Scenarios for concrete-rubble recycling in the Netherlands

An evaluation integrating Life Cycle Assessment and Life Cycle Costing

Brenda Miranda Xicotencatl

Universiteit Leiden

TU Delft

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by

Brenda Miranda Xicotencatl

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Student number:	S1573322	Leiden University
	4412796	TU Delft
Thesis committee:	Dr. M. Hu	Leiden University
	Dr. F. Di Maio	TU Delft
	E. van Roekel	GBN

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Abstract

Two main features of the construction and demolition systems translate into environmental pressure; an increasing need for building materials, to provide and maintain the infrastructure for growing urban populations, and the management of large amounts of waste streams that come from demolition and construction activities. Because of its high volume and limited management alternatives, the concrete waste is a critical stream. In the Netherlands, 95% of concrete rubble from construction and demolition waste is recycled into an application of lower grade through regular crushing. Alternative methods for reintegrating the coarse fraction into new concrete are Advanced Dry Recovery (ADR), electrical fragmentation (EF) and wet processing. Around 2% of the concrete waste stream is wet processed, but this alternative is energy intensive and expensive. Oppositely, ADR and EF are simpler technologies that also offer to retrieve the value of concrete, but are still at a pilot stage. This research project focuses on ADR as a recycling alternative to regular crushing in specific scenarios, addressing financial and environmental implications through the use of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). The main research question is: What are the environmental and economic implications of different concrete recycling scenarios in the Netherlands? The applicability of the results is that of a first estimate of the economic and environmental implications of shifting to ADR concrete-rubble recycling, with a detailed coverage of costs and types of environmental interventions. The research question is addressed from two different perspectives. First, a case study from the HISER project is evaluated integrating LCA and LCC. The case is about the demolition of an end-of-life building and the construction of a new building on the same site where the old building stood. Therefore, it includes a waste management component and a material supply component. The materials retrieved from the demolition of a building were registered and the materials required for the new building estimated. As the demolition of a building is a one-time event, the real demolition and the construction plans are compared to a virtual demolition and the consequent construction plans. The scenario from the real demolition promotes circularity regarding coarse aggregate for concrete production, by recycling with ADR the clean concrete rubble from a 'best-practice' demolition. Second, with the Life Cycle Inventory (LCI) from the first perspective, the environmental implications of using recycled coarse aggregate instead of natural coarse aggregate for the production of concrete are explored. Regarding the impact assessment method, the modelled environmental interventions were better represented with the PEF characterization factors than with the EN15804 characterization factors. The integrated LCC-LCA study indicates that recycling concrete rubble into coarse aggregate for concrete with ADR technology provided environmental benefits at a higher cost for the Steiger 113 project, compared to the virtual option of processing the stony fraction through regular crushing and sourcing imported gravel for the new construction. The reduction of transport distances between the source of CDW, the ADR facilities and the consumer of the RCA would decrease the costs and the environmental burden. Within the defined scenarios from two different perspectives, the supply chain of RCA from concrete-rubble recycling with ADR technology presents environmental advantages compared to the supply chain of NCA. The Circular Economy Index presented advantages compared to mass recycling rates while contrasting the LCC environmental profiles with simple indicators.

Acknowledgements

Herein I would like to express my gratitude towards the support received from the Leiden University Excellence scholarship programme (LEXs) and the Mexican National Council for Science and Technology (CONACYT), under the scholarship 579309/409817.

Working on a real case was interesting, exciting and inspiring; discovering about related researches and perspectives was enriching. All those learning possibilities arose from the opportunity of collaborating to the HISER research programme. My special thanks go to Dr. M. Hu, who introduced me to the project and helped me assimilate the information of the vast previous developments. Together with her, Dr. F. Di Maio shared with me fruitful comments about my research that, amongst other things, made me aware of the relevance of integrating results coming from interdisciplinary perspectives.

This research would not have been possible without the contributions of F. Rems, R. Huismans and E. van Roekel, from GBN, who provided me with the primary data of the case study and with valuable comments and insights.

During the course of recent months, I had the fortune to be witness of the kindness and hospitality of many people, many of them from the Industrial Ecology community. Stephanie, Sho, Vigil, Elizabeth, Francesca, Diana, Franco, Juanita, Daniel, Vikram, Natalia, and Oscar, thank you all for helping me deal with the unexpected.

At last in the text but first in my heart, I feel blessed with all the support that my dear family and beloved Julio have constantly been providing me with. Thanks for being a source of inspiration, strength, and love.

Declaration

My thesis derives from a research project supervised by Dr. M. Hu and Dr. V. Prado for the course “Interdisciplinary Project Groups,” code 4413INTPGY. The final deliverables consisted on: 1) a curricular report with supporting information of a comparative Life Cycle Assessment and Life Cycle Costing for two scenarios of demolition waste management of an existent building (Steiger 113, Almere), based on assumptions of compositions and waste management options; and 2) the design of datasheets to collect information of the planned demolition of the building under study. The aforementioned project contributed to the research programme entitled ‘Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste’[1] (HISER). The HISER project has received funding from the European Union’s Horizon 2020 research and innovation programme under the grant agreement No 642085.

The supervisors of this thesis, Dr. M. Hu, Dr. F. Di Maio and E. van Roekel, are, within the HISER framework, some of the representatives of the Institute of Environmental Sciences of Leiden University (CML), TU Delft, and Strukton Civiel BV (GBN), respectively. These institutions are three of more than twenty partners contributing to the HISER project.

Parallel to the present work, I collaborated with my supervisors in the elaboration of a HISER report, led by CML, exploring two redefined scenarios for the demolition of Steiger 113 and the waste management of a selection of material streams. My main tasks were to adapt the structure of the LCA and LCC to a different scope than the explored in the curricular report and to update, with the data collected during demolition, all the considered variables.

The stony rubble, containing concrete, is one of the materials followed by the mentioned report. The data and models I developed during my thesis research for the Life Cycle Assessment and Life Cycle Costing of concrete-rubble recycling were considered for the correspondent HISER report. I did not receive however, any direct economic resources from the above mentioned grant agreement.

Finally, I have been drafting, with Dr. M. Hu, Dr. V. Prado, and with my colleague D. Ita-Nagy, dissemination versions of our research findings. We are preparing a manuscript for a peer-reviewed journal and contributions for conferences.

Disclaimer: The content of this report does not reflect the official opinion of the European Union nor of the HISER partners.

[1] Official website: http://www.hiserproject.eu/

Content

Index of tables

Index of figures

1. Introduction

There are two main features of the construction and demolition systems that translate into environmental pressure. One is the increasing need for building materials to provide the infrastructure for a growing urban population and for the maintenance of the existing infrastructure. The other one is the management of large amounts of waste streams that come from demolition and construction activities.

Concrete is the artificial material that more has been used since its invention (de Brito and Saikia 2013). Because of its volume and currently limited management alternatives, the concrete waste is a critical stream.

More than 450 million tons of construction and demolition waste (CDW) are generated annually in the European Union, of which 40-67% contains end-of-life (EOL) concrete (Turk et al. 2015). Some countries, like the Netherlands, have a high level of concrete-rubble recycling but the current regime is not sustainable (Hu et al. 2013).

While the management of construction and demolition waste is a common issue on a global scale, this work will focus in the Netherlands. This decision is based on data availability and aims to reduce uncertainty regarding current practices and feasibility. In particular, a Dutch case study will be used as a base for the elaboration of scenarios that address two different perspectives of concrete-rubble recycling.

1.1 Background

This section explains the context of this research. First, it discusses the pursuit of zero-energy buildings as a driver for demolition. Second, it presents previous research that addressed the sustainability challenges that the construction and demolition sector face from a holistic perspective, mainly focusing on environmental performance. Third, it highlights results and trends of a selection of previous studies on concrete-rubble recycling. Fourth, it provides information specific to the Dutch context for concrete recycling. Then, Section 1.1.5 exposes the role of Circular Economy in reaching sustainability, and finally, Section 1.1.6 describes the case study from which this thesis project derives.

1.1.1 Energy performance of buildings as a driver for demolition

The building sector contributes to climate change with nearly 20% of the global greenhouse gas emissions (Ecofys et al. 2016). Most of the environmental burdens of the life cycle of a building associate with energy consumption during the use phase (Blengini 2009; Blengini and Garbarino 2010).

In Europe, this fact has been followed by increasing pressure on improving the environmental performance of buildings, specifically by reducing their energy demands; improving the cooling, heating and insulation technologies (Manteuffel et al. 2016).

Regarding the Paris agreement, an assessment of the alternatives for the construction sector concluded that the current efforts for meeting the target of keeping global warming below the 1.5°C threshold are insufficient at a worldwide level (Ecofys et al. 2016). The efforts mainly consist on renovating the existent stock and on designing and construction zero-energy buildings.

While several variables determine the energy consumption of a building, a widely accepted indicator of possible technical obsolescence is its age (Majcen et al. 2015). For example, an old building may lack energy saving measures or have systems whose lack of maintenance yields to a poor energy performance; on the contrary, new buildings for may have more energy saving measures.

However, land prices and market demand influence the decision to demolish more frequently than the technical factors do (Meijer et al. 2009). In this way, demolition is a more popular alternative than renovation.

For example, there is a common notion that the refurbishment of an existent building with low performance is more costly than its demolition and the construction of a new building. One of the arguments for this notion is that assessing the state of the building of bad performance, designing a plan to adapt the building to refurbish the building and implement it would consume much time and economic resources. However, some initiatives are challenging this preconceived idea[2].

Despite an increasing promotion of the renovation option, as the renovation rates are not enough to deal with the high energy consumption of buildings, the building sector is still oriented towards demolition rather than renovation.

1.1.2 A holistic approach for the construction and demolition sectors

It has been proposed that a life cycle approach could deal with the increasing need for building materials to provide and maintain the infrastructure for growing urban populations and the management of large amounts of waste streams that come from demolition and construction activities.

A holistic approach could also make evident potential trade-offs of solving issues while aggravating others. For instance, the increment on energy saving technology could imply a higher material complexity (Blengini 2009).

[2] Paraphrase of a topic exposed in the public lecture ‘Reuse, never demolish!’ by Anne Lacaton, visiting professor of the Faculty of Architecture, TU Delft, in September 20th, 2016.

In this way, Cabeza et al. (2014) reviewed Life Cycle Assessments (LCA) of buildings and the building sector. They concluded that most of the studies aimed at low-energy consumption designs, using innovative materials and systems. Furthermore, and as reported by Blengini (2009), they identified high uncertainties related to the modelling of the demolition phase; just a few demolition cases were modelled after a real case.

Conversely, Bovea and Powell (2016) discussed how LCAs evaluated the environmental performance of CDW management strategies. They identified that most popular disposal options were off-site recycling, incineration, and landfill. Furthermore, they identified that the benefits that arise from the revalorization of waste could be hampered, under certain conditions, by the need for additional transport. This implication challenges the current waste management hierarchy, which does not distinguish between on-site recycling and off-site recycling.

Both reviews (Bovea and Powell 2016; Cabeza et al. 2014) mention that the economic factor is relevant when the study intends to support decision making, but the economic assessment methods used in the current practice are still divergent. They also stress the need for transparent models and comparable functional units in order to compare similar studies and to validate generalizations.

Other tools, such as Material Flow Analysis (MFA), have been used to study topics around CDW management. For instance, Hu et al. (2010) performed a dynamic MFA for strategic CDW management in Beijing, elaborating on three future scenarios of variable characteristics: current trend extension, high GDP growth, and lengthening the lifetime of dwellings. They identified that the generation rate of CDW will rise unavoidably, and while increasing the lifetime of dwellings can postpone the CDW generation peak, improving recycling is essential to deal with the CDW management.

1.1.3 Concrete-rubble recycling as an object of study

Metals are also a heavy stream from CDW, but their management is already highly developed, as they retain value through several life cycles. Oppositely, research on concrete waste receives special attention with topics addressing the performance of recycling alternatives (Lotfi et al. 2014; Guignot et al. 2015) and innovative formulations in terms of acceptability and technical adequacy (Turk et al. 2015).

Guignot et al. (2015), for instance, studied the environmental implications of two alternatives for concrete-rubble recycling in France through a comparative LCA. The baseline consisted in the dominant practice of crushing the lithoid materials and using the output for road construction. The other alternative utilized electrical fragmentation, which leads to a gravel aggregate and a cement paste. The later output materials would then serve for purposes that originally would require the transformation of natural raw materials into new products. Therefore, the comparison included the treatment of the waste stream from demolition (1 kg of concrete wastes) and the supply of materials for construction (natural aggregate for concrete production, materials needed in clinker kiln, and crushed aggregate for road embankments). Guignot et al. paid special attention to the differences in transport schemes associated with both alternatives. A multi-scenario approach addressed the uncertainty related to variable compositions and different transport schemes. In any scenario, the use of electrical fragmentation led to environmental gains, in all the considered impact categories (climate change, fossil fuel depletion, terrestrial acidification, and natural land transformation). The EF technology is currently at a pilot stage.

Although without performing an LCA, Bakker et al. (2013) and Lotfi et al. (2014) proposed a mechanical recycling process to obtain high-grade aggregates from EOL concrete, denominated Advance Dry Recovery (ADR). Lotfi et al. (2014) performed a pilot test with rubble from an actual demolition in Groningen. They characterized the input of the ADR process that came from a 'smart demolition'[3] and the output composition. The ADR technology is intended as a mobile set. If the mobility became operational, the need for transport would decrease. The introduction of a quality sensor for the output could further reduce the transport requirements, since the concrete rubble from CDW could be processed on-site and directed to a new consumer of building materials. As the EF technology, the ADR technology is currently at a pilot stage.

Additionally, Hu et al. (2013) propose the integrated use of different analytical tools to address specific questions regarding concrete-rubble recycling in the Netherlands at different levels. The tools would be used individually, but the implementation of the results would be integrated into a Life Cycle Sustainability Assessment (LCSA) framework.

1.1.4 Concrete-rubble recycling in the Netherlands

Meijer et al.(2009) report that, in 2003, the Netherlands had higher demolition rates than Austria, Finland, France, Germany, Sweden, Switzerland and the United Kingdom. They also reported that urban renewal and low occupancy rates drove the demolition in the Netherlands; when the existing stock was unable to meet the demand for dwellings, demolition was often followed by construction activities.

The Netherlands reached a recycling rate of 95% of CDW in 2001 as a result of a landfill ban implemented in 1997. Consequently, all the concrete rubble from construction and demolition is retrieved for recycling (Hu et al. 2013).

In the Netherlands, 95% of concrete rubble is recycled into a low-grade application (e.g. road base construction) through regular crushing. However, only a small part (2%) is recycled for an application with the same grade as the original material. The technology used to obtain recycled concrete aggregate is 'wet processing', which is energy intensive, expensive, and produces a sludge whose final disposal is landfilling (Bakker et al. 2013; Hu et al. 2013).

[3] In the mentioned paper (Lotfi et al. 2014), it is referred as a selective demolition intended to reduce the level of contaminants in the crushed concrete.

It has been estimated that in the future, the demand for road base materials will stabilize, while the outflow of concrete rubble from CDW will keep on growing. However, the Dutch policy-makers abandoned a scheme that promoted concrete-rubble recycling into new concrete due to a lack of evidence of the potential environmental benefits (Hu et al. 2013).

1.1.5 Circular economy

The circular economy framework was proposed as an alternative to the dominant regime, regarded as linear (Hobson 2015), in which virgin materials are extracted from natural sources, become products after one or more transformation processes, are used, discarded, processed as wastes and released to natural sinks.

In contrast, the circular economy would offer other pathways between the life cycle stages rather than the mono-directional flow of the 'take-make-dispose' model (Valerio et al. 2017; Di Maio and Rem 2015). These alternative pathways constitute feedback loops aiming to maintain the circulation of materials, and powered through resource-efficiency, would reduce the rates of resource extraction and waste generation (Hobson 2015).

There is consensus to pursue circular economy goals at the European Union level. While a clear transition plan is still on its way, the Netherlands has innovated with some cases and shows to be a fertile ground for more experiments (Bastein et al. 2013).

1.1.6 A case study from the HISER research programme

The research programme entitled 'Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste'[4] (HISER) states its objective as it follows:

> …develop and demonstrate novel cost-effective holistic solutions (technological and non-technological) for a higher recovery of raw materials from ever more complex construction and demolition waste by considering circular economy approaches throughout the building value chain (HISER partners 2016).

In particular, one of the five study cases around Europe that the HISER research program entails is the circular demolition project of Steiger 113 in Almere, The Netherlands (Strukton 2016).

The Dutch case study includes a dismantling and demolition stage through practices aiming to retrieve components and materials from the EOL building in the best possible conditions, in order to incorporate them into new life cycles. This particular manner of dealing with an EOL building is referred in this thesis as 'best practices' (BP), and amongst other waste management alternatives, it includes processing the concrete rubble with ADR.

[4] Official website: http://www.hiserproject.eu/

Besides the dismantling and demolition stage, the HISER case study also addresses the subsequent waste management of the retrieved materials and, to achieve a circular approach, the material requirements to build another construction on the same site.

The composition of a building is complex but, for the referred HISER case study, the retrieved materials were classified into ten streams. This thesis research addresses one of these streams, which is the stony fraction.

The measured yield of stony materials from the demolition and the projected requirements of stony aggregates for the new building, according to the HISER case study are presented in Table 1-1. The EOL building stood two-stories tall, was non-residential, and had a ground surface of approximately 322m^2.

Table 1-1 Materials from demolition and for construction; Steiger 113 project

Material	Amount (t)
Stony rubble from demolition	**2097.4**
Concrete rubble	671.2
Mixed rubble	1426.2
Stony aggregates for construction	**2160.0**
Road base aggregate (RBA)	1800.0
Coarse aggregate for concrete production (CA)	360.0

It is important to acknowledge that the projected requirements used here are from estimates at early stages of the project.

The information collected and estimations made for the HISER case study described above will be the main reference for the models and analysis performed.

1.2 Research question

The main research question is:

What are the environmental and economic implications of different concrete-rubble recycling scenarios in the Netherlands?

Since this research focused in the technological level, the economic indicators were financial; namely the costs of the project, at the micro level.

This research compared the business-as-usual (BAU) alternative of transforming stony rubble into an aggregate of road base grade (RBA) and the alternative of retrieving a coarse aggregate from the concrete rubble with a low-energy-demanding technology: ADR. Scenarios for equivalent systems were defined and studied within an integrated framework of LCC and LCA. The outcomes of a first approach were used to other scenarios, which compared the use of recycled coarse aggregate (RCA) from ADR and the use of natural concrete aggregate (NCA).

The first comparison addressed financial and environmental interventions, while the second comparison addresses only environmental interventions.

The sub-questions addressed were:

- How is concrete-rubble recycling with ADR better than recycling it through regular crushing? For this comparison, which are the trade-offs or win-win situations between environmental performance and cost minimization?
- What are the environmental implications of using recycled coarse aggregate instead of natural coarse aggregate for the production of concrete?
- Which are the environmental and economic hotspots of the systems of concrete-rubble recycling?
- What are the environmental hotspots of the systems of concrete production?

2. Method

This chapter explains the approach to the research questions, including background information regarding the used tools.

The datasets generated and collected for the LCA model were managed with the assistance of the CMLCA Scientific Software v5.2[03/12/2014][5], developed by the Institute of Environmental Sciences of Leiden University (CML).

Next, Section 2.1 presents a framework for a study integrating Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Furthermore, the data collection process is described, and several topics about the LCA impact assessment are discussed.

2.1 An integrated framework of Life Cycle Assessment and Life Cycle Costing

The LCA methodology allows the comparison of environmental interventions (e.g. resource depletion and pollution) of goods and services throughout their life cycle, by modelling their product systems[6]. It is a suitable tool for identifying opportunities for reducing the impacts attributable to associated wastes, emissions and resource consumption (Pennington et al. 2004). Therefore, in the pursuit of sustainability, the use of LCA as a tool for decision-making has become increasingly popular since the 1970s (Guinée et al. 2010).

Around 1930, LCC served as a tool to analyse the present and future economic implications of potential investments (Schmidt et al. 2008). More recently, it was suggested and adapted as a complement to LCA, to account for the economic dimension of sustainability (Swarr et al. 2011a; Nakamura and Rebitzer 2008). In this thesis, the term 'life cycle costing' (LCC) refers to methods intended to integrate existing financial data with metrics in life cycle approaches (Rebitzer and Seuring 2003).

The LCA followed the framework and general guidelines established in the handbook by Guinée et al. (2002), which is regarded as a guide to meet the requirements of the ISO 14040/44 (2006) standards[7]. The link with LCC considered the recommendations of the code of practice published by the SETAC (Swarr et al. 2011b), and the computational

[5] As of January 2017, the version 5.2 [28 August 2012] was available to the general public at http://www.cmlca.eu/.
[6] Product system is defined as 'a set of unit processes interlinked by material, energy, product, waste or service flow and performing one or more defined functions'. Unit process is defined as 'the smallest portion of a product system for which data are collected in an LCA'(Guinée et al. 2002).
[7] By the time the handbook on LCA by Guinée et al. (2002) was published, the standards ISO 14040/41/42/43 were applicable. In 2006, the standards ISO 41/42/43 were edited and compiled into the standard ISO 14044 (ISO 2006b), which replace them.

structures discussed by Heijungs et al. (2013) and Moreau and Weidema (2015). The integration of LCA and LCC into a common framework is illustrated in Figure 2-1.

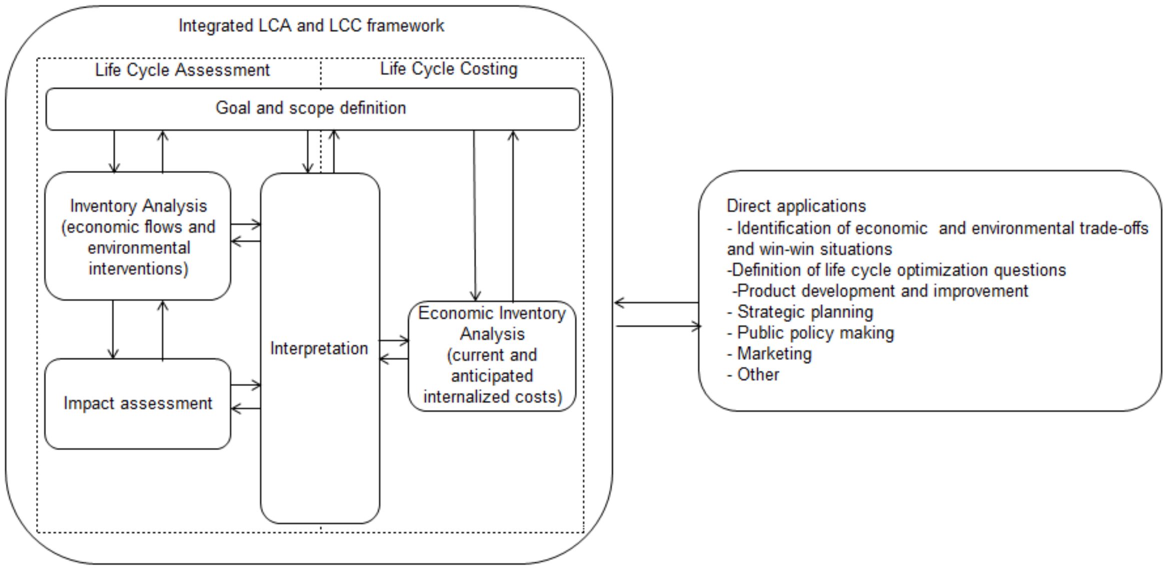


Figure 2-1 Methodological framework of an integrated LCA and LCC study based on ISO 14040 (2006) and Swarr et al. (2011a, 2011b)

2.1.1 Data collection for the environmental and economic inventories

The life cycle stages defined for the product system are the same for the LCA and LCC in the integrated study (See Figure 3-1).The performed LCC considered six kinds of costs: transport, machinery, utilities, labour, and materials purchase. The environmental interventions include direct emissions from combustion processes and indirect interventions drawn from the connected ecoinvent v2.2 modules (ecoinvent Centre 2007). The level of quality of the data is mainly case and sector specific, but some information is company specific, application specific or generic (See Section 3.1.2).

The LCA of concrete production alternatives considers the environmental inventory modelled for the LCA-LCC integrated study and generic data from ecoinvent v2.2

2.1.2 Impact-assessment approach

The standard ISO 14025 (2006) establishes the principles and procedures for developing environmental labels and declarations in the scope of business-to-business communication. However, there are many approaches for assessing the environmental performance of product systems. For instance, the standard EN15804 and the PEF guide are relevant in the realm of construction products and buildings (Passer et al. 2015).

Impact categories

The assessment of a broad variety of impact categories aims to avoid problem shifting[8]. Nevertheless, it is unfeasible to account for all the possible environmental interventions. This limitation comes from constraints on data availability and quality, and from the degree of development of characterization methods. Therefore, the selection of relevant impact categories, category indicators, and characterization factors should align to the goal and scope (Guinée et al. 2002).

The ISO framework on LCA contemplates a distinction of effects on different groups. These compartments are often called areas of protection (Udo de Haes et al. 1999; Pennington et al. 2004).

While the PEF method is suitable for evaluating any product, the standard EN15804 is specific for analyses of buildings and products of the building sector. Amongst other differences, the PEF guide sets by default fifteen different impact categories (EC 2013), while the standard EN15804 requires the use of seven (Passer et al. 2015) as illustrated in Table 2-1. In this table, the impact categories are classified into three areas of protection. The indicators of the impact categories and characterization models for both approaches are further detailed in Table A-1 and Table A-2.

The building industry is yet to reach a consensus about the advantages or disadvantages of covering the impact categories of the PEF method instead of considering the impact categories of the standard EN15804 (Passer et al. 2015; ECRA 2015). In this research, the product systems were evaluated considering the impact categories of both methods. Section 3.3 reports on the impact assessment with the PEF categories, while the impact assessment with the categories in EN15804 is presented in Figure A-1. Section 4.3.2 includes a reflection about the coinciding and differing information that both methods provide.

The indicators in both PEF and EN15804 methods address the impact assessment at a mid-point level. Thus, the impact categories presented in Table 2-1 may correspond to one or more areas of protection (Guinée et al. 2002; Hauschild et al. 2013). However, the classification that Table 2-1 provides is convenient to exemplify that both approaches address the areas of protection contemplated by the ISO framework on LCA.

[8] Problem shifting refers to the event of solving a problem at expenses of aggravating another (Guinée et al. 2002).

Table 2-1 Comparison of impact categories in the PEF and EN15804 approaches

		PEF	EN15804
Ecosystem quality	Climate change	✓	✓
	Freshwater ecotoxicity	✓	-
	Acidification	✓	✓
	Freshwater eutrophication	✓	-
	Marine eutrophication	✓	-
	Terrestrial eutrophication	✓	-
	Eutrophication (generic)	-	✓
Human health	Ozone layer depletion	✓	✓
	Carcinogenic effects	✓	-
	Non-carcinogenic effects	✓	-
	Photochemical ozone formation	✓	✓
	Respiratory effects	✓	-
	Ionising radiation	✓	-
Resources	Abiotic, non-fossil, resources depletion	-	✓
	Fossil resources depletion	-	✓
	Minerals, fossils and renewables depletion	✓	-
	Land use	✓	-
	Water depletion	✓	-

Normalization, grouping, and weighting

The normalization, grouping, and weighting[9] steps are optional according to the standards ISO 14040/46 and the PEF method. The impact assessment following the standard EN15804 only includes classification and characterization (Passer et al. 2015); while the PEF approach recommends normalization.

The ISO framework on LCA proposed the normalization step as a tool mainly to address the importance and magnitude of the indicator results, additionally to check for inconsistencies, and possibly to provide and communicate information on the relative

[9] Weighting refers to assigning a factor to each impact category, based on value choices, to 'facilitate comparison across impact category indicators' (Pennington et al. 2004)or to aggregate the environmental impacts (Guinée et al. 2002).

significance of the results (Guinée et al. 2002). Widely accepted normalization methods relate the indicator results to a geographical boundary over a certain period (Guinée et al. 2002; Pennington et al. 2004; EC 2013; Benini et al. 2014; van Oers 2016).

As for this research, normalization of the environmental profiles resulting from the PEF and EN15804 approaches was performed. The European Commission recommends the use of a certain set of normalization factors for PEF studies (Benini et al. 2014). Table 3-4 presents the environmental profile referred to EU-27[10] in the year 2010, using the recommended normalization factors.

Similarly, the characterization results of the EN15804 impact categories were normalized to the total impacts of EU25+3[11] in the year 2000 (see Table A-11). As the EN15804 impact assessment utilizes CML characterization factors, the normalization factors were retrieved from the CML-IA database v4.8 (van Oers 2016). The series of normalization factors of EU25+3 in the year 2000 was the closest option to the PEF reference from the CML-IA database.

In addition, weighting and grouping of the normalized results were performed as intermediate stages for the analysis of the environmental profiles (see Section 2.1.3). Weighting and aggregating the results is not recommended while disclosing comparative LCAs (Guinée et al. 2002); therefore, the results of weighting and aggregation are not reported in the main content of the thesis.

2.1.3 Heuristic approach to analyse the environmental profiles

A comparative analysis was performed to help identify major issues on the environmental profiles of the product systems under study. This analysis aimed to find and quantify the differences amongst the environmental profiles of the comparable alternatives under study. Also, it aimed to recognize dominant impact categories or an even distribution of potential impacts along each environmental profile.

The inputs to the analysis were the results from the characterization of the environmental LCI of the product systems under study, which constitute their environmental profiles. Several steps are performed in order to meet these targets:

1. Identification of the largest indicator result per category between the alternatives from each perspective.
2. Calculation of the indicator results relative to the magnitude of the largest result per impact category between the alternatives from each perspective.
3. Measurement, on each impact category, of the difference between the indicator results for comparable alternatives.

[10] EU-27 includes Austria, Belgium Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, and the United Kingdom.(EC 2016)

[11] The EU25+3 region includes the 25 European Union countries of 2006 plus Iceland, Norway, and Switzerland (Aymard and Botta-Genoulaz 2016).

4. Identification of the impact categories with the narrowest and the widest differences amongst comparable alternatives.
5. Normalization of the environmental profiles.
6. Sorting the normalized environmental profiles in descending order of magnitude.
7. Calculation of an aggregated total, considering an equal weighting factor for all of the impact categories within an impact assessment approach.
8. Identification of the dominant impact categories and of the category with the smallest contribution to the aggregated total.

The first three steps mentioned above were inspired by the analysis presented in the research paper entitled ‘Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles’ (Hawkins et al. 2013), which was awarded with the *Graedel Prize* to the best paper of 2014 by a junior author (Brattebø and Lifset 2015). The comparative representation of environmental profiles relative to a common reference had been promoted long before (Heijungs and Kleijn 2001).

The criteria for the classifications proposed in the last four steps were heuristic. At the fourth step, the impact categories with the narrowest differences were defined as those whose difference between alternatives was equal to or less than 0.25 times the magnitude of the largest indicator result. Similarly, the impact categories with the widest differences were defined as those whose difference between alternatives was equal to or greater than 0.75 times the magnitude of the largest indicator result.

Correspondingly, the dominant categories for each environmental profile were defined as the first impact categories whose sorted normalized values in descending order of magnitude added up to 25% from the aggregated total. This criterion provides information on the distribution of the impacts.

As for the constraints of the comparative analysis at the characterization level, it is important to avoid stating any performance claims before the interpretation stage (Heijungs and Kleijn 2001). In this way, the analysis presented in Section 3.3 is of a descriptive nature, and its implications are further discussed at the interpretation stage, in Chapter 4.

2.2 Indicators of circularity

It was stated before that the popularity of the CE framework keeps on rising (see Section 1.1.5). However, the indicators to measure the alignment to CE principles remain to be harmonized (Valerio et al. 2017). Amongst several indexes of different levels of complexity, two types of indicators simple to compute were selected to contrast the results provided by the complex environmental assessments from Perspective I. These indicators are the Circular Economy Index (CEI) and mass recycling rates (Di Maio and Rem 2015).

On the one hand, recycling rates based on mass are calculated as the mass ratio of recycled materials by a defined total (see Equation 2-1 and Equation 2-2). For example, the dataset on municipal waste for the European Union specifies as mass recycling rate ‘the tonnage recycled from municipal waste divided by the total municipal waste arising’(Eurostat 2015). Also, the recycled content of products is calculated considering the contribution of the mass of recycled materials to the total mass of the product.

$$Mass\ recycling\ rate\ based\ on\ waste\ (\%) = \frac{Mass\ of\ recycled\ waste\ (t)}{Waste\ generated\ or\ collected\ (t)} x\ 100$$

Equation 2-1

$$Recycled\ content\ (\%) = \frac{Mass\ from\ recycled\ materials\ (kg)}{Mass\ of\ products\ (kg)}$$

Equation 2-2

On the other hand, the CEI is calculated as the monetary ratio of the value of the recycled products by the value of the materials before recycling, which is ‘the material value entering the recycling facility’ (see Equation 2-3). This concept implies that the CEI was proposed as a circularity indicator that reflects the potential added value of keeping materials in feedback loops along life cycle stages, instead of prioritizing the volume, which the mass recycling rate does (Di Maio and Rem 2015).

$$CEI = \frac{Material\ value\ recycled\ from\ EOL\ product(s)}{Material\ value\ needed\ for\ (re-)producing\ EOL\ product\ (s)}$$

Equation 2-3 CEI as proposed by Di Maio and Rem (2015)

Several results of the CEI can be obtained for the same system depending on the point at which the value of materials and recycled products is considered, and on the reference that defines the added value. Di Maio and Rem (2015) recommend to consider the values closest to the collection of the EOL products and just before the recycled materials enter to new production processes.

Section 4.5 discusses the references for the basis of calculation of the indicators of circularity and presents the results for a selection of scenarios.

3. Life cycle of concrete rubble

This chapter specifies the goal and scope of the integrated LCA-LCC study and of the subsequent LCA, elaborates on the environmental and financial inventory analysis, and provides the results of the impact assessment.

3.1 Goal and scope definition

The research questions will be addressed through a comparative approach using LCA and LCC. The alternative product systems under study were modelled from two perspectives. The functions, functional units, and reference flows are defined for each perspective.

The first perspective entangles the management of concrete rubble which arises from CDW. The dominant processing option is regular crushing, which yields an aggregate of qualities suitable for road base applications or building foundation. The aggregate of such quality is here referred as 'road base aggregate' (RBA). Another option is retrieving the coarse fraction, which is an aggregate of qualities suitable for structural applications, intended for concrete production: 'recycled coarse aggregate' (RCA). Actors related to this perspective are, for instance, the construction and demolition sector, waste processors and recyclers.

Since this research focus on the use of ADR technology, the perspective from which the production of RCA from ADR competes with the production of RBA was specifically defined as 'Perspective I'. An underlying assumption for the related scenarios is that the properties of the RCA are equivalent to the properties of the natural concrete aggregate (NCA). The same assumption was made in a study comparing processing concrete rubble into RCA with wet processing or into RBA (ECRA 2015). Perspective I and its underlying assumption directly connect to the HISER case study.

The second perspective is about the possibilities of meeting the requirement of coarse aggregate for concrete production, either with RCA or NCA. Perspective II entangles the scenarios in which the RCA has different properties than the NCA, thus, affecting the formulations for concrete production of a specified performance (Lotfi et al. 2015; Coelho and De Brito 2013; de Brito and Saikia 2013).

Rather than claiming the superiority or equivalence of any of the compared alternatives, **this research aims at providing a first estimate of the economic and environmental implications of shifting to ADR concrete-rubble recycling, with a detailed coverage of financial concepts and types of environmental interventions.**

In this way, the primary data comes only from one case of study and many singular data points were selected as secondary data (See Section 3.1.2). Therefore, the research questions and sub-questions were assigned to the analysis performed from each of the defined perspectives.

From Perspective I, with LCA and LCC:

- How is concrete-rubble recycling with ADR better than recycling it through regular crushing? For this comparison, which are the trade-offs or win-win situations between environmental performance and cost minimization?
- Which are the environmental and economic hotspots of the systems of concrete-rubble recycling?

From Perspective II, with LCA:

- How is concrete-rubble recycling with ADR better than recycling it through regular crushing? (Complementary insights)
- What are the environmental implications of using recycled coarse aggregate instead of natural coarse aggregate for the production of concrete?
- What are the environmental hotspots of the systems of concrete production?

With regard to the product systems, from Perspective I, the system follows the stony flows from the demolition of a building through recycling processes. A fraction of the followed processed materials will be used for the construction of a new building on the demolition site. In order to cover the material requirements of the new construction, it is necessary to acquire materials additional to those retrieved from the demolition. The acquisition of these materials from the market is also part of the system under study. This is a *grave-to-cradle* scope for the concrete rubble (Valero and Valero 2013; Go et al. 2015).

Although the origin of RBA from the demolition site and from the market is similar (crushed aggregate from demolition waste), a distinction is made in the analysis. The distinction emphasizes that a fraction of the RBA will be supplied with the materials already on-site (RBAs) and another fraction will be purchased from a local market and transported (RBAm) to the construction site. This decision was made because the RBAm-RBAs proportion is different in both systems and this has effects on the LCC and on the environmental profile.

From Perspective II, a coarse aggregate is required for concrete production. The comparison covers the supply of the ingredients of concrete, which are coarse aggregate, cement, water, sand and, depending on the formulation, additives. This is a *cradle-to-gate* scope for the coarse aggregate.

3.1.1 Function, functional unit, alternatives and reference flows

Perspective I comprises an integrated functional unit including a waste management component (WM) and a material supply component (MS). Perspective II studies the single function of concrete production.

Table 3-1 Reference flows of the product systems under study

Perspective	Function	Alternative	Reference flow
I	WM+MS	BP	WM: Management of 671 t of concrete rubble in ADR plant and 1426 t of mixed rubble through on-site crushing MS: Supply of 360 t of RCA from ADR plant, 1426 t of RBA from site, and 374 t of RBA from market
		BAU	WM: Management of 2097 t of stony rubble through on-site crushing MS: Supply of 1800 t of RBA from site and 360 t of NCA from market
II	Concrete production	From NCA	Production of 927 dm^3 of concrete with NCA
		From RCA	Production of 927 dm^3 of concrete with RCA
		From mix	Production of 927 dm^3 of concrete with a mix of NCA and RCA

3.1.2 Data quality

The analysis of the alternatives from Perspective I includes field data from the processing of the stony rubble of a demolished building, according to Table 3-2. The primary data were measured or collected for the HISER case study.

Table 3-2 Overview of the primary data for the integrated LCA-LCC study

WM requirement	• Measured weight of materials retrieved from a building demolition: concrete rubble and mixed rubble
Machinery operation	• Type of machine and nominal power • Manufacturer (of most of the machines) • Volume of used fuel • Operation time
Transport profile	• Transport requirements from demolition site to concrete-rubble processor
Costs	• Rental costs (for all the machines that were rented) • Labour (time) • Freight cost of concrete-rubble transport from demolition site to processing site

Secondary data for the MS requirement, the machinery operation, the transport profile and costs have different levels of quality: case specific, company specific, sector specific, application specific and generic. The estimates or reference values developed for the HISER case are secondary data at the case-specific level. Consult the overview of the secondary data for the integrated LCA-LCC in Table A-3.

Examples of secondary data are the preliminary data on wage costs reported for 2015 in the Netherlands (Statistics Netherlands 2016) or the cost of lubricating oil, estimated from prices in the U.S. (LNG Publishing Company 2016).

The LCA of alternatives from Perspective II considers the LCI models of NCA and RCA supply derived from Perspective I. The proportion in which the concrete ingredients are mixed in the model imitates the formula developed in an experiment at lab scale with ADR of concrete from another demolition (Lotfi et al. 2014). The information to model the infrastructure and energy for the production processes came from ecoinvent v2.2. The LCI modules, also from ecoinvent v2.2, for the supply of water, cement, and concrete additives complement the product system of concrete production.

3.2 Inventory Analysis

3.2.1 Product-systems description for the integrated LCA-LCC study

The BP demolition yielded two stony fractions; a fraction of concrete rubble and a fraction of mixed rubble. The pieces of both fractions ranged from 0 to 500 mm. The mixed rubble might have contained metals, plastics, wood and other unspecified materials. These embedded materials were not measured. However, weight contents of 10% of ferrous metals[12] and 1.4% of wood, plastic and other unspecified materials are considered as a reference (de Vries et al. 2009). It was assumed that a BAU demolition would yield only a fraction of stony rubble.

Figure 3-1 illustrates the BAU and BP product systems, which are described in the two sections below. A distinction is made between the aggregate for foundation recycled on-site (RBAs) and the aggregate purchased from the market (RBAm).

[12] Personal communication with F. Rens, Project leader at GBN, on April 19th, 2016 at Hoorn

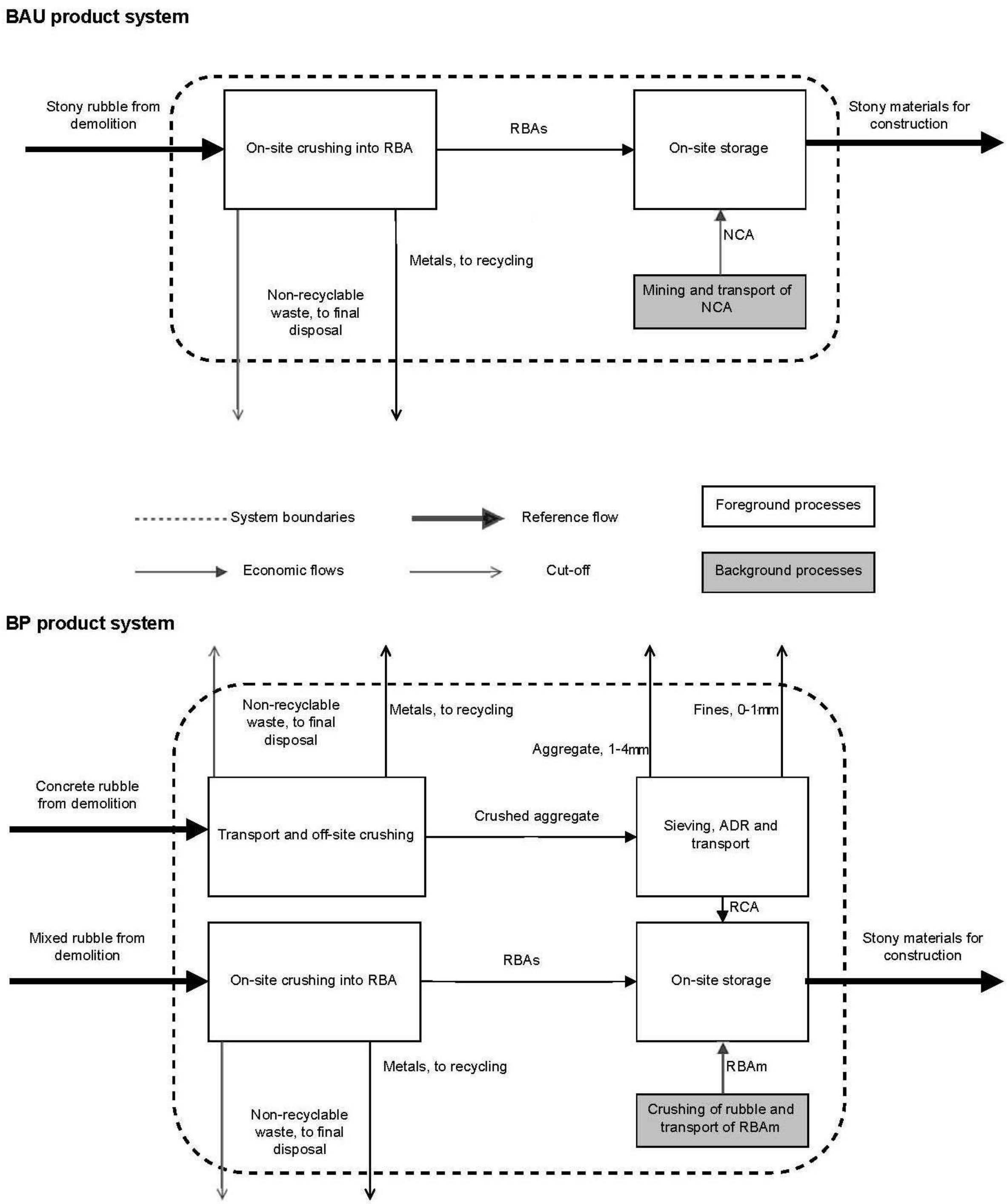


Figure 3-1 Flowcharts of the product systems of the BAU and BP alternatives

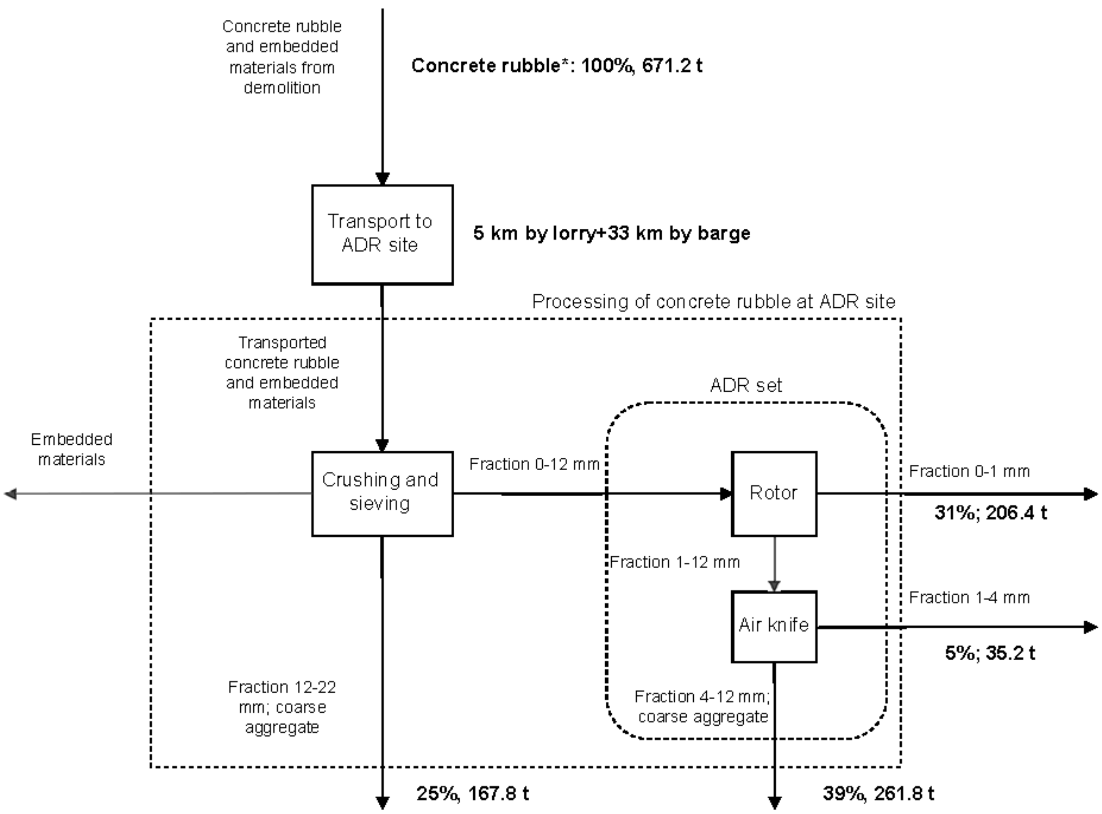
BP product system

- On-site crushing into RBA

An impact crusher reduced the size of the rubble into a 0-31.5 mm aggregate. A rubber-tire loader and an excavator helped load the crusher and accumulate the crushed aggregate (RBAs) into piles.

- Transport and off-site crushing of concrete rubble

A lorry transported the concrete rubble from the demolition site to a local port. Then, the concrete rubble travelled by barge to the ADR processing site as illustrated in Figure 3-2. There, the concrete rubble pieces from 0 to 500 mm were crushed into a 0-22 mm aggregate.



* Mass retrieved from demolition; assumed to exclude embedded materials

Figure 3-2 Processing of concrete rubble at ADR site

For the sake of simplicity, the off-site crushing process considers the same machines as on-site crushing, including the impact crusher and the machinery for handling the throughput. The required operation of the machines was modelled after the on-site crushing, adjusting for the smaller concrete-rubble throughput.

- Sieving of crushed aggregate, ADR, and transport of RCA

As Figure 3-2 illustrates, a sieve split the 0-22 mm aggregate into two fractions; a 12-22 mm coarse aggregate and a 0-4 mm aggregate. The ADR set fed from the 0-4 mm aggregate and yielded three fractions; fines (0-1 mm), a 1-4 mm aggregate and a 4-12 mm coarse aggregate. The sieved 12-22 mm aggregate and the 4-12 mm aggregate from the ADR set composed the total yield of recycled coarse aggregate for concrete (RCA). Only a fraction of the total yield (360 t of 429.6 t) would return to the demolition site; again by barge and by a lorry.

- Crushing of rubble and transport of RBA from local market

The RBAs would be insufficient to cover the estimated RBA requirement for the foundation of the new construction. Therefore, an amount of RBAm would have to be purchased from the local market. It is assumed that the RBAm would originally come from another demolition. Then, the crushing of rubble for the production of RBAm was modelled as the on-site crushing for the production of RBAs, adjusting to a different throughput.

The transport requirement considers only the distance from the local market to the demolition site. This means that freights between the source of the rubble and the local market were excluded from the model.

- On-site storage

The piles of building materials would be stored until the demolition site were clean from demolition debris and the ground were levelled. The materials would be ready for use when the construction activities started.

BAU product system

- On-site crushing into road base aggregate

Pieces from 0 to 500 mm of rocks, embedded with dust and a small amount of metals, plastics, and wood, would compose the mixed rubble from the building demolition. An impact crusher would reduce their size of the rubble into a 0-31.5 mm aggregate. A rubber-tire loader and an excavator would help load and unload the crusher and would accumulate the crushed aggregate (RBAs) into piles.

For this stage, the model of the BAU product system considers the on-site crushing in the BP product system, with an adjusted throughput. The virtual throughput is the sum of the retrieved concrete rubble and mixed rubble.

- Mining and transport of NCA

The NCA would be gravel purchased in Maastricht, mined outside the Netherlands. The model includes transport by barge from Maastricht but excludes previous freights.

- On-site storage

The piles of building materials would be stored until the demolition site were clean from demolition debris and the ground were levelled. The materials would be ready for use when the construction activities started.

3.2.2 Product-systems description for the LCA of concrete production

All the ingredients for concrete are transported to a concrete production plant. The model includes the production and supply of the concrete ingredients, and the required energy and infrastructure.

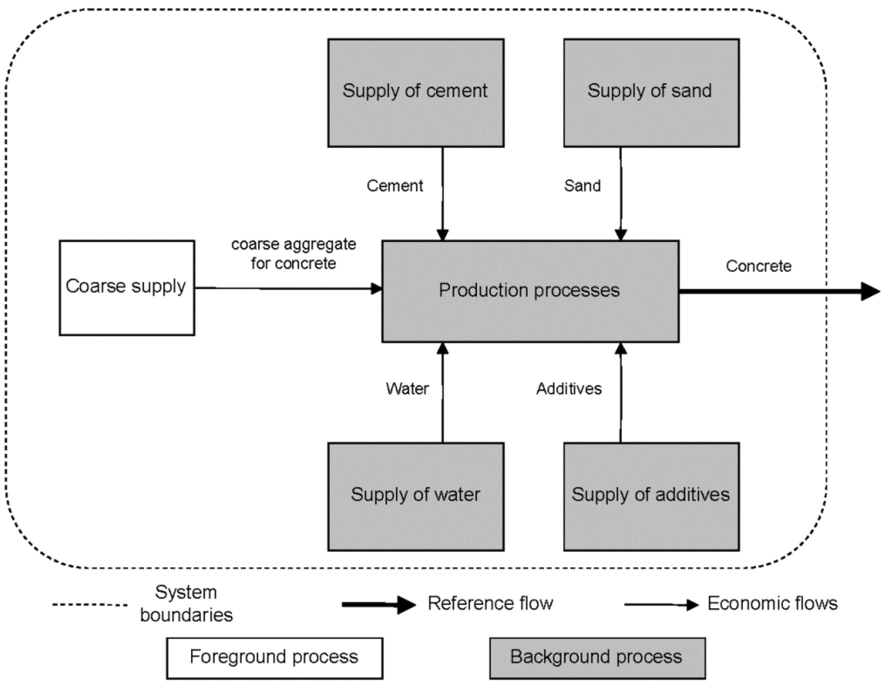


Figure 3-3 Flowchart of the product system of concrete production

The product systems of the compared alternatives differ in the source of the coarse aggregate and in the proportion in which the materials are mixed. The model assumes that the required energy and infrastructure for the production processes would be the same for all the alternatives.

3.2.3 Economy-environment system boundary

The model of the foreground processes comprises the direct emissions from fuel combustion in the machines used for processing and handling the stony fractions. Other environmental interventions considered come from the ecoinvent v2.2 modules, either connected to the foreground processes or used as proxies for the background processes.

Figure 3-4 illustrates the type of economic flows and the environmental interventions that the model considers for the operation of the machines. The decision of including the selected economic flows and emissions derives from the model of ‘diesel, burned in building machine’, developed for ecoinvent v2.2 and documented in Part II*:* ‘Cement Products and Processes’ .of the report *Life Cycle Inventories of Building Products* (Kellenberger et al. 2007).

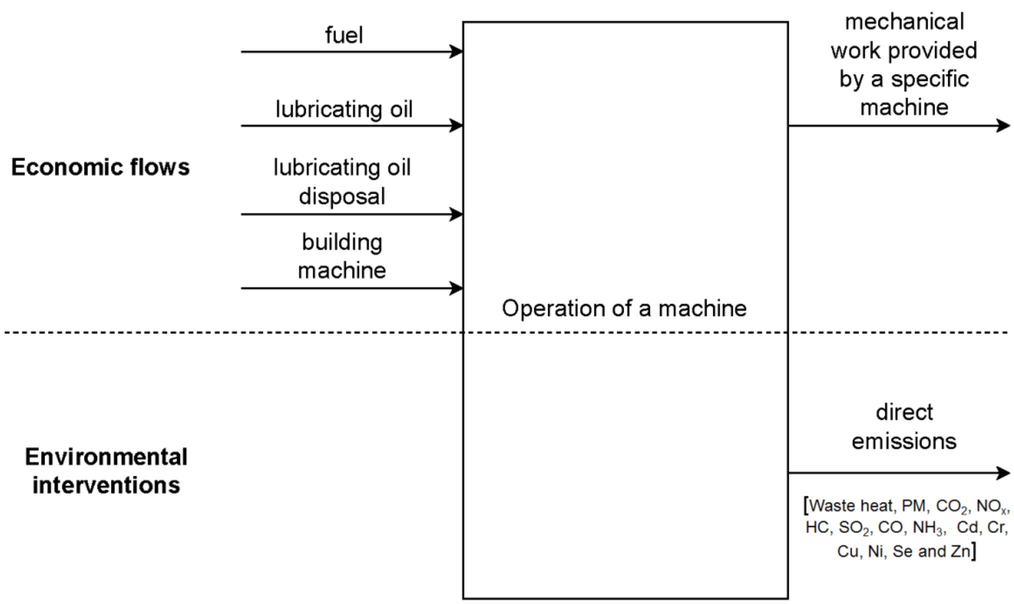


Figure 3-4 Economic flows and environmental interventions of operating a machine

3.2.4 Cut-offs

Figure 3-1 and Figure 3-2 illustrated that the materials embedded in the concrete-rubble were cut off from the product system. These are roughly estimated as less than 12% of the total mass of the concrete-rubble[13]. The metallic fraction is regarded as a product, which would be collected, scrapped and recycled, while the rest of the materials are regarded as a waste, which would be collected, sorted and processed.

Other environmental flows than the listed in the LCI were excluded from the analysis. Priority was given to the environmental interventions that could be measured or estimated, considering the available resources. For example, the emission of noise and odour, and the infiltration to the ground of water for dust control, if any, remained uncovered.

Turning to the modelled processes, the operation time and fuel consumption of the sieve were not reported. Therefore, the associated environmental interventions are not

[13] Personal communication with F. Rens, Project leader at GBN, on April 19th, 2016 at Hoorn.

considered in the model. However, a sensitivity analysis was performed, assuming that the emissions from the sieve generator could be the same as the ones from the ADR generator for the same throughput.

3.2.5 Relating data to unit processes

This section provides an overview of the way in which the foreground processes were modelled.

Direct emissions

In the Netherlands, the EMMA model (*Emissiemodel Mobiele Machines gebaseerd op machineverkopen in combinatie met brandstof Afzet*; Hulskotte and Verbeek 2009) serves to estimate the emissions of non-road mobile machinery at a national sector level (Klein et al. 2016). The model relates the year of manufacture, the power rating of the machine, and application to the work output. The emissions in this model are carbon dioxide, hydrocarbons, nitrogen oxides, particulate matter, sulphur dioxide, carbon dioxide, nitrous oxide, and ammonia.

Other emissions from fuel combustion not included in the EMMA model are waste heat, chromium, copper, cadmium, nickel, selenium, and zinc (Kellenberger et al. 2007). An energy balance served to include the waste heat in the model, while the hydrocarbons composition and metallic emissions are based on the ecoinvent v2.2 dataset ‘diesel, burned in building machine’ (Kellenberger et al. 2007). More details are provided in Appendix B.

Lubricating oil

While the estimated service life reported in the data collection sheets was used to calculate the capital consumption due to machinery depreciation, an average of operational life related to the rated power of the machines (EPA 2010) and to the kind of activity (Hulskotte and Verbeek 2009) was considered. The machines reported had several types of mechanisms that required lubricating oil, such as the engine, hydraulic system, and transmission system. Whereas recommended oil drain intervals and capacity for containing lubricating oil of a mechanism were available from the manufacturers or commercial sites, the demand was estimated.

Different mechanisms and machines require different lubricating oil specifications, such as certain viscosity. However, according to the current scope, the total lifetime requirement of lubricating oil for a machine was considered as the sum of the requirements of the different mechanisms. To account only for the operation of the machine in the system under study, the oil requirement considers a fraction of lifetime equivalent to the machine operation within the product systems.

No information about the lifetime requirement of lubricating oil was collected for the generator in the ADR set. Therefore, the lubricating oil requirement was estimated using the same relation used in the ecoinvent v2.2 module ‘diesel, burned in building machine’. More details are provided in Appendix B.

Concrete formulations

For the analysis of the different formulations that the use of RCA or NCA might imply, it was assumed that the recycled coarse fraction of 12-22 mm, containing a minimum amount of fines, would behave as NCA. Moreover, it was assumed that the 4-12 mm coarse fraction would behave as the recycled aggregate 4-16 mm studied by Lotfi et al. (2014).

The RCA is composed by a mix of 39% sieved fraction (12-22 mm) and 61% coarse fraction from the ADR process (4-12 mm). Therefore, the concrete formulation for the RCA was considered a weighted average of the concrete formulations presented by Lotfi et al. (2014). The formulation for the concrete with 100% NCA was retrieved from the same paper without any changes.

Similarly, the formulation for the mix 30% RCA and 70% NCA is a weighted average from the derived formulation using RCA and the retrieved formulation using NCA.

Table 3-3 Formulations of concrete for different sources of CA

Material	Amount for different sources of CA (kg)		
	NCA	RCA	70% NCA-30% RCA
Cement – CEM I 42.5R	380	380	380
Water	137	167	146
CA	1063	1162	1093
Sand	603	508	575
Superplasticizer	0	3.04	0.91
Air-entraining admixture	0	1.52	0.46

Based on Lotfi et al. (2014)

3.2.6 Multi-functionality and allocation

The multi-functionality of processes is handled with mass allocation. A sensitivity analysis was performed to account for the effects of using economic allocation instead.

3.2.7 Results of the inventory analysis

The life cycle inventories (LCIs) of the studied product systems report on 1369 different environmental interventions. This information was submitted for evaluation with this thesis report as an Excel file and as a CMLCA file and might not be available to the general public. However, the results from the characterization of the LCIs are presented and discussed in section 3.3

Now, Figure 3-5 illustrates the financial inventory for the BAU and BP alternatives. Two options are presented for the BP scenario; the first one considers the incurred fee for the transport of the concrete rubble to the processing site and the second one considers a virtually reduced fee in the same transport scheme as in the BAU scenario.

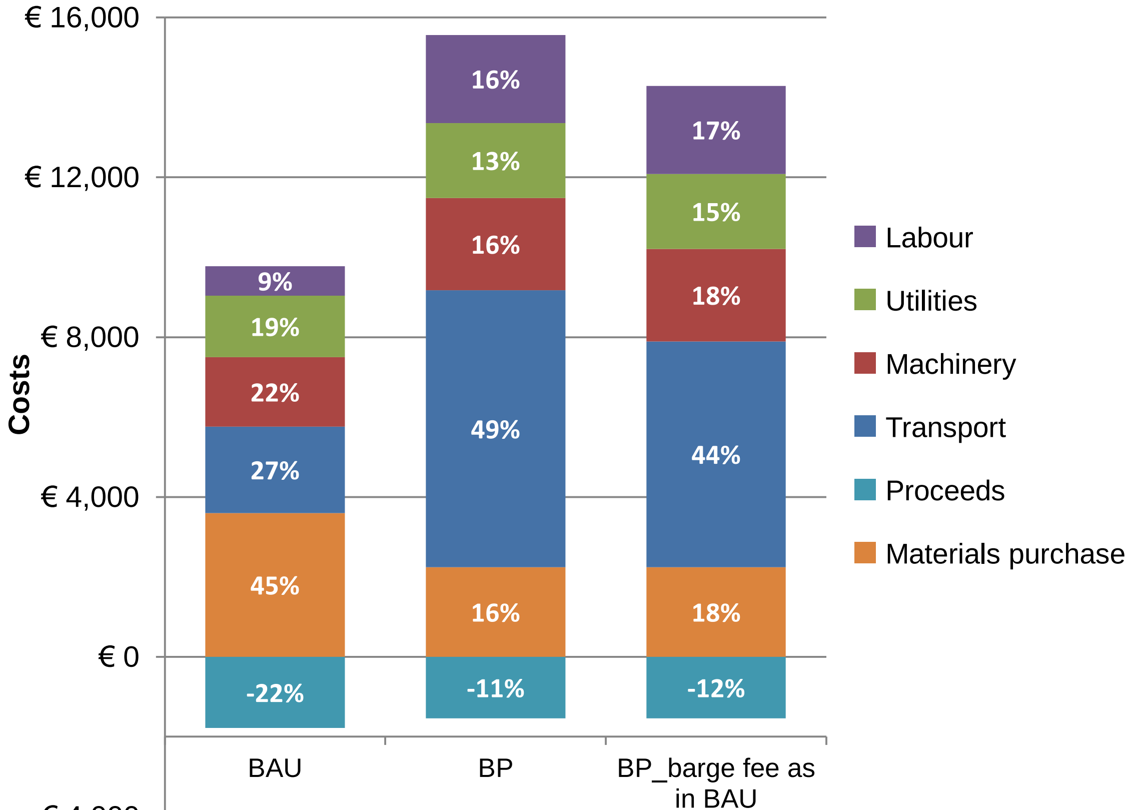


Figure 3-5 Costs profiles of the BAU and BP scenarios

The costs associated with the product systems under study are higher for the BP alternative than for the BAU alternative. The results imply that the net costs would potentially decrease by 37-43% of the BP alternative costs if shifting to the BAU alternative.

Although crushing, sieving and ADR of concrete rubble occurred in Hoorn, only the costs associated with crushing were included in the WM function, considering that the concrete rubble reaches an end-of-waste state when it is transformed into crushed aggregate. This is under the assumption that the hypothetical crushed aggregate from concrete-rubble could have been sold as RBA. Then, the costs of transporting and processing the concrete rubble and of transporting the RCA back to the construction site were charged to the MS costs (consult Table A-4 and Table A-5).

It follows that the costs of the MS requirement dominate over the costs of the WM requirement. In particular, the purchase of NCA constitutes the largest contributions to the total costs of the BAU scenario; it is 45% of its gross costs[14].

Similarly, the transport is the dominant kind of cost for the BP product-system. It represents 44-49% of the gross costs of BP. These costs are primarily attributed to the transport of mixed rubble to the ADR facilities and of the coarse aggregate back to the construction site. In other words, the transport of RBAm is only 3% of the BP transport costs.

Regarding the virtual proceeds for the sale of the excess of recycled materials, in the BAU scenario, these are higher than in the BP scenario. While in the BAU scenario, 297.4 tonnes of RBA from the demolition are sold at €6 per tonne, in the BP scenario, 69.6 tonnes of RCA and 241.6 tonnes of sieved sands are sold, respectively, at €10 and €3.50 per tonne. The price of the excess RBA in the BAU scenario is higher than the average price of the excess materials in the BP scenario (€4.95 per tonne), but the excess of materials in BP offsets the price factor.

Turning to the additional processes to crushing in the BP scenario compared to the BAU scenario, more operations require more machinery use, which in this case also implies personnel to operate the machines. The costs difference is more notorious in labour than in machinery or utilities.

3.3 Impact assessment

The main results of the impact assessment stage are the environmental profiles and normalized environmental profiles of the product systems under study (Guinée et al. 2002). This section presents a comparative analysis of the environmental profiles from each defined perspective (see section 2.1.3). First, the environmental profiles and normalized results for the alternatives from Perspective I (BAU and BP) are illustrated and commented, and then the same steps are performed for the alternatives from Perspective II (concrete from NCA, from RCA or from a mix).

As this section prioritizes the comparison between the alternatives, refer to the appendix, from Table A-6 to Table A-10, if you want to consult the environmental profiles in terms of the category indicator results. See the category indicators and the underlying characterization models in Table A-1.

3.3.1 Comparison of environmental profiles from Perspective I

An integrated function of waste management and material supply was evaluated from Perspective I based on a real case of the demolition of a building and the planned construction of a new building on the same site.

[14] Costs before proceeds

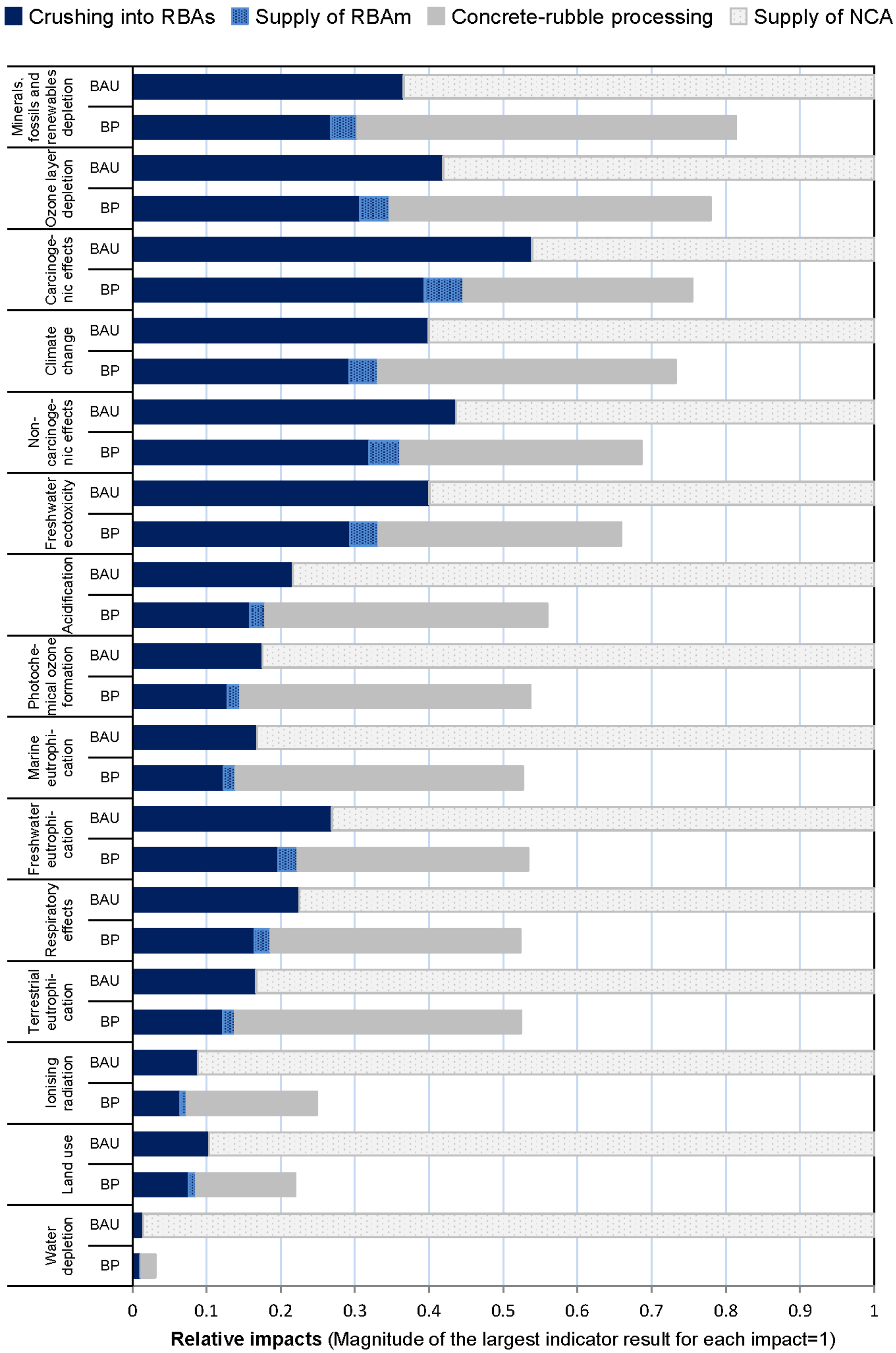


Figure 3-6 Environmental profiles of the BAU and BP product systems, PEF

Figure 3-6 illustrates the differences between the environmental profiles of the BAU and BP product systems with the categories established in the PEF guide (EC 2013). In this figure, the indicator results have been divided by the largest result for each impact category.

The indicator results of the BAU alternative are larger than those of the BP alternative for all the impact categories evaluated.

The indicator results of the BP and BAU alternatives are closer to each other (difference of less than 0.25 times the largest indicator result) on minerals, fossils and renewables depletion, ozone depletion, and carcinogenic effects. The environmental profiles of the alternatives are further apart from each other (difference of more than 0.75 times the largest indicator result) on ionising radiation, land use, and water depletion.

Turning to the relative magnitude and distribution of the environmental impacts amongst the different impact categories, Table 3-4 presents the normalized environmental profiles calculated with the factors for EU27 in the year 2010 presented by Benini et al. (2014).

Table 3-4 Normalized environmental profile (years) for alternatives from Perspective I, referred to the PEF category totals for EU27 in the year 2010

	BP	BAU
Carcinogenic effects	3.08E-08	4.22E-08
Water depletion	4.29E-10	1.31E-08
Freshwater ecotoxicity	3.73E-09	5.7E-09
Non-carcinogenic effects	3.13E-09	4.63E-09
Photochemical ozone formation	2.47E-09	4.52E-09
Terrestrial eutrophication	1.67E-09	3.13E-09
Marine eutrophication	1.58E-09	2.96E-09
Acidification	1.53E-09	2.71E-09
Land use	5.17E-10	2.32E-09
Ionising radiation	5.74E-10	2.2E-09
Climate change	1.37E-09	1.9E-09
Respiratory effects	8.46E-10	1.59E-09
Freshwater eutrophication	7.62E-10	1.43E-09
Minerals, fossils and renewables depletion	1.16E-09	1.42E-09
Ozone layer depletion	7.15E-11	9.34E-11

It is evident that the largest normalized results for both alternatives are on carcinogenic effects. For the BP alternative, this impact category is followed in descending order of magnitude by freshwater ecotoxicity, non-carcinogenic effects, and photochemical ozone formation. The second largest normalized result for the BAU alternative is on water depletion, followed by freshwater ecotoxicity and non-carcinogenic effects. The smallest normalized results are on ozone layer depletion.

3.3.2 Comparison of environmental profiles from Perspective II

The function of concrete production using different sources of CA is analysed from Perspective II. The environmental profile of the production of concrete with the NCA and RCA alternatives is presented in Figure 3-7.

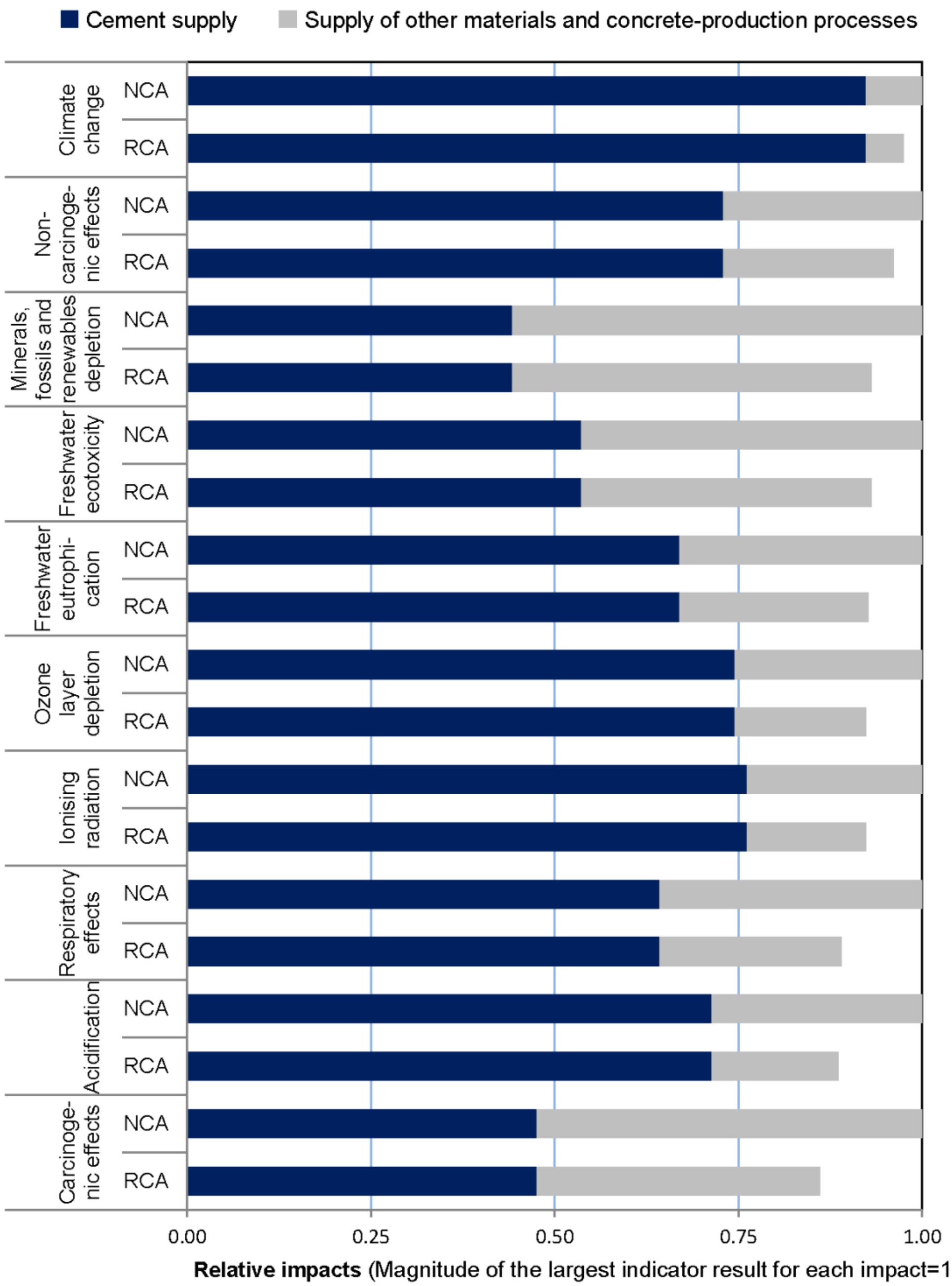


Figure 3-7 Environmental profiles of the production of concrete with NCA and RCA, PEF

The indicator results from the NCA and RCA alternatives are very close to each other; most of them have a difference between 0.03 to 0.16 times the magnitude of the largest indicator result. The difference is greater than 0.25 only on water depletion (0.44) and land use (0.49).

By representing more than 50% of the indicator results for each alternative in 11 out of the 15 PEF impact categories, the cement supply is the largest contributor to the environmental impact.

As for the normalized profiles for the production of concrete with NCA, RCA and a mix 70% NCA-30% RCA, the largest results are on carcinogenic effects, followed by non-carcinogenic effects (Table 3-5). For the concrete with NCA, this impact category is followed in descending order of magnitude by water depletion, freshwater ecotoxicity, and climate change. The third largest normalized results for the mix and RCA alternatives are on freshwater ecotoxicity, followed by water depletion and climate change. The smallest normalized results are on ozone layer depletion.

Table 3-5 Normalized environmental profile (years) for alternatives from Perspective II, referred to the PEF category totals for EU27 in the year 2010

	NCA	Mix	RCA
Carcinogenic effects	2.40E-10	2.29E-10	2.05E-10
Non-carcinogenic effects	9.63E-11	9.50E-11	9.19E-11
Water depletion	8.81E-11	7.65E-11	4.94E-11
Freshwater ecotoxicity	7.94E-11	7.75E-11	7.33E-11
Climate change	7.36E-11	7.30E-11	7.16E-11
Ionising radiation	6.27E-11	6.12E-11	5.76E-11
Photochemical ozone formation	5.00E-11	4.77E-11	4.25E-11
Terrestrial eutrophication	3.50E-11	3.34E-11	2.97E-11
Acidification	3.46E-11	3.34E-11	3.05E-11
Marine eutrophication	3.20E-11	3.05E-11	2.70E-11
Freshwater eutrophication	2.34E-11	2.28E-11	2.14E-11
Respiratory effects	2.08E-11	2.01E-11	1.84E-11
Minerals, fossils and renewables depletion	1.50E-11	1.46E-11	1.38E-11
Land use	1.18E-11	1.01E-11	6.05E-12
Ozone layer depletion	1.10E-12	1.07E-12	1.01E-12

The dominance of this impact category relative to the other impact categories could be more related to the PEF impact assessment method rather than to the product systems.

3.3.3 Interventions for which characterization factors are lacking

The PEF impact assessment method provides more characterization factors for the inventoried emissions than the EN15804 impact assessment method. This fact is discussed in Section 4.2.

With the PEF approach, 3 out of 19 direct emissions modelled in foreground processes lack characterization factors. These 3 emissions to air are heat waste, particulates between 2.5 and 10 µm and polycyclic aromatic hydrocarbons. In comparison, 119 out of 225 resources and 499 out of 1125 emissions from background processes lack characterization factors.

No comparisons of environmental performance between the alternatives were performed for the interventions lacking characterization factors.

4. Interpretation of LCC and LCA

The first sections of this chapter discuss the robustness of the models regarding consistency, completeness, and uncertainty, which is addressed through sensitivity analysis. Then, potential issues are identified with the results of the impact assessment and expanding the contribution analysis performed for the alternatives from Perspective II. Finally, the indicators of circularity calculated for each scenario are presented.

4.1 Completeness check

Most of the relevant information and data, according to the defined system boundaries, are available and complete. The lack of information about the operation time and fuel consumption for the sieving process is a limitation that is addressed with a sensitivity analysis.

4.2 Consistency check

The assumptions, methods, and data are consistent with the goal and scope. The next paragraphs justify this statement.

Regarding the integrated LCA-LCC study of product systems from Perspective I, the level of sophistication at which the LCA was performed was higher than the level at which the LCC was performed regarding the data processing. The product systems were modelled in a way in which the LCA and LCC addressed the same life cycle stages from grave to cradle. The sensitivity of the LCA model to allocation methods which compared physical allocation to economic allocation was based on the outcomes of the LCC. These outcomes were also the input of the calculation of the CEI.

The degree at which characterization factors are available for the considered environmental emission is consistent between the alternatives under study and along the two defined perspectives. The selection of the impact assessment method based on the PEF impact categories as a baseline instead of the EN15804 method provided the opportunity to characterize a larger share of the environmental interventions in the LCIs. For instance, the PEF impact assessment covers most of the direct emissions from the foreground.

The modelling decision of cutting off the materials potentially embedded in the stony fraction would symmetrically affect the environmental profiles of the product systems. In other words, as a homogeneous content of metals and embedded materials in the concrete rubble and mixed rubble was assumed, the impacts that would be allocated to the function of retrieving recyclable metals would be the same for the on-site and off-site crushing processes. This is also the case for the impacts that would be added to the system if considering the processing of the non-metallic embedded materials, which in the stony rubble system are regarded as waste. An exception to these implications would be that the downstream alternatives for the embedded materials were different because of the conditions of both locations; it could be that the demolition site were closer than the ADR processing site to a scrapping facility.

Field information about the machinery operation, fuel consumption and labour was compiled for all the relevant processes, except sieving. Furthermore, the actual split between concrete rubble and mixed rubble was also reported. The virtual alternatives are based on this information and complemented with secondary data that came mainly from the early estimations in the scope of the HISER case study or from sources at the sector-specific level, company-specific level or application-specific level. The direct emissions for the foreground processes were highly detailed and consistent with the method used for the same kind of machines at the Dutch national level. All of the complementary LCIs required to model the environmental interventions for the processes were retrieved from ecoinvent v2.2.

An important factor that was not addressed during this study is the relevance of the use of a dataset that might be outdated, such as the ecoinvent v2.2 module ‘gravel, round, at mine’, modelled after the production in Switzerland from 1997 to 2001.

4.3 Uncertainty

The uncertainty of some topics was addressed through sensitivity analysis. While this is not a numerical approach, the consequences of specific changes to the variables defined for the main analysis are explored.

4.3.1 Performance of concrete from RCA

The scenarios defined from Perspective I assume that certain amount of RCA could be used as a substitute for the same amount of NCA. The possibility in which the use of RCA requires a different formulation for the production of concrete was explored when defining the scenarios from Perspective II, based on an experimental formulation at a lab scale (Lotfi et al. 2014). In the referred experiment RCA from ADR is used to make concrete, but there is no a fraction equivalent to the RCA from the sieve addressed in this paper. As no further treatment for the RCA from the sieve was required, it was assumed that the fraction that came from the sieve had equivalent properties to the NCA.

In a worst case scenario with this regard, the RCA from the sieve and from the ADR would have the same properties, so the ratio admixtures to RCA could be as in the study by Lotfi et al. (2014). The evaluation of this scenario yielded differences between the environmental profiles of concrete production from RCA and from NCA that were even narrower than the reported in Section 3.3.2. Also, an inversion was observed in acidification, freshwater eutrophication and ozone layer depletion; the largest indicator result belonged to the concrete from RCA instead of the concrete from NCA.

4.3.2 Impact assessment methods

Both PEF and EN15804 approaches include categories addressing the impacts of the product systems on the ecosystem quality, human health, and resoures conservation (see Table 2-1).

The impact assessment method selected as a baseline (PEF approach) provided characterization factors for most of the environmental interventions of the foreground processes in the LCIs. In comparison, with the EN15804 approach 12 out of 19 direct emissions modelled in foreground processes lack characterization factors.

Furthermore, 120 types of resources and 923 types of emissions from background processes lack characterization factors. This is one type of resource and 424 types of emissions without characterization factors more than with the PEF approach.

The indicator results on climate change and ozone depletion according to the PEF approach are consistent to those of the EN15804 approach. Both impact assessment methods have the same underlying characterization models for these categories. However, the reference source for the characterization factors differs; the PEF guide refers to IPCC 2007 and WMO 1999 (EC 2013) while the standard EN15804 refers to IPCC 2013 and WMO 2003 (Passer et al. 2015; van Oers 2016), correspondingly to climate change and ozone depletion. These would explain slight variances between the corresponding indicator results.

The characterization models for acidification are different amongst the PEF and EN15804 approaches. Nevertheless, the PEF and EN15804 comparison of the results on acidification between alternatives yielded similar results from both defined perspectives. This was not the case for the category on photochemical ozone formation.

While both approaches indicate that the impacts of BP are lower than the impacts of BAU, the differences between the results of their impact-category indicators seem larger with PEF than with EN15804.

The narrowest differences between BP and BAU with the PEF approach are on minerals, fossils and renewables depletion, ozone layer depletion, and carcinogenic effects. In contrast, these are ozone layer depletion, fossil resources depletion, and climate change with the EN15804 approach.

The widest difference amongst the environmental profiles of the BAU and BP alternatives with the EN15804 impact categories is on eutrophication (0.43 times the largest indicator result), closely followed by acidification. Although the difference between the PEF acidification results of the BP and BAU alternatives is similar (0.44 times the largest indicator result), wider differences exist on many other PEF impact categories.

These categories with wider differences are photochemical ozone formation, marine eutrophication, freshwater eutrophication, respiratory effects, terrestrial eutrophication, ionising radiation, land use and, with the maximum difference (0.97 times the largest indicator result), water depletion.

As for the concrete production alternatives from Perspective II, also both impact assessment approaches indicate lower indicator results for using RCA than for using NCA. With a maximum difference of 0.49 times the largest indicator result between the indicator results of both alternatives, the difference range is much lower than the range for the comparisons from Perspective I. Still the differences between the indicator results of NCA and RCA are narrower with the EN15804 approach than with the PEF approach. With the EN15804 approach, the widest difference is on eutrophication (0.13 times the largest indicator results), and the narrowest difference is on abiotic, non-fossil resources depletion (0.02 times the largest indicator results).

It follows that, with the selected normalization factors for PEF and EN15804, the ozone layer depletion has the lowest normalized impacts in the environmental profiles of all the alternatives from both defined perspectives. Similarly, the carcinogenic effects dominate the PEF normalized environmental profiles of all the alternatives from both defined perspectives.

On the other hand, climate change is the dominant impact category of the EN15804 normalized profiles of the alternatives from Perspective I. This impact category adds to fossil resources depletion and acidification as the dominant impact categories of the EN15804 normalized profiles of the alternative from Perspective II. However, if the PEF normalization is used instead, climate change takes the eighth place for the BP alternative, the eleventh place for the BAU alternative, and the fifth place for all the alternatives from Perspective II in a ranking of descending order of magnitude.

4.3.3 Allocation methods

The environmental profiles discussed in Section 3.3 used physical allocation based on mass. The results of LCC provided reference costs that complemented the cost estimates developed in the early stages of the HISER case. The environmental profiles were calculated for four different cost scenarios of the product systems from Perspective I. The differences between the indicator result of each alternative slightly variated along the scenarios. However, the main trends still hold. The scenarios evaluated were:

a) Price of rubble based on processing into 0-32 mm aggregate, coarse concrete fraction based on price from rubble to RCA at construction site.
b) Price of rubble based on RBAm, coarse concrete fraction based on price from crushed aggregate to RCA at construction site.
c) Price of rubble based on RBAm, coarse concrete fraction based on price from crushed aggregate to RCA at construction site, no market for the ADR coproducts.

d) Price of rubble based on RBAm, coarse concrete fraction based on price from crushed aggregate to RCA at construction site, market for the ADR coproducts with a higher price than RBAm (1.30 times the RBAm price)

4.4 Expansion of the contribution analysis for Perspective II

The narrow difference amongst the environmental profiles is partially due to the fact that the cement supply is the largest contributor to the environmental impact: it represents more than 50% of the indicator results for each alternative in 11 out of 15 PEF impact categories and in 7 out of 7 EN15804 impact categories. The indicator results on carcinogenic effects are a special case because cement contributes with 55% of the total magnitude for the RCA alternative, but with 48% of the total magnitude for the NCA alternative. However, this value is only 2% far from the reference value, and cement supply is still the largest contributor.

Land use, water depletion, and minerals, fossils and renewables depletion are the PEF impact categories for which the contribution of cement supply to the individual indicator results is smaller than 50%. Considering both alternatives, the contributions of the cement supply to the total indicator result on each of these impact categories ranges from 19 to 48%.

Figure 4-1 zooms into the contribution to the indicators results of the components whose attributed impacts are not as dominant as those of cement. The impact of the infrastructure and energy for the concrete production processes is the same for both alternatives, but it was included in the figure as a supporting reference of the magnitude of the difference between the alternatives.

The difference between the RCA and NCA alternatives on some indicator results is evidently larger than the contribution of the production processes; for instance on water depletion, land use, photochemical ozone formation, terrestrial eutrophication and marine eutrophication.

The transport plays an important role that defines the difference between the supply chains of RCA and NCA in many impact categories, such as photochemical ozone formation, ozone depletion, terrestrial eutrophication and marine eutrophication. The need for additives reduces the advantages that the supply chain of RCA offers over NCA, but the impacts from transport are still much larger for the latest.

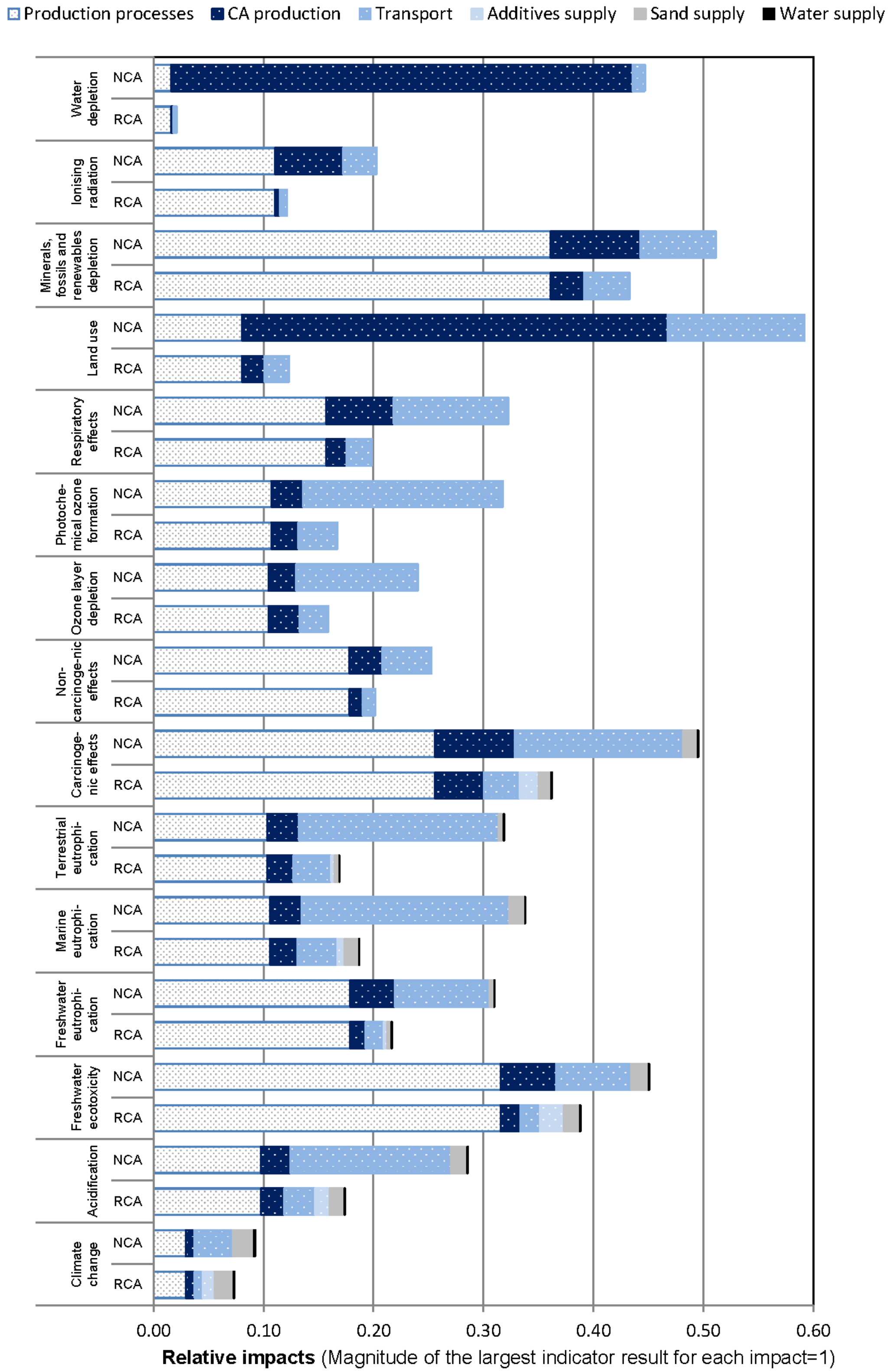


Figure 4-1 Contribution analysis of concrete production with NCA and with RCA

4.5 Indicators of circularity

The indicators of circularity were calculated for each alternative from Perspective I. The results on the selected indicators depended on the selection of the basis of calculation and on the market values assumed for the materials before and after recycling.

Therefore, Table 4-1 presents the results of the indicator referenced to three different analyses:

1) Recycled materials from the demolition
2) Recycled materials from the demolition absorbed by the new building
3) Recycled materials used in the new building

Although a minimum cost of €21.05 per tonne at the site was calculated for the RCA due to an incurred high fee of transport in the LCC, the price of NCA, €16 per tonne, was used for the CEI, assuming that, with this price, the RCA could compete better with NCA. This decision illustrates a narrower difference between the mass based rates and the CEIs than a value of 21.05 EUR/t would have caused. You may consult the definitions of the indicators in Section 2.2 and the other values considered for the results presented here in Appendix C.

Table 4-1 Indicators of circularity for the project Steiger 113

Indicator	Ref.	BP	BAU	Ind. BP / Ind. BAU
Mass recycling rate based on waste (%)	1	100	100	1.00
Mass recycling rate based on waste (%)	2	85	86	0.99
Recycled content in new building (%)	3	100	83	1.20
CEI	1	4.2	3.4	1.25
CEI	2	3.7	2.9	1.28
CEI	3	4.2	3.4	1.24

The first reference considers the amount of materials recycled into building products. In both scenarios, the rubble from the demolition is completely recycled, but the difference in the value of the applications is illustrated only by the CEI, case in which the CEI of the BP scenario is 1.25 times the CEI of the BAU scenario. This difference happens because the RCA has a higher value than the RBA.

The second reference considers the amount of recycled materials from the demolition that the new building can absorb. While the RCA replaces the NCA, the amount of RBA available for the new building decreases in BP compared to BAU. In this case, the mass recycling rate is higher for the BAU scenario than for the BP scenario, but the value of both rates is almost the same. Alternatively, the CEI presents the highest ratio amongst the evaluated cases due to the increased value resulting of recovering the CA from the concrete rubble.

The third reference considers the content of recycled materials in the new building, also taking into account the purchased RBA in the BP scenario, which is assumed to be 100% recycled from another demolition. Therefore, the BAU scenario has a lower recycled content than the BAU scenario. In other words, more recycled materials are used in the BP scenario than in the BAU scenario, for which NCA is quarried.

Although the CEI with the possible references studied increases for both scenarios when increasing the value of the mixed rubble, the ratio between them is constant. This is not the case when variating the value of the RCA or the RBA because the ratios of the CEI of the alternatives decrease when the value of the RCA approaches to the value of the RBA. In this way, considering a market value of €6.50 per tonne of RBA, the minimum market value for which the CEIs of the BP scenario are equal or higher than the CEIs of the BAU scenario is €8.19 per tonne of RCA. Furthermore, considering the calculated incurred costs of €21.05 per tonne of RCA, the ratios would have been 1.41, 1.44 and 1.37 for the first to third references, respectively.

Calculating and comparing the CEI of two recycling alternatives allows the identification of the alternative with the largest revalorization potential. In this case, the comparison within three different references succeeded to promote the alternative with better environmental performance (BP over BAU). For the same references, the mass-based indicators showed less distinction amongst the scenarios and even favoured the BAU scenario in one of the cases (Reference 2).

Although in this case, a higher CEI comes along with environmental benefits, this indicator is unable to communicate the complexity of the environmental interventions, which are more elaborated with the LCA methodology.

5. Recommendations and conclusions

The integrated LCC-LCA study indicates that recycling concrete rubble into CA with ADR technology represented environmental benefits but higher costs, for the Steiger 113 project, compared to the virtual option of processing the stony fraction through regular crushing and sourcing gravel for the new construction. However, the reduction of transport distances between the source of CDW, the ADR facilities and the new consumer would represent a decrease in costs and in environmental burden.

Furthermore, within the defined scenarios from two different perspectives, the supply chain of RCA from concrete-rubble recycling with ADR technology presents environmental advantages compared to the supply chain of NCA. There is a clear difference between the environmental implications of using RCA instead of NCA when the analysis refers to the supply of a certain amount of CA. However, when the analysis refers to the production of concrete, the environmental impacts of the cement supply prevail over the potential reductions arising from substituting the NCA with RCA. Besides, depending on the quality of the RCA retrieved, the concrete formulation could need admixtures to improve their performance in structural applications. The advantages of the use of RCA over NCA for concrete formulation are sensitive to the addition of admixtures.

The narrowest potential reduction of indicator results if shifting from the BAU product system to the BP product system was calculated on minerals, fossils and renewables depletion, ozone depletion, and carcinogenic effects. For these impact categories, the indicator results of the BP and BAU alternatives presented a difference of a magnitude lower than 25% of the BAU indicator results. Ionising radiation, land use, and water depletion are the impact categories with the widest potential reduction, which represents in magnitude more than 75% of the BAU indicator result.

The indicator results from the NCA and RCA alternatives for concrete production are very close to each other. Most of the potential reductions of indicator results if shifting from production of concrete with RCA to production of concrete with NCA are of a magnitude between 3 to 16% of the indicator result for the NCA alternative. The difference is greater than 25% of the NCA alternative indicator result only on water depletion (44%) and on land use (49%).

The impact category on carcinogenic effects dominates the environmental profile when referring to the category totals for the EU27 in the year 2010. Other impact categories whose contributions to an aggregated total based on the PEF normalization with equal weighting factors, added up to 25% were considered hotspots within this research framework. For the BP alternative, these are, in descending order of magnitude:

freshwater ecotoxicity, non-carcinogenic effects, and ozone formation. For the BAU alternative: water depletion, freshwater ecotoxicity, and non-carcinogenic effects. For the concrete production with NCA and with an NCA-RCA mix, these are non-carcinogenic effects, water depletion, and freshwater ecotoxicity. Moreover, for the concrete production with RCA: non-carcinogenic effects, freshwater ecotoxicity, and climate change.

The next question arises as a consequence of the potential impact reductions: Should the Dutch legislation return to a scheme that targets a level of replacement of primary aggregates in structural concrete?

The results of this research indicate a possibility in which shifting from the current construction and demolition framework, regarding the management of concrete rubble in the Netherlands, to a circular framework utilizing ADR would possibly bring along economic and environmental improvements. However, the assessment was performed for a limited number of scenarios, mainly relying on the information of only one case study. Therefore, additional research is required to test if the financial and environmental advantages observed for the case, at a micro level, are scalable at a sector level. Furthermore, there is a risk that a replacement target would cause a rebound effect by promoting recycling schemes that prioritize the substitution of NCA instead of looking at the implications from a system perspective. While the extractions of virgin aggregates would decrease, other factors of the supply chain could cause unwanted results. For instance, this would be the case if wet processing was promoted, of if the ADR was not strategically located.

A similar risk is possible when failing to evaluate the implications of a technology system or to communicate them to relevant stakeholders. The use of simplified indicators promoting CE could allow to easily keep track of the developments of the associated plans, or as rough estimates for first approaches, but they might not be suitable to sustain policies. However, for the analyses performed, the CEI presents advantages over the mass recycling rates.

The inclusion of an integrated functional unit in the analysis allowed to observe the consequences of recycling mixed rubble into RBA or into RCA in a broader system. The products from the two recycling alternatives have different applications, but both can be required for the same construction. Therefore, the HISER case represented an opportunity to study the waste management function, related to demolition activities, and the material supply function, related to construction activities.

Regarding the impact assessment method, the modelled environmental interventions were better represented with the PEF characterization factors than with the EN15804 characterization factors. This is favourable for the use of the PEF method if ecoinvent v2.2 modules datasets are used in further research related to the building sector. The adequacy of the impact categories and the robustness of the characterization models of the PEF and EN15804 approaches belong to an ongoing harmonization debate and were not discussed here. The dominance of the impact category on carcinogenic effect in comparison to the other impact categories could be more related to the PEF impact assessment method rather than to the product systems.

However, there are still things to explore regarding the processing technology. There are many variables affecting the composition of materials in a building. The demolition process adds to the uncertainty of the composition of the stony rubble.

In a best-case scenario, all the concrete from an EOL building would be retrieved from the demolition activities and kept away from all the other material fractions. Still, there would be embedded materials within the concrete rubble but the content of coarse aggregate for concrete would be at its maximum level. The settings of the ADR set are another variable that determines the quality of the recovered coarse aggregate.

The assessment of the composition of the stony fraction from CDW could provide information to adjust the settings of the ADR set. The assessment of the composition of the ADR output could provide information about any necessary adjustments that should be performed to the concrete formulation.

Considering the current demolition and construction rates, and the efficiency of concrete-recycling processes it is unlikely that the CDW streams could cover the demand for new concrete. Therefore, mining or quarrying natural concrete aggregate would still be required. LCA is not a suitable tool by itself to analyse the interactions of this rates. However, if a tool such as Material Flow Analysis was used to study the generation and recycling rates of concrete rubble and the demand for stony aggregates in the Netherlands, new scenarios could be defined and, subsequently studied with LCC and LCA.

While the technical aspects of concrete recycling determine the possible applications of its output, socioeconomic factors drive or limit the actual potential. Therefore, a holistic approach to the system alternatives, including a thorough analysis of socioeconomic factors, is necessary. It is proposed that the models developed in this thesis at the micro level could be integrated in studies at a broader scale, using other Industrial Ecology tools, by identifying variables that connect the micro and the macro level. In this way, new scenarios could be defined and variations to the model proposed to assess different goals and scopes.

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List of abbreviations

ADR	Advanced Dry Recovery
CA	Coarse aggregate for concrete production
CDW	Construction and demolition waste
CEI	Circular economy index
CFC-11	Trichlorofluoromethane, also called 56reon-11 or R-11
CTUe	Comparative toxic unit for ecosystems
CTUh	Comparative toxic unit for humans
EC	European Commission
EF	Electrical Fragmentation
EOL	End-of-life
GDP	Gross Domestic Product
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life cycle inventory
LCSA	Life Cycle Sustainability Assessment
MFA	Material Flow Analysis
MS	Material supply
NCA	Natural coarse aggregate for concrete production
NMVOC	Non-methane volatile organic compounds
PEF	Product Environmental Footprint
PM 2.5	Particulate matter with a diameter of 2.5 µm or less
RCA	Recycled coarse aggregate for concrete production
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
WM	Waste management

Appendix A

Characterization models, secondary data, environmental profiles and LCC summary

Table A-1 Indicators and models for the default impact categories of the PEF method (EC 2013)

Impact category	Indicator	Method	Original source
Climate change	kg CO_2 eq	Bern model	IPCC 2007
Freshwater ecotoxicity	CTUe	USEtox model	Rosenbaum et al. 2008
Acidification	mol H^+ eq	Accumulated exceedance model	Seppälä et al.2006; Posch et al. 2008
Freshwater eutrophication	kg P eq	EUTREND model	Struijs et al. 2009 as in ReCiPe
Marine eutrophication	kg N eq	EUTREND model	Struijs et al. 2009 as in ReCiPe
Terrestrial eutrophication	mol N eq	Accumulated exceedance model	Seppälä et al. 2006; Posch et al. 2009
Ozone layer depletion	kg CFC-11eq	EDIP model	WMO 1999
Carcinogenic effects	CTUh	USEtox model	Rosenbaum et al. 2009
Non-carcinogenic effects	CTUh	USEtox model	Rosenbaum et al. 2010
Photochemical ozone formation	kg NMVOC eq	LOTOS-EUROS model	Van Zelm et al. 2008 as in ReCiPe
Respiratory effects	kg PM2.5 eq	RiskPoll model	Humbert 2009
Ionising radiation	kg U^{235} eq (to air)	Human health effect model	Dreicer et al. 1995
Minerals, fossils and renewables depletion	kg Sb eq	Ultimate reserves and extraction rates approach	Oers et al. 2002 as in CML-IA v2.6
Land use	kg (deficit)	Soil organic matter (SOM) model	Milà i Canals et al. 2007
Water depletion	m^3 water use	Swiss ecoscarcity model	Frischknecht et al. 2008

Table A-2 Indicators and models for the default impact categories of EN15804:2012+A1:2013

Impact category	Indicator	Method	Original source*
Climate change	kg CO_2 eq	Bern model	IPCC 2013
Acidification	kg SO_2 eq	RAINS10	Huijbregts, 1999; average Europe total, A&B
Eutrophication (generic)	kg $(PO_4)^{3-}$ eq	Stoichiometric procedure	Heijungs et al. 1992
Ozone layer depletion	kg CFC-11 eq	EDIP	WMO 2003
Photochemical ozone formation	kg ethene eq	UNECE Trajectory model	Jenkin & Hayman, 1999; Derwent et al. 1998; high NOx
Abiotic, non-fossil, resources depletion	kg Sb eq	Ultimate reserves and extraction rates approach	Oers et al. 2002 as in CML-IA v2.6
Fossil resources depletion	MJ, net calorific value	Ultimate reserves and extraction rates approach	Oers et al. 2002 as in CML-IA v2.6

* The standard EN15804 indicates the use of characterization factors in CML-IA v4.1 as the characterization method. The original source of the methods was compiled from CML-IA v4.8 (van Oers 2016).

Note:

In this research, the impact assessment based in the standard EN15804 uses the characterization factors in CML-IA v3.3 (Oers 2008) as drawn from ecoinvent v2.2

Table A-3 Overview of the secondary data for the integrated LCA-LCC study

Group	Description	Source remarks	Level
MS requirement	Material requirements for the construction of a new building	HISER case	Case specific
Machinery operation	Emission certification of machines, lubricating oil capacity	Machinery manufacturers or commercial databases	Company specific
	Intervals of lubricating oil change per machine	Machinery manufacturers or commercial databases	Company specific
	Emission factors specific to the type and rated power of machines	Non-road engine emission model in the Netherlands	Sector specific
	Heating value of fuel	Non-road engine emission model in the Netherlands	Application specific
	Other emissions from fuel-burning building machines	ecoinvent v2.2	Application specific
	LCIs of fuel supply, lubricating oil for machine use, water supply, lubricating oil disposal, machine production and unspecified machines	ecoinvent v2.2	Generic
	Estimates of lifespan and characteristic cycle	HISER case, non-road engine emissions models in the Netherlands and in the US	Case specific / Sector specific
Transport profile	Transport requirements for material supply in BP and BAU	HISER case	Case specific
Costs	Investment costs (some purchased machines)	HISER case	Case specific
	Market price of aggregates (for concrete and for road base)	HISER case	Case specific
	Fuel costs (EUR/L)/Lub.oil costs	Netherlands, 2016 / U.S. 2016	Generic
	Labour (EUR/man-hour)	Construction sector in the Netherlands	Sector specific

Table A-4 Summary of LCC results for the BAU product system (EUR)

Stages and activities	Transport	Machinery	Utilities	Labour	Proceeds	Materials purchase	Grand total
Waste management		**€ 1,737**	**€ 1,543**	**€ 734**	**-€ 1,784**		**€ 2,231**
On-site crushing		€ 1,737	€ 1,543	€ 734	-€ 1,784		€ 2,231
Material supply	**€ 2,160**					**€ 3,600**	**€ 5,760**
Purchase of RBA						€ 0	€ 0
Purchase of NCA	€ 2,160					€ 3,600	€ 5,760
Grand total	**€ 2,160**	**€ 1,737**	**€ 1,543**	**€ 734**	**-€ 1,784**	**€ 3,600**	**€ 7,991**

Table A-5 Summary of LCC results for the BP product system (EUR)

Stages and activities	Transport	Machinery	Utilities	Labour	Proceeds	Materials purchase	Grand total
Waste management		**€ 1,737**	**€ 1,543**	**€ 734**			**€ 4,015**
On-site crushing		€ 1,181	€ 1,049	€ 490			€ 2,720
Off-site crushing		€ 556	€ 494	€ 245			€ 1,295
Material supply	**€ 6,928[a]** **€ 5,652[b]**	**€ 576**	**€ 334**	**€ 1,469**	**-€ 1,542**	**€ 2,243**	**€ 7,765[a]** **€ 8,732[b]**
ADR concrete recycling	€ 6,741[a] € 5,465[b]	€ 576	€ 334	€ 1,469	-€ 1,542	€ 0	€ 7,578 € 6,302
Purchase of RBA	€ 187					€ 2,243	€ 2,430
Grand total	**€ 6,928[a]** **€ 5,652[b]**	**€ 2,313**	**€ 1,878**	**€ 2,203**	**-€ 1,542**	**€ 2,243**	**€ 14,022[a]** **€ 12,747[b]**

There are two sets of costs calculated for the BP scenario: **a**, considering the incurred cost for the transport of concrete rubble to the ADR processing facilities and **b**, considering a transport scheme similar to the one assumed for the BAU scenario.

Table A-6 Environmental profile of the BP alternative (Perspective I)

	Impact category	PEF Indicator result		EN15804 Indicator result	
Ecosystem quality	Climate change	6.29E+03	kg CO_2 eq	6.29E+03	kg CO_2 eq
	Freshwater ecotoxicity	1.63E+04	CTUe	-	-
	Acidification	3.60E+01	mol H^+ eq	2.68E+01	kg SO_2 eq
	Freshwater eutrophication	5.65E-01	kg P eq	-	-
	Marine eutrophication	1.34E+01	kg N eq	-	-
	Terrestrial eutrophication	1.46E+02	mol N eq	-	-
	Eutrophication (generic)	-	-	6.75E+00	kg $(PO_4)^{3-}$ eq
Human health	Ozone layer depletion	7.72E-04	kg CFC-11eq	7.72E-04	kg CFC-11 eq
	Carcinogenic effects	5.68E-04	CTUh	-	-
	Non-carcinogenic effects	8.33E-04	CTUh	-	-
	Photochemical ozone formation	3.90E+01	kg NMVOC eq	8.83E-01	kg ethene eq
	Respiratory effects	1.61E+00	kg PM2.5 eq	-	-
	Ionising radiation	3.24E+02	kg U^{235} eq	-	-
Resources	Abiotic, non-fossil, resources depletion	-	-	5.74E-02	kg Sb eq
	Fossil resources depletion	-	-	8.68E+04	MJ
	Minerals, fossils and renewables depletion	5.84E-02	kg Sb eq	-	-
	Land use	1.93E+04	kg soil	-	-
	Water depletion	1.74E+01	m^3 water use	-	-

Physical allocation

The reference flow is the management of 671 t of concrete rubble in ADR plant and 1426 t of mixed rubble through on-site crushing and the supply of 360 t of RCA from ADR plant, 1426 t of RBA from site, and 374 t of RBA from market.

Table A-7 Environmental profile of the BAU alternative (Perspective I)

Impact category		PEF Indicator result		EN15804 Indicator result	
Ecosystem quality	Climate change	8.75E+03	kg CO_2 eq	8.75E+03	kg CO_2 eq
	Freshwater ecotoxicity	2.48E+04	CTUe	-	-
	Acidification	6.39E+01	mol H^+ eq	4.69E+01	kg SO_2 eq
	Freshwater eutrophication	1.06E+00	kg P eq	-	-
	Marine eutrophication	2.50E+01	kg N eq	-	-
	Terrestrial eutrophication	2.74E+02	mol N eq	-	-
	Eutrophication (generic)	-	-	1.24E+01	kg $(PO_4)^{3-}$ eq
Human health	Ozone layer depletion	1.01E-03	kg CFC-11eq	1.01E-03	kg CFC-11 eq
	Carcinogenic effects	7.77E-04	CTUh	-	-
	Non-carcinogenic effects	1.23E-03	CTUh	-	-
	Photochemical ozone formation	7.14E+01	kg NMVOC eq	1.30E+00	kg ethene eq
	Respiratory effects	3.02E+00	kg PM2.5 eq	-	-
	Ionising radiation	1.24E+03	kg U^{235} eq	-	-
Resources	Abiotic, non-fossil, resources depletion	-	-	9.19E-02	kg Sb eq
	Fossil resources depletion	-	-	1.18E+05	MJ
	Minerals, fossils and renewables depletion	7.12E-02	kg Sb eq	-	-
	Land use	8.67E+04	kg soil	-	-
	Water depletion	5.31E+02	m^3 water use	-	-

Physical allocation

The reference flow is the management of 2097 t of stony rubble through on-site crushing and the supply of 1800 t of RBA from site and 360 t of NCA from market.

Table A-8 Environmental profile of concrete production with NCA (Perspective II)

	Impact category	PEF Indicator result		EN15804 Indicator result	
Ecosystem quality	Climate change	3.38E+02	kg CO_2 eq	3.38E+02	kg CO_2 eq
	Freshwater ecotoxicity	3.46E+02	CTUe	-	-
	Acidification	8.17E-01	mol H^+ eq	6.13E-01	kg SO_2 eq
	Freshwater eutrophication	1.73E-02	kg P eq	-	-
	Marine eutrophication	2.70E-01	kg N eq	-	-
	Terrestrial eutrophication	3.07E+00	mol N eq	-	-
	Eutrophication (generic)	-	-	1.50E-01	kg $(PO_4)^{3-}$ eq
Human health	Ozone layer depletion	1.19E-05	kg CFC-11eq	1.19E-05	kg CFC-11 eq
	Carcinogenic effects	4.41E-06	CTUh	-	-
	Non-carcinogenic effects	2.56E-05	CTUh	-	-
	Photochemical ozone formation	7.89E-01	kg NMVOC eq	2.11E-02	kg ethene eq
	Respiratory effects	3.96E-02	kg PM2.5 eq	-	-
	Ionising radiation	3.53E+01	kg U^{235} eq	-	-
Resources	Abiotic, non-fossil, resources depletion	-	-	6.46E-03	kg Sb eq
	Fossil resources depletion	-	-	1.57E+03	MJ
	Minerals, fossils and renewables depletion	7.53E-04	kg Sb eq	-	-
	Land use	4.42E+02	kg soil	-	-
	Water depletion	3.58E+00	m^3 water use	-	-

Physical allocation

The reference flow is the production of 927 dm^3 of concrete with NCA.

Table A-9 Environmental profile of concrete production with a mix 70% NCA and 30% RCA (Perspective II)

	Impact category	PEF Indicator result		EN15804 Indicator result	
Ecosystem quality	Climate change	3.36E+02	kg CO_2 eq	3.36E+02	kg CO_2 eq
	Freshwater ecotoxicity	3.38E+02	CTUe	-	-
	Acidification	7.88E-01	mol H^+ eq	5.92E-01	kg SO_2 eq
	Freshwater eutrophication	1.69E-02	kg P eq	-	-
	Marine eutrophication	2.57E-01	kg N eq	-	-
	Terrestrial eutrophication	2.93E+00	mol N eq	-	-
	Eutrophication (generic)	-	-	1.45E-01	kg $(PO_4)^{3-}$ eq
Human health	Ozone layer depletion	1.16E-05	kg CFC-11eq	1.16E-05	kg CFC-11 eq
	Carcinogenic effects	4.22E-06	CTUh	-	-
	Non-carcinogenic effects	2.53E-05	CTUh	-	-
	Photochemical ozone formation	7.54E-01	kg NMVOC eq	2.07E-02	kg ethene eq
	Respiratory effects	3.82E-02	kg PM2.5 eq	-	-
	Ionising radiation	3.45E+01	kg U^{235} eq	-	-
Resources	Abiotic, non-fossil, resources depletion	-	-	6.42E-03	kg Sb eq
	Fossil resources depletion	-	-	1.54E+03	MJ
	Minerals, fossils and renewables depletion	7.36E-04	kg Sb eq	-	-
	Land use	3.77E+02	kg soil	-	-
	Water depletion	3.11E+00	m^3 water use	-	-

Physical allocation

The reference flow is the production of 927 dm^3 of concrete with a mix 70% NCA and 30% RCA.

Table A-10 Environmental profile of concrete production with RCA (Perspective II)

	Impact category	PEF Indicator result		EN15804 Indicator result	
Ecosystem quality	Climate change	3.29E+02	kg CO_2 eq	3.29E+02	kg CO_2 eq
	Freshwater ecotoxicity	3.20E+02	CTUe	-	-
	Acidification	7.19E-01	mol H^+ eq	5.44E-01	kg SO_2 eq
	Freshwater eutrophication	1.59E-02	kg P eq	-	-
	Marine eutrophication	2.28E-01	kg N eq	-	-
	Terrestrial eutrophication	2.60E+00	mol N eq	-	-
	Eutrophication (generic)	-	-	1.31E-01	kg $(PO_4)^{3-}$ eq
Human health	Ozone layer depletion	1.09E-05	kg CFC-11eq	1.09E-05	kg CFC-11 eq
	Carcinogenic effects	3.77E-06	CTUh	-	-
	Non-carcinogenic effects	2.45E-05	CTUh	-	-
	Photochemical ozone formation	6.71E-01	kg NMVOC eq	1.98E-02	kg ethene eq
	Respiratory effects	3.49E-02	kg PM2.5 eq	-	-
	Ionising radiation	3.25E+01	kg U^{235} eq	-	-
Resources	Abiotic, non-fossil, resources depletion	-	-	6.35E-03	kg Sb eq
	Fossil resources depletion	-	-	1.47E+03	MJ
	Minerals, fossils and renewables depletion	6.97E-04	kg Sb eq	-	-
	Land use	2.26E+02	kg soil	-	-
	Water depletion	2.01E+00	m^3 water use	-	-

Physical allocation

The reference flow is the production of 927 dm^3 of concrete with RCA.

Figure A-1 illustrates the differences between the environmental profiles of the BAU and BP product systems with the categories established in the standard EN15804. The results were divided by the largest indicator result for each impact category.

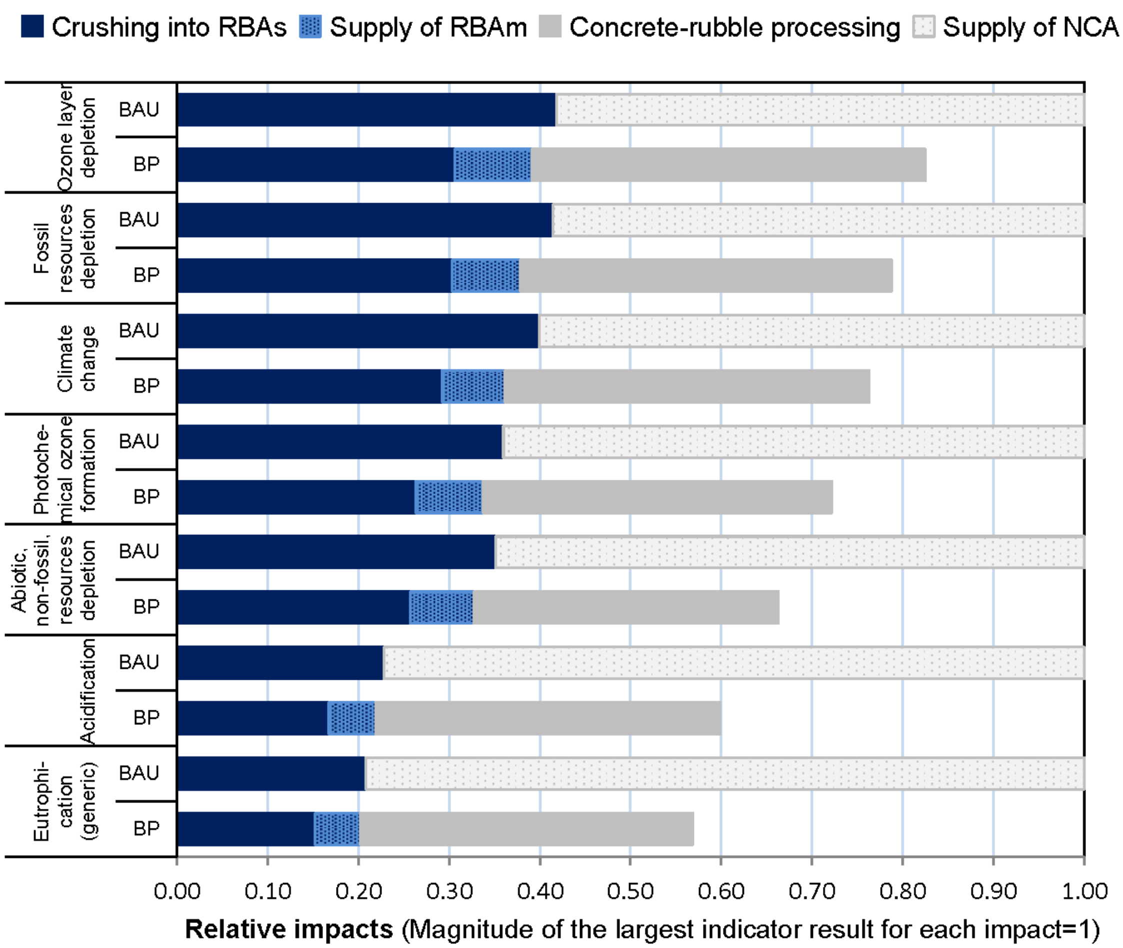

Figure A-1 Environmental profiles of the BAU and BP product systems, EN15804

Table A-11 Normalized environmental profile (years) for alternatives from Perspective I, referred to the EN15804 category totals for EU25+3 in the year 2000

	BP	BAU
Fossil resources depletion	2.47E-09	3.35E-09
Acidification	1.59E-09	2.79E-09
Climate change	1.21E-09	1.68E-09
Photochemical ozone formation	5.1E-10	7.54E-10
Eutrophication (generic)	3.65E-10	6.71E-10
Abiotic, non-fossil, resources depletion	3.54E-10	5.67E-10
Ozone layer depletion	7.57E-11	9.88E-11

The normalization factors for EU25+3 in the year 2000 were retrieved from the CML-IA database v4.8 (van Oers 2016).

Figure A-2 illustrates the differences between the environmental profiles of the product systems for concrete production using NCA or RCA, with the categories established in the standard EN15804. The indicator results were divided by the largest result for each impact category.

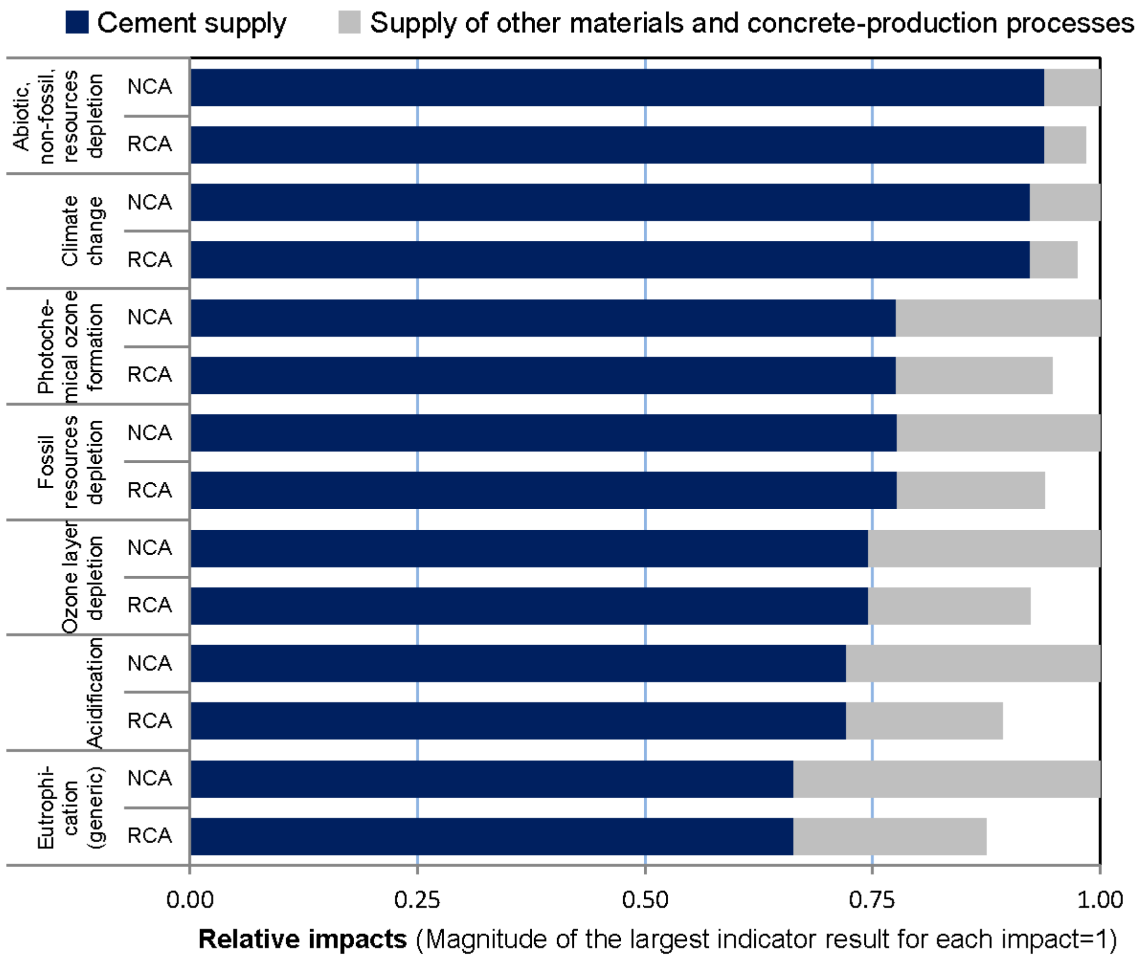

Figure A-2 Environmental profiles of the production of concrete with NCA and RCA, EN15804

Table A-12 Normalized environmental profile (years) for alternatives from Perspective II, referred to the EN15804 category totals for EU25+3 in the year 2000

	NCA	Mix	RCA
Climate change	6.48E-11	6.43E-11	6.31E-11
Fossil resources depletion	4.48E-11	4.39E-11	4.18E-11
Abiotic, non-fossil, resources depletion	3.98E-11	3.96E-11	3.92E-11
Acidification	3.64E-11	3.52E-11	3.23E-11
Photochemical ozone formation	1.22E-11	1.20E-11	1.14E-11
Eutrophication (generic)	8.13E-12	7.82E-12	7.08E-12
Ozone layer depletion	1.16E-12	1.14E-12	1.07E-12

Appendix B

Supporting information for the LCA foreground processes

Equations to calculate the emissions from the machinery operation

First, the work delivered by the machine was calculated considering the reported fuel consumption and the machine specifications, according to Eq. 1.

$$Work\ \ (kWh) = \frac{Fuel\ consumption(g)}{Fuel\ consumption\ factor\ \left(\frac{g}{kWh}\right) \times TAF} \qquad \text{Equation 1}$$

Where

- Fuel consumption is the volume of fuel reported by STRUK, converted to mass, considering the fuel density.
- Fuel consumption factor is the specific fuel consumption associated with the year of manufacture and power rating of the machine.
- TAF (Transient Adjustment Factor) is an adjustment parameter that takes into account the deviation from the average use of a certain type of machine application due to changing power demand.

Then, the emissions of carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter are calculated according to Eq. 2.

$$Emission\ (g) = Work\ (kWh) \times Emission\ factor\ \left(\frac{g}{kWh}\right) \times TAF \qquad \text{Equation 2}$$

Where

- Work is calculated according to Eq. 1
- Emission factor is the relevant average emission factor associated with the year of manufacture and power rating of the machine.
- TAF (Transient Adjustment Factor) is an adjustment parameter that takes into account the deviation from the average use of a certain type of machine application due to changing power demand.

The calculation of energy yield by the combustion of fuel served to estimate the waste heat and other emissions. It was calculated according to Equation 3.

$$Fuel\ consumption\ \left(MJ_{fuel}\right) = Fuel\ consumption\ (kg) \times Heating\ value\ \left(\frac{MJ}{kg}\right) \quad \text{Equation 3}$$

The emissions of sulphur dioxide, carbon dioxide, nitrous oxide and ammonia are directly related to the fuel composition, and were calculated with Eq. 3.

$$Emission\ (g) = Fuel\ consumption\ (MJ_{fuel}) \times Emission\ factor\ \left(\frac{g_{emission}}{MJ_{fuel}}\right) \qquad \text{Equation 4}$$

Where

- Fuel consumption is the mass of fuel consumed times its heating value.
- Emission factor is the relevant average emission factor associated with the fuel specifications for a certain period.

The waste heat was calculated performing an energy balance, according to Eq. 5

$$Waste\ heat\ (MJ) = Fuel\ consumption\ (MJ) - Work\ (MJ) \quad \text{Equation 5}$$

Variables in the unit processes of machinery

The next sections present the variables used as input for the calculation of fuel combustion and emissions.

B.1. Density of fluids

Fluid	Density (g/L)	Remarks	Ref.
Diesel	840	EU reference, average at 15°C (Min. 835g/L, Max. 840g/L)	[1]
Lubricating oil	900	UK Petroleum Industry, average at 15°C (Min. 850g/L, Max. 950g/L)	[2]
Petrol	750	UK Petroleum Industry, average at 15°C (Min. 710g/L, Max. 790g/L)	[2]
Water	1000	Approximation. At 15°C water density is 999.099 g/L.	[3]*

*The original source is “Water: Density at Atmospheric Pressure and Temperatures from 0 to 100°C,” Tables of Standard Handbook Data, Standartov, Moscow, 1978." The information was retrieved from Ref. [3].

B.2. TAFs for fuel consumption and emissions of machinery

The Transient Adjustment Factor (TAF) is a dimensionless parameter, in the estimation of fuel consumption and related emissions, that takes into account the deviation from the average use of a certain type of machine application due to changing power demand. The combustion emissions of the ADR set and the crusher are due to the fuel use of the generators that power them.

Type of machine	Fuel	CO	HC	NOx	PM
Rubber-tire loader	1.04	3.68	1.07	0.96	2.02
Excavator	1.03	0.44	1.4	0.87	0.89
Generator	1.18	2.57	2.29	1.1	1.97

Source: Tables 8 and 9 in the EMMA report published by TNO [4]

B.3. Consumption and emission factors of machinery (g/kWh$_{work}$)

The emission certification of a machine is related to the year of manufacture. It can be traced from the model information of the machine or engine. In the EMMA, the emission certification and the power rating of a machine indicate the mass of fuel consumed or the mass of pollutants emitted per unit of work output (g/kWh$_{work}$). Source of emission factors: Table 3 in the EMMA report published by TNO [4].

Machine	Emission Certification	Power range (kW)	Fuel	CO	HC	NO_x	PM
Rubber-tire loader	Stage IIIA [5]	130-560	250	0.075	0.014	3.3	0.1
Excavator	Stage IV [6]	130-560	250	0.075	0.014	0.36	0.02
Crusher generator	Stage IIIA [7-9]	130-560	250	0.075	0.014	3.3	0.1
ADR generator	Stage IIIA*	37-75	260	0.075	0.014	3.8	0.2

*The model of the ADR generator remained unreported at the time this thesis was submitted for evaluation. It was assumed that the emission certification was in accordance to the Stage IIIA, based on the certification of the crusher generator.

B.4. Operation time, fuel consumption and energy balance for machinery used for crushing and ADR

The combustion heat or fuel consumption expressed in MJ was calculated with Eq. 3, considering the density of diesel reported in B.1 and the next value:

Heating value of diesel	42.7	MJ/kg	[4]

Based on the operation time and fuel consumption reported for each machine, the work supply was calculated with Eq. 5. The work that each machine provided was calculated in kWh with Eq. 1, according to the density of diesel reported in B.1, the TAFs of fuel consumption reported in B.2, and the fuel consumption factor reported in B.3. The ratio 3600 MJ: 1000 kWh was considered for expressing the work in MJ. The waste heat was calculated according to Eq. 5 and the efficiency was calculated as the percentage of combustion heat transformed in to work.

Machine	Operation time (h)	Fuel consumption (L)	Work(MJ)	Waste heat (MJ)	Heat released (MJ)	Efficiency (%)
Rubber-tire loader	8	142.5	1657	3454	5111	32
Excavator	8	142.5	1673	3438	5111	33
Crusher generator	8	420	4305	10759	15065	29
ADR generator	16	71	700	1847	2547	27

Source: The operation time and fuel consumption were reported for each machine according to the data-collection sheets (internal documents 1.10 and 1.12).

B.5. Emissions modelled according to the ecoinvent module 'diesel, burned in diesel machine'

Emission factors of machinery for Cd, Cr, Cu, Ni, Se and Zn

Element	Emission factor ($kg_{element}/kg_{diesel}$)
Cd	1.00E-08
Cr	5.00E-08
Cu	1.70E-06
Ni	7.01E-08
Se	1.00E-08
Zn	1.00E-06

Composition of HC emissions in 'diesel burned in building machine'

Substance	Fraction (%)
Benzo(a)pyrene	0.001
Methane, fossil	3.004
NMVOC, non-methane volatile organic compounds, unspecified origin	96.932
PAH, polycyclic aromatic hydrocarbons	0.063
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.122E-09
HC	100.000

Description of the dataset

The next paragraph is quoted directly from the description of the ecoinvent dataset, which is included in the supporting ecoinvent report and in the metadata of the dataset.

> Includes the inputs 'building machine' for infrastructure, lubricating oil and fuel consumption, and some measured air emissions as output. This module is based on the data included in the report Oekoinventare von Energiesystemen

1996. The diesel consumption and the emissions are updated using the Swiss "Offroad database" and applied to year 2000. This module should not be used if its relative importance would be high in a certain environmental inventory [10]

Sources: Documented in Part XVIII, 'Additional products and processes' in Ref. [10] Validity period: 1996-2001. This module considers a heating value of 42.8 MJ per kg of diesel. Frischknecht et al. (1996) and BUWAL (2000) are referred as the sources of the data for this module. Diesel and emissions, excluding waste heat: BUWAL (2000) Handbuch: Offroad-Datenbank. In: Vollzug Umwelt. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern. Waste heat and Economic inflows, except diesel Frischknecht R., Suter P., Bollens U., Bosshart S., Ciot M., Ciseri L., Doka G., Hischier R., Martin A., Dones R. and Gantner U. (1996) Ökoinventare von Energiesystemen, Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3. Aufl. Edition. Bundesamt für Energiewirtschaft (BEW/PSEL), Bern.

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Appendix C

Supporting information for the calculation of the indicators of circularity

1) Scenarios information

1.1) Stony materials from an EoL building in reference scenarios

Materials from demolition (t)	BP	BAU	Disposal
concrete rubble	671.2	0.0	Recycling into a 4-22 mm fraction of coarse concrete aggregate with ADR. The coproducts (36% of the concrete rubble) are sieved sands 0-4 mm.
mixed rubble	1,426.2	2,097.4	Recycling into a 0-32 mm aggregate for road base

1.2) Demand of stony materials for a new building in reference scenarios

Materials demand (t)	BP	BAU	Origin
RBAs	1,426.2	1,800.0	Recycling
RBAm	373.8	0.0	Recycling
RCA	360.0	0.0	Recycling
NCA	0.0	360.0	Virgin resources

2) Mass based indicators

2.1) Mass recycling rate

a

Recycled materials from the demolition absorbed by the new building. Calculation of mass recycling rate with the WM and MS functions, considering the stony waste generated from the demolition of an EOL building and the fraction of it that would be used in the construction of a new building in the demolition location.

Scenario	BP	BAU
Materials recycled absorbed by the new building (t)	1,786.2	1,800.0
Waste generated (t)	2,097.4	2,097.4
Mass recycling rate based on waste (%)	85	86

b **Recycled materials from demolition**. Calculation of mass recycling rate from the WM function, considering the stony waste generated from the demolition of an EOL building and the fraction of it that was transformed into recycled materials.

Scenario	BP	BAU
Materials recycled (t)	2,097.4	2,097.4
Waste generated (t)	2,097.4	2,097.4
Mass recycling rate based on waste (%)	100	100

2.2) Recycled content

Recycled materials used in the new building. Calculation of recycled content from the material supply function, considering the requirements of stony materials for the construction of a new building and the origin of the materials to meet the demand. Origin: recycling/ virgin resources.

Scenario	BP	BAU
Supply sourced from recycled materials (t)	2160.0	1800.0
Material demand (t)	2160.0	2160.0
Recycled content (%)	100	83

3) Circular Economy Index

3.1) Material value of unprocessed materials and products

Material	Unitary Value (EUR/t)	Reference
Mixed rubble	1.93	On-site crushing costs calculated from LCC
Concrete rubble	1.93	Assumed the same as of mixed rubble
RBAm	6.50	On-site price of purchase, estimated at the early stages of the HISER case
RBAs	6.50	Assumed the same as of RBAm
RCA	16.00	Assumed the same as of NCA
NCA	16.00	On-site price of purchase, estimated during the early stages of the HISER case

3.2) **Recycled materials used in the new building**

	BP		BAU	
	Mass (t)	Value (EUR)	Mass (t)	Value (EUR)
Materials before recycling	2,160.0	4,162	1,800.0	3,468
RBAs in mixed rubble	1,426.2	2,748	1,800.0	3,468
RBAm in mixed rubble	373.8	720	0.0	0
RCA in concrete rubble	360.0	694	0.0	0
Recycled products	2,160.0	17,460	1,800.0	11,700
RBAs	1,426.2	9,270	1,800.0	11,700
RBAm	373.8	2,430	0.0	0
RCA	360.0	5,760	0.0	0
Circular Economy Index	**4.2**		**3.4**	

3.3) **Recycled materials from the demolition**

	BP		BAU	
	Mass (t)	Value (EUR)	Mass (t)	Value (EUR)
Materials before recycling	2,097.4	4,041	2,097.4	4,041
Mixed rubble	1,426.2	2,748	2,097.4	4,041
Concrete rubble	671.2	1,293	0.0	0
Recycled products	2,097.4	16,989	2,097.4	13,633
Sieved sands (0-4 mm)	241.6	846	0.0	0
RBAs	1,426.2	9,270	2,097.4	13,633
RCA	429.6	6,873	0.0	0
Circular Economy Index	**4.2**		**3.4**	

3.4) **Recycled materials from the demolition absorbed by the new building**

	BP		BAU	
	Mass (t)	Value (EUR)	Mass (t)	Value (EUR)
Materials before recycling from the demolition	2097.4	4041.31	2097.4	4041.31
Mixed rubble	1426.2	2748.03	2097.4	4041.31
Concrete rubble	671.2	1293.28	0.0	0.00
Recycled products for the new building	1786.2	15030.30	1800.0	11700.00
RBAs	1426.2	9270.30	1800.0	11700.00
RCA	360.0	5760.00	0.0	0.00
Circular Economy Index	**3.7**		**2.9**	