.15	3.26	2.73	0.12
	15%	2.00	1.52	7.50	4.27	0.92	0.21	6.96	3.20	2.66	0.12
	20%	1.95	1.48	7.40	4.21	0.94	0.20	6.77	3.14	2.60	0.12
	30%	1.85	1.40	7.19	4.09	0.98	0.19	6.39	3.03	2.46	0.11
	40%	1.75	1.32	6.99	3.98	1.02	0.18	6.02	2.91	2.32	0.11
	50%	1.66	1.24	6.79	3.86	1.06	0.18	5.64	2.79	2.18	0.10
	60%	**1.58**	**1.16**	**6.60**	**3.75**	**1.09**	**0.17**	**5.28**	**2.67**	**2.09**	**0.10**
	70%	1.53	1.09	6.41	3.65	1.12	0.16	4.97	2.56	2.07	0.09
	80%	1.49	1.02	6.22	3.55	1.16	0.15	4.65	2.45	2.05	0.08
	90%	1.44	0.94	6.04	3.45	1.19	0.14	4.34	2.33	2.03	0.08
	100%	**1.39**	**0.87**	**5.85**	**3.35**	**1.22**	**0.13**	**4.02**	**2.22**	**2.01**	**0.07**

Source: authors' own elaboration, based on data table from

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