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Developing ECO_2: A Performance Based Ecological and Economic Framework and Tool for Sustainability Assessment of Concrete

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Developing ECO$_2$: A Performance Based Ecological and Economic Framework and Tool for Sustainability Assessment of Concrete

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A thesis submitted in partial satisfaction of the requirements of the University of Northumbria in Newcastle for the degree of Doctor of Philosophy in Civil Engineering

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Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. The ethics approval application was prepared on the 4th of December 2018 under the submission number 13168 and was approved on the 27th of February 2019.

I declare that the Word Count of this Thesis is 55,036 words

Name: Hisham Tarek Hafez

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Abstract

The use of concrete is associated with immense negative environmental impacts. More than 50 billion tonnes of aggregates are extracted annually for use in concrete, which presents high risks of depleting natural resources. Moreover, concrete has an embodied carbon footprint of 350 kg eq CO_2/m^3 on average of which 90% is attributable to the production of ordinary Portland cement (OPC). Although this is less than that of steel and most polymers per unit mass, the intensive use of concrete results in an alarming 7% share of the global carbon emissions. Therefore, increasing interest is being directed towards producing sustainable concrete. Conducting a Life cycle assessment (LCA) is a widely accepted tool to assess and compare the acclaimed environmental gains of these sustainable concrete types, while calculating the base line cost of each of these mixes could suffice for economic comparisons. However, sustainability is a multifaceted concept and in order to validate the sustainable of a concrete mix, multi criteria sustainability frameworks are needed. The critical examination of the only two frameworks found in the literature that fits this description, MARS-SC and CONCRE*Top*, showed the need to develop a new one that covers their gaps, which inspired the main contribution in this PhD project.

A novel ECOnomic and ECOlogical assessment framework for concrete (hence the name ECO_2 which also refers to the symbolic carbon dioxide formula) was created with the following distinguishing features:

1. The scope specified for the LCA study is selected as Cradle-to-Grave in order to account for the whole life cycle of concrete. Therefore, the LCA inventory data, for which site-specific primary data is prioritized, would include upstream data such as the impact allocation from previous processes from which the raw materials originated and downstream data such as the demolition and disposal impact of concrete.
2. The ECO_2 framework considers the amount of carbon sequestration, which is the term used to describe how much carbon dioxide is absorbed by concrete from the environment. The accurate calculation of the carbon footprint of a concrete mix is vital for its absolute environmental impact assessment, but would soon in the near future also affect its economic impact when carbon taxation becomes a normal practice.

Aside from filling the technical gaps of the sustainability assessment method, the main contribution the ECO_2 framework brings is a shift in the philosophy related to the inclusion of the concrete performance in the process. In both reviewed frameworks (MARS-SC and CONCRE*Top)*, concrete performance is assessed as a separate pillar of sustainability

perpetuating that the higher performance is rewarded with a higher sustainability index value. Instead, the ECO_2 framework brings forward a two layered performance based methodology that promotes a value of resource efficiency. First, the user sets a minimum requirement for the workability and strength depending on the project specifications. The second layer is to correlate the expected service life of each qualifying concrete mix to the required service life of the concrete application within the project through a factor N. This factor, for which the minimum value is 1, is then multiplied by the functional unit used for the LCA to ensure that the economic and ecological assessment are not only accurate but also truly reflective of sustainability. An MS-excel tool was also developed to self-validate the ECO_2 framework in what could be labelled as a methodical contribution. Finally, three case studies were conducted using the newly developed ECO_2 framework as follows:

1. The first case study was experimental using electric arc furnace slag as a precursor for alkali activated concrete and comparing its ECO_2 sustainability index to a basic alkali activated concrete mix based on fly ash as a precursor. The case study showed that the deterioration in the mechanical properties of the novel alkali activated slag concrete largely overshadow the ecological and economic merits of recycling it.
2. The second case study was analytical using a database of more than 2500 data points to predict and hence optimize the functional, environmental and economic performance of blended cement concrete using the ECO_2 framework. The mixes included varying combinations of five different types of SCMs based on plain and reinforced concrete scenarios of different strength and service life requirements.
3. The final case study was prepared to investigate an issue facing the UK Green concrete market which is the need to shut down all coal operated electrical power plants by 2022 and the subsequent absence of fly ash. The case study used the ECO_2 framework to compare between importing fly ash from China, Germany and recycling locally existing stockpiled fly ash in the UK. The vital parameter in the comparison was the environmental and economic impact resulting from the transportation of fly ash from its source to the location of the concrete batch plant in the UK.

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Nomenclature

Abiotic Depletion Potential (ADPE)

Accelerated carbonation rate (Ka)

Acidification Potential (AP)

Alkali activated concretes (AAC)

Artificial intelligence (AI)

Blended cement concrete (BCC)

Calcined clay (CC)

Carbon dioxide (CO_2)

Carbon dioxide concentration in the carbonation chamber (CCa)

Carbon dioxide concentration in the environment (CCn)

Carbonated depth of concrete (Xc)

Chloride concentration on the concrete surface (Co)

Chloride diffusion coefficient (D)

Chloride Penetration Test (RCPT)

Chloride threshold level (Cc)

Concrete cover (X)

Construction and demolition waste (CDW)

Energy consumption demand (CED)

Environmental product declarations (EPD)

Eutrophication potential (EP)

Evolutionary Algorithms (EA)

Extreme Gradient (XG)

Fly ash (FA)

Functional Units (FU)

Genetic Algorithms. (GA)

Global Warming Potential (GWP)

Global Warming Potential (GWP)

Ground granulated blastfurnace slag (GGBS)

Hydraulic lime (HL)

Kc (the carbonation rate of concrete)

Life cycle assessment (LCA)

Lime pozzolanic concrete (LPC)

Machine learners (ML)

Mean absolute percentage error (MAPE)

Mean-squared prediction error (MSPE)

Method for the Relative Sustainability Assessment of Building Technologies (MARS-SC)

Multi-dimensional criteria analysis (MDCA)

Naturally sourced aggregates (NA)

Ordinary Portland cement (OPC)

Ozone Depletion Potential (ODP

Photochemical ozone creation potential (POCP)

Predicted service life (SLP-Cr)

Random Forrest (RF)

Recycling aggregate concrete (RAC)

Relative Humidity (RH)

Self-compacted concrete (SSC)

Silica fume (SF)

Supplementary cementitious materials (SCM)

UK Quality Ash Association (UKQAA)

World's gross domestic product (GDP)

Dedication

To the Palestinian people and to those we lost in the struggle against the hegemonic forces of global capitalism, I dedicate this work wishing it inspires young researchers to go beyond the marketed consumeristic forms of empirical research and thrive to answer the specific questions organically developed in their communities in innovative sustainable ways.

Acknowledgments

I would like to first acknowledge that my friend and mentor Ahmed Teirelbar, besides his continuous support, helped me develop, within his capacity as a data scientist, the regression and optimization models used in Chapter 5 of this project.

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Chapter 1: Introduction

1.1. Background

The first documented use of the word sustainable in the literature was in the 1970s corresponding to a wave of UN-led efforts aiming to shed light on the alarming ecological footprint of human activity and the fact that it exceeded the carrying capacity of earth, therefore rendering the human existence unsustainable (Kidd, 2005). This piece of information might imply that, sustainability as a concept and as a framework for the impact assessment and objectives of human activity, was first created at that time, when in fact it is as old as humanity existed (Scholes, 2003). The ability of humans, before communities were formed, to recognize their needs and satisfy the requirements of well-being and livelihood while conserving the environment without labelling their lifestyle as sustainable is an embodiment of the falsehood of the former statement (Clark, 1989). Although the terms might seem similar, the interpretation of the classic and modern sustainability is totally different. The modern semantic refers to a specific definition by the UN that encourages the development i.e., the expansion in wealth without, supposedly, jeopardizing the ability of future generations to fulfil their needs, a duality that has been proven to be unachievable given the hegemonic global capital (Mensah, 2019). On the other hand, a 1400 years old quote by the prophet Muhammad that says “An individual should not squander water, even if next to a running river” (Ibn Majah, 1952) provides a vision that allows human beings to be considerate, in all their activities, of the risk of depleting Earth’s natural resources, which is a proven recipe for environmental resources preservation (Hummels and Argyrou, 2021).

This discrepancy between the acclaimed benefits behind the trending calls for making human activities sustainable and the deteriorating reality of the environmental resources is the main inspiration behind this dissertation. Recent reports by the World Bank show that the highest rate of growth in population is happening among the low-income countries such as my own, Egypt (Scrivener et al., 2018). This increase in population size is equitable with an even higher 65% increase in the urbanization within these countries, a social trend that is encouraged by the urban policies within most of these countries (Miller et al., 2017). Ideally, the urban development would have been limited to the vernacular construction techniques with limited environmental risk, but large-scale construction projects using technological techniques are regarded as cornerstones to the modern urban interventions (Conte, 2019). In Egypt’s case, there has been a nation-wide investment worthy of hundreds of billion dollars in infrastructure projects. Besides the need to accommodate the increase in population, these investments are also encouraged by the promised economic return from the real estate development (Belal et al., 2020). Hence, the route to a sustainable built environment only passes through decreasing the environmental impact of the prevailing construction building materials and techniques.

Concrete is the second most used substance on Earth after water primarily due to its proven record of robustness and resilience (Serres et al., 2015). However, the use of concrete is associated with immense negative environmental impacts such as being responsible for 7% of the global CO_2 emissions from the Portland cement production (Colangelo et al., 2018). In China for example, the over reliance on concrete resulted alone in approximately 1.5 billion tonnes of greenhouse gases (GHG) emissions in 2014 (Miller et al., 2016), which represents around 20% of the total produced in the same year (Yuli et al., 2018). Concrete also risks depleting natural resources since more than 50 billion tonnes of aggregates are being extracted annually for use in concrete (Ding et al., 2016). Nevertheless, the reality is that concrete will remain the principle building material and its use to satisfy the growing urbanization needs will not seize in the foreseeable future. Hence, the objective of most researchers in the concrete domain as well as that of the concrete industry has been focused on producing more sustainable concrete. Governments and regulatory boards are also emphasizing policies such as carbon taxation and incentives for environmentally friendly building materials. Imbabi et al. (2013) argue that a carbon tax of ₤30 per tonne of CO_2 would push cement producers to utilize non-fossil fuel and reduce the environmental impact by at least 10%. Shima et al. (2004) mentioned the possibility of the Japanese government offering the equivalent of ₤6 per m^3 of concrete if it proves to be sustainable or “Green” as referred to sometimes commercially.

The literature suggests three main strategies to produce more eco-friendly concrete. First, to decrease the environmental impact of the OPC industrial process by using recycled and renewable fuel sources instead of fossil fuels in the cement kiln incinerators (Huntzinger and Eatmon, 2008). Second, to decrease the needed amount of binders by increasing the fineness of the binder itself, optimizing the particle packing of the dry contents or through the use of superplasticizers (Franco de Carvalho et al., 2019; Hooton and Bickley, 2014). The third is the integration of recycled materials in the concrete mix through integrating recycled aggregates in concrete which reduces the landfilling potential of concrete by 50-75% and its embodied carbon by 10-30% (Serres et al., 2015; Shan et al., 2017). Moreover, partially or totally replacing OPC in the concrete binder by various supplementary cementitious materials SCMs such as fly ash, ground granulated blastfurnace slag, silica fume, and calcined clay. This causes 10-70% reduction in GHG compared to OPC concrete mixes (Grist et al., 2014).

In order to judge the sustainability of any of these strategies for concrete production, even if it is relative to the original process for conventional concrete, there needs to be a reliable sustainability assessment methodology. This is dependent on the reliability of the environmental impact assessment, which is contingent on the accuracy of the conducted LCA study as well as encompassing the multi-faceted nature of sustainability. The classical definition of sustainability dictates a combination of the environmental, economic and social aspects of the subject matter (Suarez Silgado et al., 2018). However, concrete related assessment frameworks replace the social pillar, which is more popular among frameworks related to construction works with the material's functionality or functional performance (Wang et al., 2017). The two frameworks found in the literature, MARS-SC and CONCRE*Top* were examined carefully and were found to have several gaps. The gaps were found to be divided into two groups: a logical one concerning the calculation method of the functional performance of concrete in the sustainability assessment process. The second group is a precision one, where the boundary conditions, source of data and several others LCA related parameters were found to be missing or wrongfully specified.

1.2. Problem statement

Concrete is a versatile material that is critical to the growing needs for global urbanization. However, conventional concrete production is proven to have a significant environmental impact as a process. Hence, concrete producers and researchers are racing to identify strategies that would decrease the environmental impact of concrete and come up with more sustainable concrete. The pressure stems from legislators and political bodies demanding to coin the growing sustainability policy trends on one of the largest industries in the world; concrete production. However, the existing frameworks that could help all these stakeholders produce a judgement on the relative, or absolute, sustainability of a concrete mix, were found to be unreliable.

1.3. Research inspiration

This RDF-funded PhD project (Northumbria University's Research Development Fund) was based on a proposal that was pivoted on a UK based concrete LCA project published by the main supervisor (Tait and Cheung, 2016) and was hence directed mainly towards improving the LCA methodology. However, as explained in section 1.1, the inspiration to do this research study went, through a critical literature review, from the motivation to contribute to a more sustainable built environment in general, to forming a critical opinion on the acclaimed environmentally friendly strategies for sustainable concrete production and aiming at creating a reliable framework for concrete sustainability assessment.

1.4. Research Scope

The aim of this dissertation is to devise a reliable concrete sustainability assessment framework. This primarily requires an extensive research of the existing domain of concrete sustainability through examining the existing assessment frameworks as well as the different sustainable concrete solutions recently proposed.

Hence, the objectives of this research are:

- Review the literature to identify gaps in the existing frameworks for concrete sustainability assessment and in the methodology for concrete LCA as well as proposing the most promising concrete alternatives in regards to sustainability.
- Devise a reliable concrete sustainability assessment framework that builds on the gaps identified in the review. The novel framework is based on both the ECOlogical and ECOnomic impact assessment and hence it was decided to call the novel framework the "ECO_2".
- Develop a tool that applies the ECO_2 framework and then use it to assess the optimum sustainable concrete mix across several case studies that were proposed in the literature review.

1.5. Methodology

The previous subsections paved the way for the hypotheses of this research project. The research methodology is the way by which a problem is systematically solved (Kothari, 2004). Hence, in the next subsections, the selected methodology to solve the intended research questions in this project is explained.

i. Research Design

Kothari (2004) defines research design as "the arrangement of conditions for collection and analysis of data in a manner that aims to combine relevance to the research purpose with economy in procedure". Figure 1.1 below shows a summary of the research design and methodology.

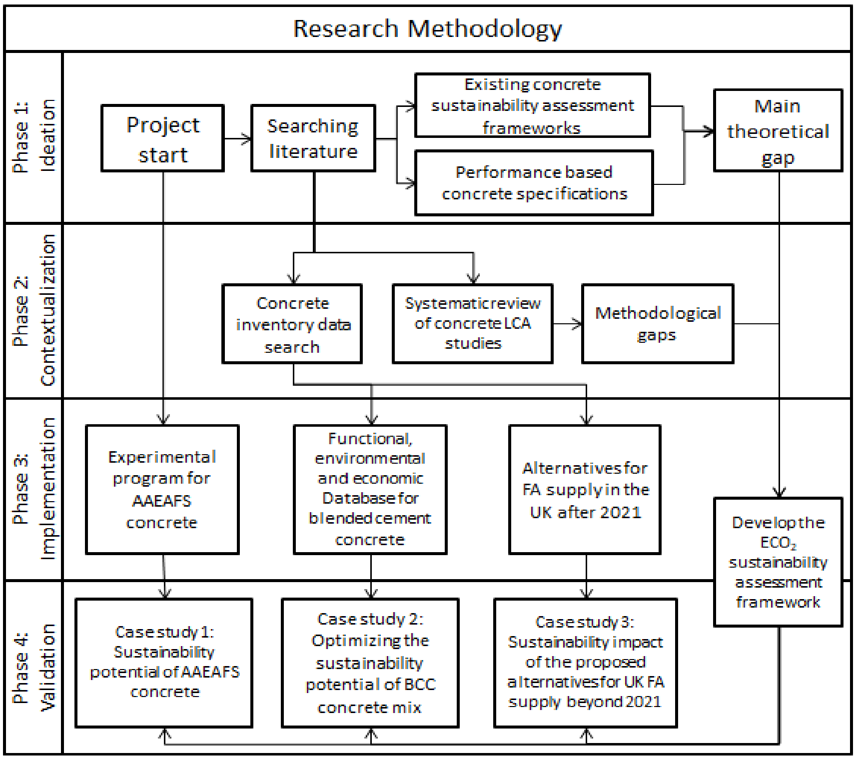


Figure 1.1: A flowchart of the methodology following in this research project

ii. Step 1: Ideation

The present research follows a positivist philosophy where the knowledge about the sustainability assessment of concrete is perceived as independent from the subject. This is more suited for the hypothesis drawn concerning the possibility of creating a reliable sustainability assessment framework in isolation of the sources of the data included in the study. The philosophical approach assumed that the theory concerning the intended research subject exists and that the research examines it in order to support it or reject it. This approach is labelled as a deductive one in which the research is structured, as seen in Figure 1.1, in a layered fashion that advances from the general concept to the details of the sustainability assessment of concrete in order to identify the gaps. The objective then is to address these identified gaps in the newly proposed sustainability assessment framework. However, it is worth noting that, due to the initial literature review, the research methodology included an element of induction. The inductive approach, which works backwards from an observation that occurs within the research scope towards conceptualizing a new theory is embodied in the attempt of this research project to present a paradigm shift to the sustainability assessment logic. As will be explained in the body of this dissertation, the novel framework being developed in this project presents a new theory that interprets the functional performance of a concrete mix not as a separate pillar of sustainability, rather as an underlying one. The functional performance of a concrete mix is, as will be presented through the framework, compared to project based specifications to make the sustainability assessment performance based rather than absolute.

iii. Step 2: Contextualization

The second step of the methodology is to name the research gaps and validate them. For this purpose, a literature review was done on two stages. The first was focused on critiquing the existing sustainability assessment frameworks. After identifying the logical gap in the existing frameworks, the following subjects were researched simultaneously to validate the remaining research gaps. The first group of literature was concerning the principles of multi-criteria decision analysis frameworks in order to obtain the criteria for evaluating the reliability and accuracy of the previously identified concrete sustainability assessment frameworks. The second group was concerned with a systematic review of the life cycle assessment studies published on concrete in order to identify the gaps in the existing method for the environmental impact assessment and address it as a pillar within the sustainability assessment framework to be created. The final survey of the literature focused on investigating the sustainability potential of some of the popular concrete types that are believed to be environmentally friendly. The reason is that these types of concrete would be used as a validation for the newly developed sustainability assessment framework. The literature findings, which were meant to contextualize the overlying objectives of this research group, are all summarized in the next chapter.

iv. Step 3: Implementation

The third step of the methodology followed in this research project is related to the implementation, which is divided between the methods used for the data collection and for developing the novel concrete sustainability assessment framework. Due to the nature of the research questions in this project, the selected methods were all quantitative. The method used for the data collection for the sake of the framework development was surveying the existing literature and extracting the environmental, economic and functional data from all the relevant references to form an extensive database. The excel sheet database was also significant in providing the input data for the second case study conducted in this research project.

The second method used was experimental, which is also quantitative. In order to evaluate the first case study to validate the novel framework, an experimental program was prepared. The experiments were done on an alkali activated electric arc based concrete mix, which is considered relatively novel and untapped in the literature. The experiments, which were all ran in the labs in Instituto Superior Técnico, University of Lisbon, Portugal, varied between the cone slump test, the compressive strength test, the accelerated carbonation and the rapid chloride penetration test. The final method used was analytical. In the second case study, which explores the optimization of blended cement concrete mixes based on supplementary cementitious materials, a regression model was developed using non-linear multi-layered machine learning methods. The model and the optimization genetic algorithm that built on it were developed in collaboration with a data scientist whose efforts were acknowledged in the start of this dissertation.

v. Step 4: Validation

The sequence of work of this research project involved coming up with the sustainability assessment first, in which the theoretical and practical contributions are included by changing the functional performance assessment of concrete and the LCA methodology respectively. Upon the completion of the formulation of the framework, which will be explained in detail in Chapter 3, it was necessary to employ suitable criteria to validate it.

Typically, the first step for validation would have been to take expert opinion. This could have been done through questionnaires, focus groups or interviews. However, the attempts to connect with several established authors did not materialize and the tight schedule of the project did allow for these attempts to be reiterated. However, the framework has been published in a high impact journal, so the peer-review process acted as an equivalent of the relevant expert opinion. Furthermore, the validation for the developed concrete sustainability framework was decided to be done through three phases: the first is to attempt its applicability through developing an excel based tool that could be used by concrete manufacturers and researchers. The second phase is to compare the output of the novel sustainability assessment framework, ECO_2, against existing ones. In Chapter 3, where the framework and the resulting tool are explained, a typical case study was shown to compare the output of the ECO_2

framework to that of the more established MARS-SC and CONCRETop frameworks. The third phase of validation for the framework was done through applying it on three different case studies: 1) exploring the sustainability potential of a novel alkali-activated concrete utilizing electric arc furnace slag as a binder 2) optimizing the components of blended cement concrete based on supplementary cementitious materials 3) judging the future policy making effects of stopping coal based power plants in the UK on the availability of fly ash as a concrete component.

1.6. Dissertation structure

This dissertation documents the journey of this research project as follows:

- **Chapter 1:** The introduction chapter included a background on the research project, the inspiration, main aims and objectives and the project methodology.
- **Chapter 2:** The literature review chapter included the review over the concrete sustainability policies, sustainable concrete types, previous concrete sustainability assessment frameworks and concrete LCA studies.
- **Chapter 3:** This chapter included the detailed explanation of the main contribution of this project, the ECO_2 framework as well as an explanation of the theoretical basis of performance based sustainability assessment and a comparison against other sustainability assessment frameworks.
- **Chapter 4:** This chapter included the first case study in which the ECO_2 framework was utilized to explore the sustainability potential of a novel alkali activated concrete mix utilizing electric arc furnace slag and comparing that with the more established fly ash based mix.
- **Chapter 5:** This chapter included the second case study, which utilized the aggregated performance assessment database of five blended cement concrete mixes in order to develop a regression model that predicts their functional properties. The model outputs were then used as input for an optimization algorithm that optimizes the mixing proportions of a generic blended cement concrete mix using the ECO_2 sustainability assessment framework.
- **Chapter 6:** This chapter was concerning the third and final case study for the validation of the ECO_2 framework by studying the sustainability potential of three different policy driven solutions to the expected problem of not having locally produced FA in the UK beyond 2022.
- **Chapter 7:** The final chapter included the aggregated conclusions from the project, the limitations of the project as well as the recommendations and further research.

Chapter 2: Literature Review

2.1. Introduction

Due to its inherent strength and durability properties, concrete is the second most used substance on Earth after water (Serres et al., 2015). Around 30 billion tonnes of conventional concrete, comprised primarily of ordinary Portland cement (OPC) and natural aggregates (NA), were produced in 2015 (Miller et al., 2018). Unfortunately, the use of concrete is associated with immense negative environmental impacts. Hence, policies and international regulations have been directed to meet the "2015 Paris climate conference" guidelines of achieving the sustainability of the built environment focusing primarily on concrete (Viñuales et al., 2017). However, sustainability of concrete is a multi-faceted parameter and determining it requires examination of the combined assessment of its functionality, environmental impact and cost. There has been several suggestions in the literature in recent years of strategies and material additions that would make concrete more sustainable. Nevertheless, the absence of a reliable framework to assess the sustainability of these presumed sustainable concrete mixes would not allow the desired transition of the lab findings to the market place and favourably to the specifications and later on policies. Hence, in this chapter, the literature reviewed is divided into a section on the existing policies and specifications to support concrete sustainability in the UK, then a review of the existing concrete sustainability frameworks, then a section on the concrete types that are believed to be more sustainable than conventional concrete and finally a review of the sustainability potential of the selected acclaimed sustainable concrete types.

The contents of this chapter were published in the "Applied Sciences" journal on 30th September 2020 under the title "A Systematic Review of the Discrepancies in Life Cycle Assessments of Green Concrete". The paper included the following authorship responsibilities, conceptualization, (Wai Ming Cheung, Brabha Nagaratnam, and Rawaz Kurda), data collection, data analysis, data interpretation, and writing the paper (Hisham Hafez), and revision (Wai Ming Cheung, Brabha Nagaratnam, and Rawaz Kurda).

2.2. Sustainable concrete policies

The UK government issued the climate change act in 2008, which was the first time a country had introduced a legally binding framework for tackling climate change. The act sets targets, establishes systems to ensure accountability and addresses resilience to climate change (Oyenuga, 2016). In 2006, the UK government committed that from 2016 all new homes would be ‘zero carbon’ and introduced the “Code for Sustainable Homes”, against which the sustainability of new homes could be rated. This was translated into the development of the ENVEST tool by the Building Research Establishment Environmental Assessment Method (BREEAM), upon which points are determined for the environmental impact assessment and rating of buildings as a whole (Kim et al., 2017). However, the focus of this rating system in the construction industry is on reducing the operational energy consumption by buildings not the environmental impact of the building materials. Until recently, the BS EN 206-1:2013, which defines concrete specifications, did not allow for the integration of replacement of OPC by other recycled binders except minimally (Clear, 2012). More recently, the PAS 2080 concrete standard on the other hand provides guidelines for the integration of several sustainable concrete materials to designers and concrete manufacturers (McAlinden, 2016). This is one of several strategies aiming to decarbonize the concrete industry and go beyond its net-zero target by 2050 (Pamenter and Myers, 2021).

The impact of policies such as the Waste Management Licencing Regulations in the UK is evident in the 75% increase in the recycling of construction and demolition waste (CDW) in 2012 due to the more efficient process of sorting waste (Oyenuga, 2016). The role of legislations is also fundamental for the integration of sustainable concrete in the market in terms of material availability. Several cement manufacturers such as Hanson Heidelberg Cement Group produce ready blended cement packages with 35% and 70% replacement of OPC by recycled materials such as fly ash (FA) and ground granulated blastfurnace slag (GGBS) (Tait and Cheung, 2016). However, in order to minimize their harmful emissions, the UK is aiming to shut down all coal fired electrical power plants by 2022, which means the seize in local supply of FA.

Another overlap between the local regulations and the use of sustainable concrete in the UK is EPDs. For the placing on the market of any product in the European Union (with the exception of Switzerland), Regulation (EU) No. 305/2011 applies which specifies that the product needs to declare its environmental impact following the methodology in ISO 14025. However, an incentive that could have been influential in decreasing the environmental impact is a form of a taxation on the environmental impact of products similar to the e-fuel duty escalator (FDE) which was attempted in the UK in the 1990s, but did not materialize (Pearce, 2003).

2.3. Concrete sustainability assessment frameworks

In order to tackle the environmental impact generated by building materials from a policy point of view, there needs to be a definition of the indicators of the environmental impact, then an agreement on an assessment method, which is the scope of this research project. These assessment methods could be deployed to quantify this impact and set targets for companies and regulatory boards (Gao et al., 2013). In construction terms, the selection of the optimum concrete type and mix by the project engineer or any other stakeholder is a vital step in any project. However, in business as-usual cases, the selection is based on a single functional criterion that satisfies the minimum requirements of the project (Kurda et al., 2019) as in Figure 2.1:

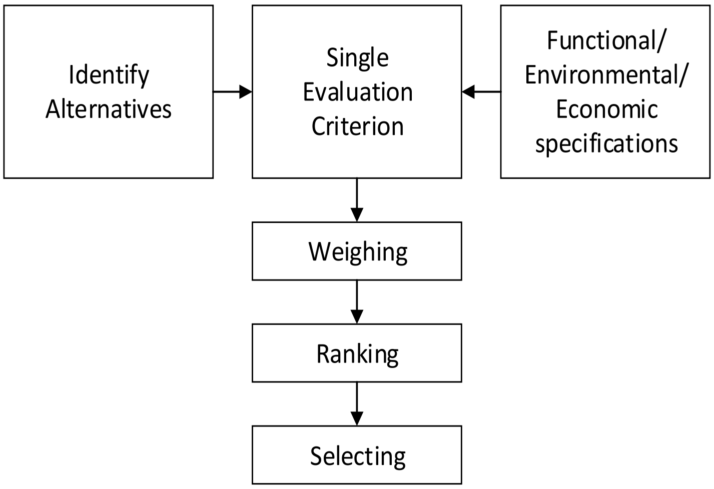


Figure 2.11: Single Criterion concrete selection decision support framework

A single criterion analysis framework that ignores the multi-dimensional nature of the targeted sustainability objective is not suitable. Muller et al. (2014) asserts that the sustainability of concrete should be perceived as a targeted objective between the functionality of concrete and its associated environmental impact. However, for a concrete product to be realised by users, an economic benefit should be evident against existing alternatives (Suarez-Silgado et al., 2018). Hence, the assessment of the sustainable development potential of a material depends on three main parameters: functionality, environmental impact and economic viability (Gettu et al., 2018).

The sustainability assessment framework developed by Suarez Silgado et al. (2018) combines the environmental and economic impacts of concrete as shown in Figure 2.2. The framework uses VIKOR, which is a method used to solve multi-criteria decision analysis (MCDA) problems with conflicting and incommensurable criteria that has been applied successfully in the field of environment and materials engineering. However, the framework ignores the functional properties of the concrete alternatives.

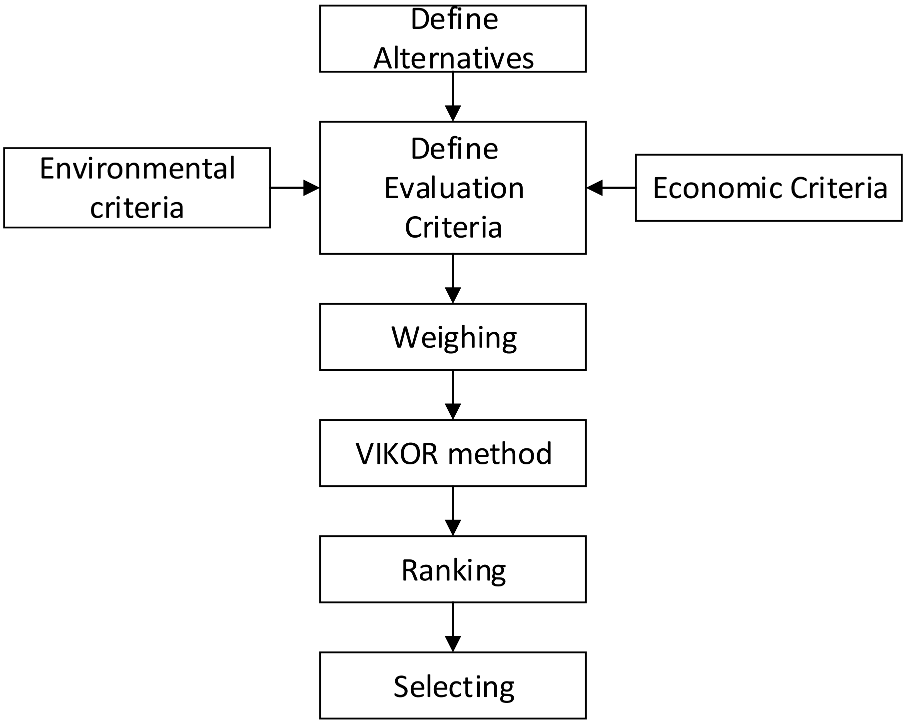


Figure 2.2: MDCA methodology proposed by Suarez Silgado et al., 2018

This issue was solved in the MDCA presented by Rahla et al. (2019) and Kurda et al. (2019) in the form of MARS-SC and CONCRETop frameworks simultaneously. Both frameworks present a methodology of assessing the sustainability across different concrete alternatives based on a combined score of functional, environmental and economic aspects. The fact that MARS-SC presents the findings of the MDCA along with a sensitivity analysis is more suitable to the large uncertainties associated especially with the environmental impact assessment of concrete (Rahla et al., 2019). CONCRETop on the other hand is more complete in the sense that the values for each of the indicators used is compared locally to the alternatives presented, but also globally to literature values and/or standards (Kurda et al., 2019). However, both frameworks are missing some features in the approach that will be discussed thoroughly in the coming chapter 3, but most primarily neglecting the overlap between the three aspects of sustainability such as:

- The overlap between the functional and environmental aspects in the comparison between the service life predictions and the required service life of the alternatives as well as the deduction of the sequestered carbon from the embodied carbon.
- The overlap between the functional and economic aspects in the need for replacing the concrete alternative to satisfy the required service life and the associated costs.
- The overlap between the environmental and economic aspects in the fact that changing the market price would affect the economic allocation in case of SCMs.

2.4. Types of sustainable concrete

The current production rate of more than 4 billion tonnes of OPC annually is responsible for 7% of the global CO_2 emissions (Colangelo et al., 2018). It also risks depleting natural resources since more than 50 billion tonnes of aggregates are being extracted annually (Ding et al., 2016). Concrete has an environmental impact of 300 kg eq CO_2/m^3 on average of which 90% is attributable to OPC (Habert et al., 2011). Although this is less than that of steel and most polymers per unit mass (Ashby, 2012), the intensive use of OPC concrete results in alarming environmental hazards. In China for example, the over reliance on concrete resulted alone in approximately 1.5 billion tonnes of greenhouse gases (GHG) emissions in 2014 (Miller et al., 2016), which represents around 20% of the total produced in the same year (Yuli et al., 2018). Nevertheless, projections indicate that the growing global urbanization would double the demand on concrete by 2050 (Miller et al., 2017).

As seen in Figure 2.3, there are three main strategies in the literature that contribute towards producing more eco-friendly concrete. First, to decrease the environmental impact of the OPC production process. Li et al. (2014) suggested the use of burned tyres and biofuel instead of fossil fuels in the cement kiln incinerators and Huntzinger and Eatmon (2008) showed the merits of recycling some of the produced cement kiln dust as raw materials. Second, to decrease the needed amount of binders. This could be achieved by optimizing the particle packing of the dry contents through increasing the fineness of the binder itself, adding filler such as powdered lime (LP) or the use of superplasticizers (Franco de Carvalho et al., 2019; Hooton and Bickley, 2014). The third is the integration of recycled materials in the conventional OPC mix through:

i. Recycled aggregate concrete **(RAC)** where construction and demolition waste (CDW) are reused as aggregates in concrete. This reduces the landfilling potential by 50-75% of concrete and its embodied carbon by 10-30% (Serres et al., 2015; Shan et al., 2017; Turk et al., 2015).

ii. Blended cement concrete **(BCC)** where OPC in the binder is partially replaced with various pozzolanic materials called supplementary cementitious materials SCMs. Examples of these are FA, which is a by-product of coal combustion, GGBS which is a by-product of steel manufacturing, silica fume (SF) which is generated from glass manufacturing as well as calcined clay (CC). The mechanical and durability properties of the resulting concrete varies significantly between the different types of materials and the percentages by which OPC is being replaced and similarly the environmental impact varies (Dhanya et al., 2018). For example, the embodied emissions of concrete could decrease up to 30% and 60% with incorporation of 35% and 70% of FA and GGBS, respectively (Tait and Cheung, 2016).

iii. In order to totally replace OPC, alkali activated concretes **(AAC)** are made with precursors of 100% FA, CC or GGBS that are activated using an alkaline solution. This means that the GHG emissions from this (AAC) are 70-75% less than OPC concrete.

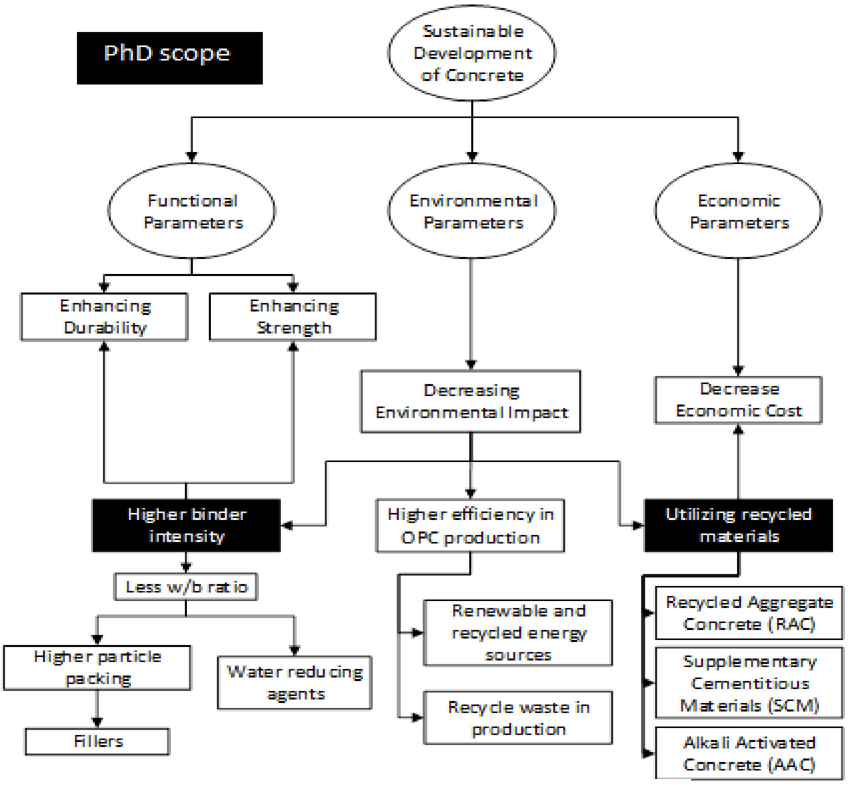


Figure 2.3: A schematic of some potential strategies and types for sustainable concrete production

The scope of this PhD, in application of the sustainability assessment framework that will be explained in Chapter 3, would be to explore the sustainability potential of three of these concrete types. Due to the fact that it is an OPC free cement, the first case study will explore the sustainability potential of utilizing a slag with low recyclability in concrete applications. An AAC mix including electric arc furnace slag (EAFS) would be produced, tested for its functional properties and then studies for its environmental and economic impact using primary data. The second case study would aim at BCC mixes. As will be explained in the next section, there are conflicting parameters in the mix design of BCC mixes from SCMs such as FA, GGBS, CC, SF and LP. Hence, it would be relevant to optimize the BCC mixes with accordance to their sustainability score which would be calculated using the novel framework. Finally, the decision of the UK government to seize production of electricity from coal by 2021 means there would be no FA available from local production starting then (BEIS, 2017). Responding to the potential problem, two private companies; Power Minerals Co. (Paoli, 2016) and Ecocem Co. (Lambe, 2018) have already started importing FA from Europe (Germany, Italy, Spain, and Portugal) and China respectively. However, this raises concerns on the environmental impact associated with long transportation distances that might end up cancelling the benefits of the imported FA (IFA) replacing OPC. Since FA carries negligible emissions as a product, most of the weight of importing FA could be attributed to its transportation process (O'Brien et al., 2009). Hence, the third and final case study is to calculate the environmental impact of importing FA to the UK versus other solutions from the literature such as the recovery of landfilled FA in the UK, which is believed to be around 50 million tonnes (McCarthy et al., 2013).

2.5. Sustainability potential of selected concrete types

2.5.1. Quantifying Functional aspects

The use of concrete in several engineering infrastructural and building solutions is an indication of its versatility and reliability (Chopra et al., 2014). Concrete's ability to perform its required function within any designated application is defined by its mechanical properties and durability (Gettu et al., 2018; Muller et al., 2014). That is why these functional aspects usually serve as the principal basis for selecting a certain concrete type and mix (Alexander and Thomas, 2015). The functional parameters of concrete are to be workable enough for casting, to have enough strength to withstand the applied load and the durability for the required service life (Alexander and Thomas, 2015). Among several intrinsic properties of a concrete mix that were found in the literature to describe these parameters, only the most significant were selected for this project as shown in Figure 2.4 which is based on a similar diagram by Kurda et al. (2019).

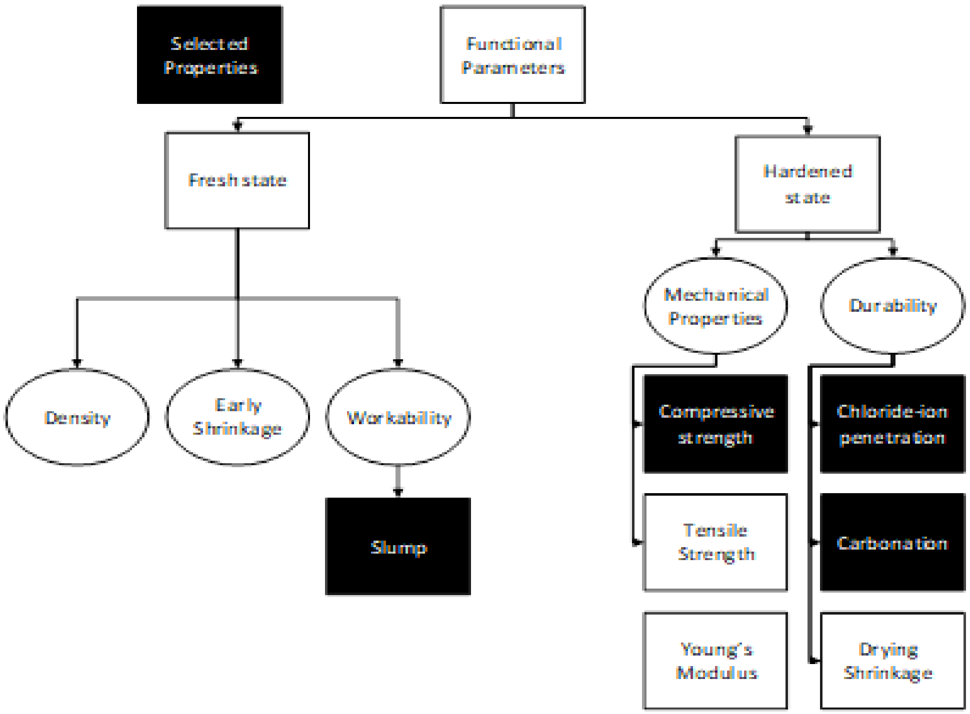


Figure 2.4: Selected concrete functional properties for the research scope

2.5.1.1. Workability

Workability is the ease by which fresh concrete can be casted, compacted and finished in the formwork for the intended shape. The more workable a concrete mix is, the easier it flows. Hence, self-compacted concrete (SSC); a special concrete with the highest workability is more suitable for use in heavily reinforced elements (Felekoglu et al., 2006). According to the BS EN 12350-2: standard, the slump of concrete is measured by measuring the distance from the top of the 300mm cone to the level of the top of the concrete cone. The concrete slump is hence divided into five classes as shown in Table 2.1.

Table 2.1: Concrete slump classes according to EN 206-01

Slump Class	**S1**	**S2**	**S3**	**S4**	**S5**
Slump (mm)	0-40	50-90	100-150	160-210	220-300

Workability could be attributed to the available free water in a concrete mix, which is dependent on the ratio between the volume of the paste and aggregates (Chandwani et al., 2015). This means that workability of concrete is a by-product of the selected mixing proportions rather than the type of concrete.

2.5.1.2. Mechanical Properties

As agreed, compressive strength is the main indication of a concrete mix's mechanical properties. According to Table 2.2, adapted from Kurda et al., 2019, there are four main strength classes of concrete each of which is a predecessor for the concrete use in a certain application. Another classification by the IS 456:2014 specifies that concrete with characteristic 28 days curing compressive strengths of 10-20 MPa are labelled as ordinary, 25-55 MPa as standard, 55-80 MPa as high strength while those with strengths higher than 80 MPa are labelled as ultra-high strength. A standard test to determine the 28 days compressive strength of concrete could be achieved following the BS EN 12390-3 standard.

Table 2.2: Concrete strength classes adopted from Kurda et al., 2019

28 days Compressive strength (MPa)	**Strength Class**	**Application**
<20	Low strength	Non-structural elements, kerbs and floor slabs.
20-30	Normal strength	Structural elements of "low to medium rise" buildings
31-50	High strength	Foundations and "small to medium" bridges.
>50	Ultra-high strength	Structural members of high-rise buildings and bridges.

The variables that define a concrete's compressive strength change depending on the type of concrete understudy. Except for AAC, hydration is the main chemical activation mechanism, which means that the water to binder (w/b) ratio is the main strength gaining control parameter (Felekoglu et al., 2006). In an **AAC** mix, matching the chemical composition of the activator and precursor is key in determining the compressive strength (Provis et al., 2017). The use of SP to decrease the w/b ratio at a fixed slump class would also increase strength (Sathyan and Anand, 2019). In high strength concrete, the quality of the used aggregates become the dominant parameter (Einsfeld et al., 2006). Therefore, the type, size and origin of recycled aggregates (RA) are the main controlling parameters of high strength **RAC** that determine the compressive strength (Silva et al., 2014).

In a **BCC** mix, pozzolanic reactivity of the SCM and % replacement of OPC determine the concrete compressive strength (Poon et al., 2000). Pozzolanic reactivity is the ability of the SCM to react with the portlandite present in the chemical phases from the hydration of the OPC forming further calcium silicate hydrate gel (Sim and Lee, 2015). The pozzolanic reactivity is dependent on the chemical composition, % of impurities in the SCM as well as its surface area (Hedayatinia et al., 2019). Given a fixed w/b ratio, aggregate type and mixing proportions, a **BCC** would generally have slower strength gain and lower 28 days strength than an OPC one (Poon et al., 2000). However, after 90 days of curing, it was found that **BCC** can have similar and higher strengths to OPC with replacements level up to 30 and 70% of FA and GGBS respectively (Oner et al., 2005; Bilim et al., 2008). It could then be concluded that depending on the concrete type, several variables of the concrete mix would determine its compressive strength. Let alone the curing temperature and relative humidity, which was proven to affect the strength of AAC massively (Shin et al., 2019).

2.5.1.3. Durability Properties

Service life of concrete is the time needed till it reaches the ultimate limit of deterioration under specific exposure conditions and upon which either repair or replacement is needed (Garcia-Segura et al., 2014). In plain concrete, water absorption is considered as the main indicator of the durability against deterioration mechanisms such as freeze-thaw and sulphate attacks (Nanukuttan.et al., 2017). In reinforced concrete, corrosion of the steel reinforcement is the main deterioration mechanism, which makes resistance to chloride penetration and resistance to carbonation the main indicators of durability (Tang et al., 2015). Typically, prescriptive codes and standards such as Euro Code 2 are used to ensure that the concrete mix is designed to have a service life of 50 to 100 years by defining deemed-to-satisfy ranges for variables of the mix such as maximum w/b ratio, minimum depth of cover and maximum OPC replacement depending on the aggressiveness of the environment as seen in Table 2.3. An example of the deemed-to-satisfy specifications of concrete against 100 years' service life at XC4 exposure conditions is shown in Table 2.4 (Greve-Dierfeld and Gehlen, 2016).

Table 2.3: Exposure class given in EN 206-1:2000

Exposure class	Definition	Example
XC1	Dry or permanently humid	Reinforced concrete under non-aggressive water
XC2	Humid, rarely dry	Reinforced concrete under non-aggressive soil
XC3	Moderately humid	Outer surfaces of reinforced concrete sheltered from wind-driven rain
XC4	Cyclically humid and dry	Reinforced concrete exposed to wetting/drying cycles

Table 2.4: Constraints for concrete durability against XC4 exposure according to (Greve-Dierfeld and Gehlen, 2016)

Exposure Class	Material Specifications			
	min. cement content (kg/m^3)	**maximum w/b ratio**	**type of cement**	**min. cover (mm)**
XC4	280	0.6	CEM I only	40

However, concrete structures designed according to these prescribed methodologies are suffering from major durability problems. The annual cost of repairing and replacing concrete due to corrosion worldwide was estimated at £1.7 trillion in 2010, which is about 3% of the world's gross domestic product (GDP) of £55 trillion (Alexander and Thomas, 2015). In 2011, the annual cost of repair and rehabilitation due to corrosion in the United Arab Emirates (UAE) was £10 billion, which is about 5.2% of their GDP (Alexander and Thomas, 2015). A consensus is reached in the literature that the reasons behind this inadequacy in the design methodology are: first, according to Markeset and Kioumarsi (2017), it is not flexible to accommodate for variable service life requirements (less than 50 and more than 100 years) and second, there is only a few codes recognizing emerging potentially sustainable concrete types such as AAC, BCC and RAC (Hooton and Bickley, 2010). Another reason is the climate change which renders the assumptions related to the exposure condition of the structures at the time of their design obsolete.

Hence, it has been a trend to shift towards performance based specifications. The term performance based is associated with a trend in specifying concrete durability called performance based specifications. The definition of performance based specifications given by the Canadian standard CSA-A23.1 is “A specification method in which the final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods. The processes, materials or activities used by the contractors, subcontractors, manufacturers and material suppliers are then left to their discretion” (Lobo et al., 2006). It would be long before performance based specifications for time dependant properties like concrete carbonation or chloride resistivity are as widely used as prescriptive specifications. However, prediction models such as DuraCrete and ClinConc (Tang et al., 2015), are able to predict the service life of a specific mix of concrete can be calculated, with uncertainties, against exact exposure conditions. This could pave the way for performance based specifications to be generalized in concrete construction.

The following review of the reported findings from the literature of durability properties of the concrete types studies within this PhD in a short summary. However, a more detailed review of the durability characteristics of each of the concrete types are explained in Chapters 4 and 5, which include the relevant case studies.

i. Chloride penetration

Chloride penetration is the primary mechanism for the corrosion of steel reinforcement in reinforced concrete. For the corrosion to be initiated, the chloride concentration at the steel-concrete interface should reach a maximum, which is described by a parameter called the chloride threshold (Garcia et al., 2013). The chloride threshold potential of a concrete mix is dependent on a set of exposure conditions such as temperature, RH and % of free chlorides as well as intrinsic variables such as the concrete type and w/b ratio (Lars-Olof et al., 1996). A standard test to measure the resistance of a concrete mix to chloride penetration is called Rapid Chloride Penetration Test (RCPT) according to ASTM C1202 – 18 (Mahima et al., 2018). The ranges in Table 2.5 set the limits for the chloride penetration resistance D_{nssm} of concrete measured through a RCPT and the corresponding quality class according to Kurda et al., 2019.

Table 2.5: Concrete classes against corrosion due to chloride penetration (Kurda et al., 2019)

D_{nssm} (10^-12 m^2/s)	> 15	15-10	10-5	5-2.5	< 2.5
Chloride ion penetration resistance	Low	Moderate	High	Very high	Excellent

In an attempt to attribute the difference in some of the aforementioned sustainable concrete types and the corresponding resistance to chloride penetration, the following review was done. Regarding RAC, the higher the integration of recycled fine aggregates, the less resistance (more D_{nssm}) concrete has to chloride penetration regardless of the binder content. However, in the presence of high volume FA in a BCC, the more recycled coarse aggregates there is, the higher the resistance of concrete is found (Kurda et al., 2018). It was found that regardless the source and type of the recycled aggregates, RAC has less resistance to chloride penetration than OPCC (Stambaugh et al., 2018). In BCC, more extensive review concerning the impact of different SCM types on concrete is done in Chapter 5, but generally BCC possess better resistance to chloride penetration than OPCC at similar water to binder ratios (Gettu et al., 2018). Regarding AAC, Ravikumar and Neithalath (2013) showed that resistance to chloride penetration in AAC is highly dependent on the % of silicon in the activator as well as the ratio of activator: precursor. Albeit, Provis et al., (2017) reviewed more than 100 papers related to AAC and outlined that the data provided for resistance to chloride penetration do not present a pattern at the current state that is large enough to form a conclusion. This means that the existing testing setups could be suitable for the nature of AAC and that not enough studies were done on the durability of AAC in general (Provis et al., 2017).

ii. Carbonation

Carbon dioxide from the environment reacts with the calcium hydroxide available in the exposed concrete to form calcium carbonate decreasing its alkalinity. This process, given a range of temperature and RH, decreasing the alkalinity of the concrete cover exposing the embedded reinforcement steel to corrosion with time (Marques et al., 2013). Reviewing the literature, it was apparent that the agreed method of calculating K_c, the carbonation rate of concrete, is to plot the carbonation depth versus the duration of exposure, then calculate the slope of the best fit curve (Van den Heede and De Belie, 2018). A more thorough analysis of the performance of BCC compared to OPCC in terms of carbonation is presented later in Chapter 5. Generally the replacement of OPC with 25% of FA or GGBS is expected to cause an increase in the natural carbonation for concrete cured for 28 days by a factor of 2.3 and 1.3 respectively (von Greve-Dierfeld et al., 2020). It is important to note that if the two samples under comparison were of the same concrete type, having a mix of lower w/b ratio or more curing time would have a higher resistance to carbonation (Silva et al., 2015).

2.5.2. *Quantifying environmental aspects*

The starting point of studying the sustainability of concrete is to create alternatives that reduce the environmental impact of OPCC (Guo et al., 2018). LCA is the most widely accepted tool to assess and compare these acclaimed environmental benefits (Anastasiou et al., 2015). According to ISO 14040:2006, LCA is defined as ‘the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle’. An LCA study is divided into 4 main stages: 1) Scope and goal definition, 2) Defining the inventory for the life cycle processes, 3) Characterising and measuring the life cycle impact and 4) Interpretation of results (Teh et al., 2017).

First, definition of goal and scope, which involves the system boundary, the functional unit selection and any assumptions and/or limitations that need to be considered. A system boundary of a concrete product could be Cradle-to-Gate, which means including all processes and emissions until the production of its different constituents or Cradle-to-Grave, which includes the “Use” and “End-of-Life” phases as per Figure 2.5 (Hafez et al., 2019). Many LCA studies opt for a Cradle-to-Gate system boundary due to the large uncertainties present in the remaining phases (Wu et al., 2014). A functional unit is the basis for quantifying the inputs and outputs between alternatives. Hence, its selection needs to be reflective of the nature of the LCA subjects (Panesar et al., 2017).

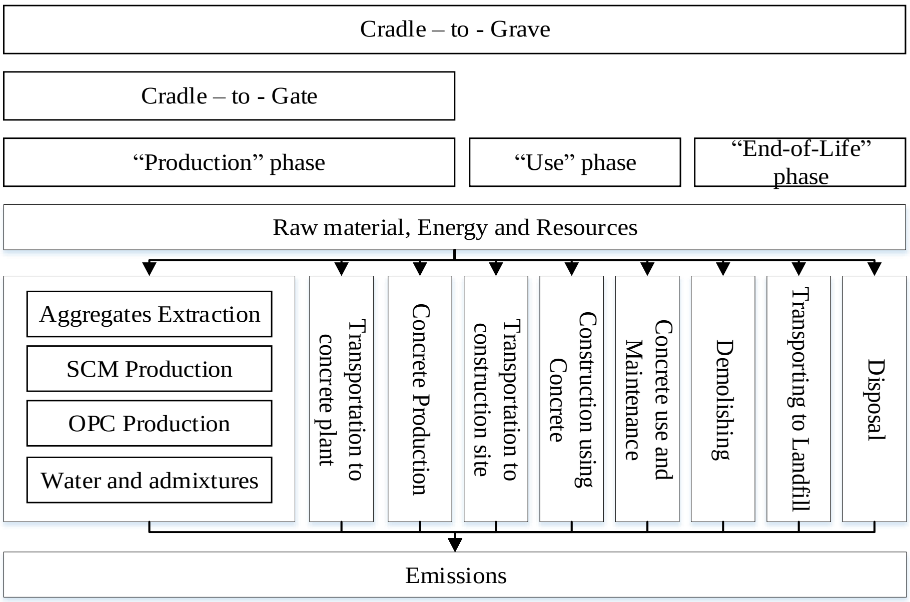


Figure 2.5: Different system boundaries of sustainable concrete LCA

The next LCA stage includes collecting the data of energy and emissions associated with the aforementioned scope. The data needed for standard processes can mostly be found in databases such as Ecoinvent and ELCD (Sagastume Gutierrez et al, 2017). Another source of inventory data is the environmental product declarations (EPD) of the concrete raw materials, which are produced by the local manufacturers according to a local legal framework (Wu et al., 2014). Another important parameter to decide at this stage is the allocation, which is basically portioning the environmental burden of the original process to the product under study (Marinkovic et al., 2017).

The third and final stage of an LCA is to calculate the environmental impact of the studied product. This is performed by adding up the individual impacts of all the associated processes to calculate an environmental impact indicator; a number that makes the output of the impact assessment study more understandable to the user (Bjorn et al., 2015). According to Menoufi (2011), there are two main types of indicators: mid-point indicators, which correlates the calculated impact to a specific change in the environment such as global warming potential and end-point indicators, which correlate the same increase to a further on damage in the cause-effect change such as human health.

In an attempt to compare the absolute values for the environmental impact of alternative concrete types to that of OPCC, a review of around 300 different mixes from 30 journal papers (Appendix A) was done. As seen in Figure 2.6, large discrepancies were found in the reported data. Using the most predominant environmental impact indicator Global Warming Potential (GWP), the impact per unit volume of the concrete mix varied between 84 and 609 kg eq CO_2/m^3. Huijbregts (1998) attributes these large discrepancies to the uncertainties involved in the current use of LCA methodology. Hafliger et al. (2017) claim that the source of these uncertainties is modelling choices by the user of the system boundary, functional unit and source of data. On the other hand, Menoufi (2011) differentiates between the uncertainties due to the nature of the inventory data used and those from choices such as the impact allocation and functional unit. The first affects the accuracy of the results, while the latter affects the reliability of the study.

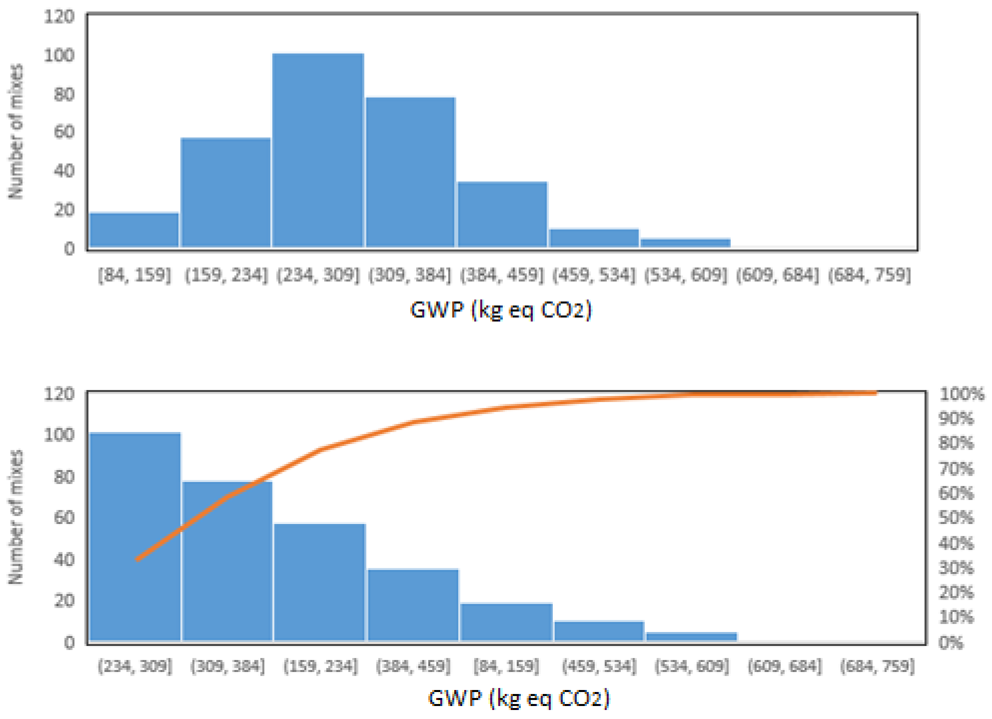


Figure 2.6: A review of the values for the equivalent CO_2/m^3 of 300 concrete mixes from the literature

In order to investigate the sources of the discrepancies in a concrete LCA and aiming to clarify the difference between reliability issues and uncertainties, a systematic review was done using EThOS, Google scholar, SCOPUS, Science Direct and Research Gate as online databases. The keywords were a combination of "LCA" and "concrete" and the 102 peer-reviewed articles published between 2008 and 2018 were filtered based on relevance to the topic in hand. Figure 2.7 shows meta data about the reviewed papers, the journal's title, country of origin and the year of publication. The latter indicated a growing interest in the studies around the environmental impact of concrete.

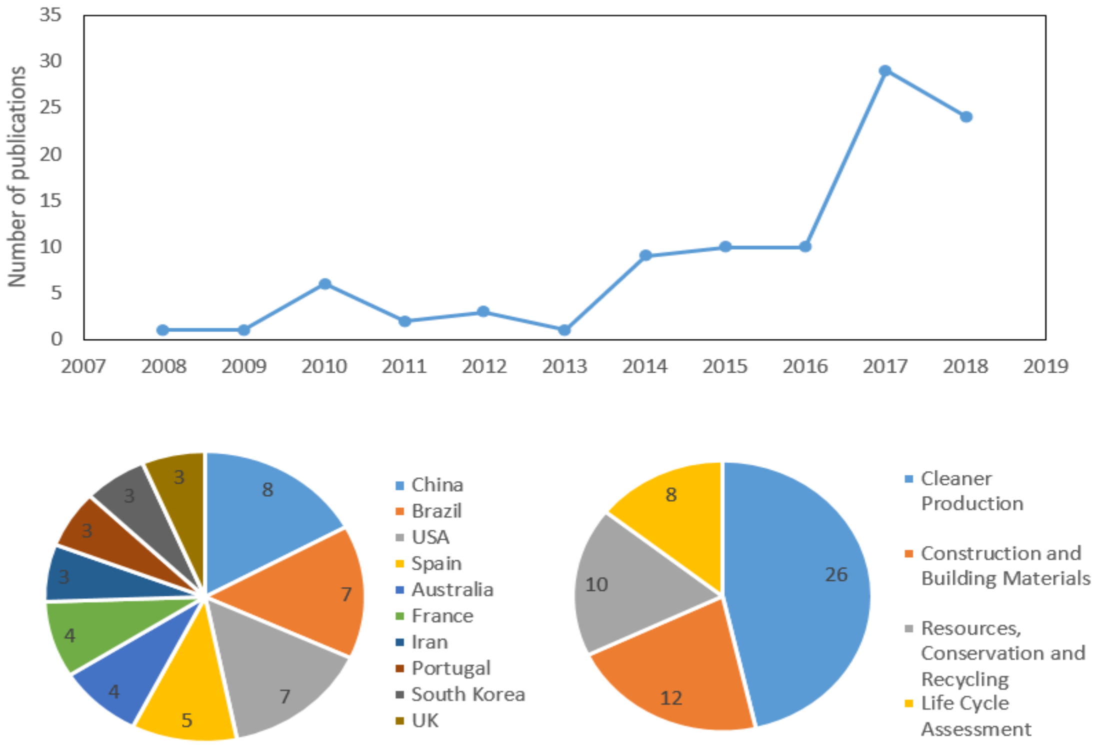


Figure 2.7: Meta data about the year of publication, journal and origin of the 102 papers reviewed

2.5.2.1. LCA scope

More than 50% of the surveyed papers that explore the environmental impact of a concrete alternative (18 out of 33) used a Cradle-to-Gate system boundary. As agreed, a Cradle-to-Gate system boundary would limit the scope of the processes and resulting emissions and energy studied in the LCA up until the production stage, excluding the use and end-of-life stages. As opposed to the ISO 14044, which presents general guidelines for an LCA, the ISO 24067, released in 2013, aims at providing more details to the LCA process to enhance the credibility of LCA results. As stated by Wu et al. (2014), the ISO 24067 specifies that for an LCA to exclude the use and end-of-life stages, there needs to be enough evidence that it this will not have enough influence on the results. Hence, it would not be acceptable to cut-off the use and end-of-life phases from a concrete LCA scope due to the following reasons:

i. A justifiable cut-off percentage is when the processes affect less than 1% of the total environmental impact according to Wu et al. (2014) and 5% according to Gursel et al. (2014). However, through the carbonation process concrete can absorb, throughout its whole service life, 13-48% of the carbon dioxide it emitted during the production phase (Collins et al., 2010). This value of captured carbon dioxide, denoted as sequestered carbon, varies depending on the concrete type. OPCC can capture up to 47% of its embodied carbon during use and end-of-life phases while BCC can capture only up to 22% (Garcia Segura et al., 2014). In both cases, it is apparent that the sequestered carbon ought to be included in an LCA study unlike most LCA methodologies followed in the literature.

ii. By omitting the use phase, the user is assuming that all concrete mixes being compared will sustain the required service life. However, in line with the established differences in the durability performances of several alternative concrete types in section 2.5.1.3, the Table below shows proof from the literature that this assumption is not true.

Table 2.6: A review of the predicted service life of several BCC mixes from the literature

OPC (%)	**FA (%)**	**GGBS (%)**	**SF (%)**	**Cover (mm)**	**Deterioration mechanism**	**Service Life (years)**	**Author**
100				50	Chloride penetration	24	Van Den Heede et al. 2017
85	15					51	
50	50					60	
50	40		10			185	
75		25				138	Panesar 2010
50		50				200	
100				35	Carbonation	100	Van Den Heede et al. 2017
65	35					100	
50	50					100	
35	65					10	
75		25				200	Panesar 2010
50		50				200	

iii. Having an end-of-life phase included in the LCA system boundary is a prerequisite to studying RAC. De Schepper et al. (2014) assumed that the aggregates used in a concrete mix are fully recyclable, which means that there is no environmental impact for landfilling it. By selecting a Cradle-to-Cradle system boundary, it was calculated that the use of fully recyclable concrete reduces the environmental impact compared to OPCC by 4-15%. A Cradle-to-Grave system boundary was selected by Ding et al. (2016) to assess the environmental impact of CDW based RAC compared to OPCC. The result was that the environmental indicator CMR, which measure the consumption of natural resources decreased by 46%.

The second part of the scope definition of a LCA is determining a functional unit. A FU is the parameter responsible for adjusting the quantification of the environmental impact between the products in an LCA (Dobbelaere et al., 2016). Most of the FU found in the literature that uses to assess the environmental impact of sustainable concrete versus OPCC can be classified into the following three main categories:

i. Simple Functional Units

These are mass or volume based FU that compares a simple unit (1 kg or 1 m^3) of an OPCC to the same unit of a sustainable concrete. A mass based FU is more suitable in comparing raw materials of a concrete. For example, Huntzinger and Eatmon (2008) used a FU of 1 kg to measure a 5% reduction in the environmental impact of OPC production due to the use of recycled cement kiln dust. Cheng et al. (2018) also used a FU of 1 kg to show that the use of chromium-based slag as an SCM would cause a 6% reduction in GWP compared to GGBS. On the other hand, Tait and Cheung (2016) used a FU of 1 m^3 when measuring the environmental impact of BCC containing 35% FA or 70% GGBS. The results for the GWP were 339 kg eq CO_2/m^3, 227 kg eq CO_2/m^3 and 127 kg eq CO_2/m^3 for OPCC, FA-BCC and GGBS-BCC respectively (Tait and Cheung, 2016). Ding et al. (2016) and Kleijer et al. (2017) also used a 1 m^3 FU to reach a conclusion of a minimal reduction (3-5%) in environmental impact of RAC compared to AAC. However, these impact calculations were based on an assumption that both concrete types being compared possess the same functional properties and hence are able to achieve the same function using a unit volume. As agreed in the section aforementioned, this is not true for most cases depending on the exposure conditions, mix design and type of concrete. Hence, simple FU are seen as the least accurate in quantifying the environmental impact of OPC concrete compared to a sustainable concrete one. Panesar et al. (2017) claims that it is not accurate to call a unit volume a functional unit since it is not indicative of enough comparable functional properties. It should be called a declared unit instead (Panesar et al. (2017). According to Sagastume-Gutiérrez et al. (2017), the comparison between the environmental impacts of two construction materials can be reliable, only after considering the combined effects of mechanical and durability characteristics.

ii. Complex Functional Unit - Mechanical Properties

A work around the simple FU is to include the mechanical properties of the mix under study in the calculation. Chiaia et al. (2014) came up with a FU that divides the unit volume of concrete by compressive strength, flexural strength, tensile strength and creep. However, the ability to predict or test all these parameters would prove challenging. Instead, Fan and Miller (2016) used 28 days compressive strength to show that a more efficient mix would achieve the highest compressive strength causing the same environmental impact. In an attempt to verify that some of the communicated environmental benefits of sustainable concrete in the literature are misleading, the following investigation was done to show how changing the FU would alter the outcome of an LCA study for each concrete type:

- RAC: Maintaining the same binder, replacing fresh aggregates with coarse and/or fine recycled aggregates from CDW will decrease the strength of the resulting mix (Yazdanbakhsh et al., 2018). Hence, as shown in Figure 2.8, when the data from Kurda et al. (2018) was drawn for a FU of kg eq CO_2/MPa instead of kg eq CO_2, the impact was larger than that of OPCC not less.

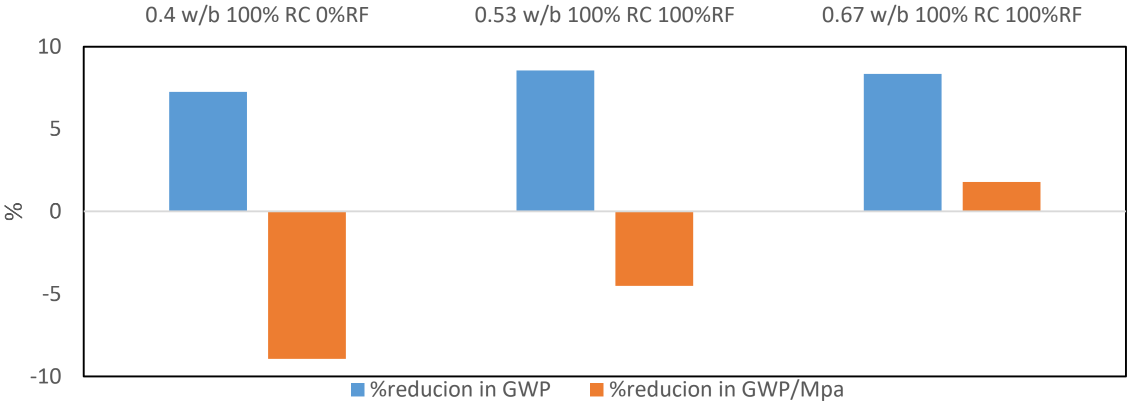


Figure 2.8: A comparison between the impact of RAC using volume based FU and a FU normalized to strength (Kurda et al., 2018)

- BCC: The results from Celik et al. (2015) suggest that the optimum replacement of OPC with FA in a BCC mix is 70%. Considering only a unit volume FU, the less OPC would mean less environmental impact for the resulting concrete. However, as agreed in section 2.3.1, adding FA beyond a certain threshold would decrease the compressive strength. As seen in Figure 2.9, when the same GWP results were modelled using a FU of kg eq CO_2/MPa, the optimum replacement % dropped to only 40%. Less gap between both FU results were found when examining the results for GGBS from Bilim et al. (2009).

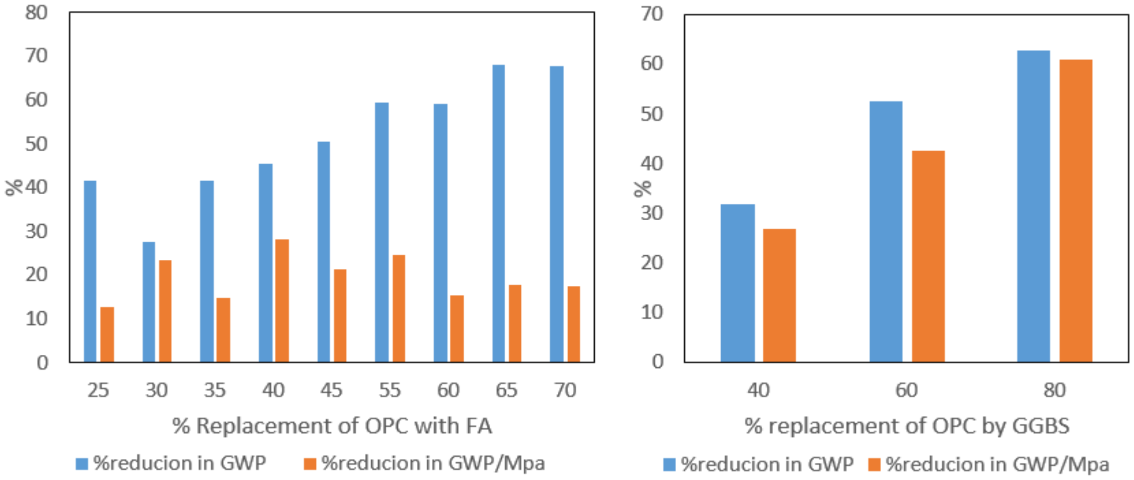


Figure 2.92: A comparison between the impact of FA based BCC (left from Celik et al., 2015) and GGBS based BCC (right from Billim et al., 2009) using volume based FU and a FU normalized to strength

- AAC: In the four papers that were examined for AAC results (Habert., 2011,; Markovic et al., 2018; Robayo-Salazar et al., 2018; Salas et al., 2018), it was found that the mixes were designed initially to achieve the same target compressive strength. Hence, even though the FU used was only volume based, the same environmental gains against the use of OPC prevailed when using a complex FU based on compressive strength as shown in Figure 2.10.

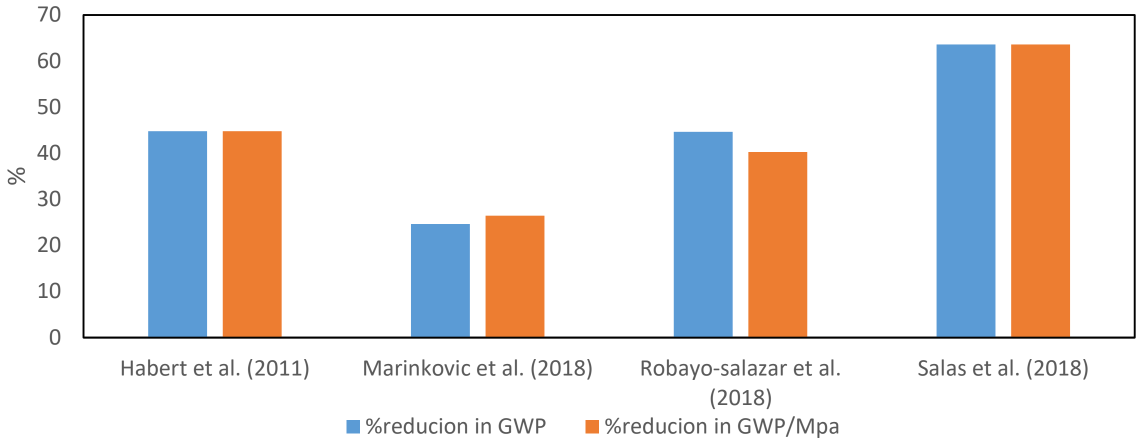


Figure 2.10: A comparison between the impact of AAC using volume based FU and a FU normalized to strength

It is apparent that including the mechanical properties in the FU of the LCA would enhance the reliability of the LCA results. However, according to Mahima et al. (2018), premature concrete deterioration, due to carbonation and chloride penetration, is responsible for US$ 2.2 trillion, which is equivalent to 3% of the world's gross domestic product (GDP). Thus, durability of concrete is an essential factor that needs to be included when LCA of reinforced concrete is carried out.

iii. Complex Functional Unit - Durability Properties

Panesar et al. (2017) defined a functional unit where the volume of the BC concrete is multiplied by its compressive strength and the chloride ion penetration resistance, and compared to the FU of an equivalent OPC concrete. Celik et al. (2015) and Kurda et al. (2018) used experimental data of the different BC concrete mixes in terms of compressive strength and chloride penetration to compare the performance of BC concrete with OPC concrete. Souto-Martinez et al. (2017) included accelerated carbonation test result for OPCC in the FU for a whole building to correct the calculated environmental impact results. However, in order to for the absolute environmental impact values to be credible, these durability properties need to be translated into the service life to describe a performance parameter of concrete (Sagastume-Gutierrez et al., 2017).

Van den Heede and De Belie (2010) accounted for a 100 years timeframe as the service life of concrete, but only carbonation was used to determine the service life and the compressive strength was left out. Sagastume-Gutierrez et al. (2017) devised a FU that divides the volume of cement by the number of years of durability from both chloride penetration and carbonation. Furthermore, an accurate methodology was proposed by Gettu et al. (2018), where the test results of thirty different BC concrete mixes were incorporated into a FU (A-indices) that converts carbonation and chloride penetration parameters into expected service life predictions. However, in all of the aforementioned, concretes with more than 100 years of durability will have a better environmental impact using both indices, while the specified service life for the mix is only 100 years. The same applies to compressive strength. Not capping the performance nor the durability of the concrete understudy, though maximizes the sustainability potential according to Muller et al. (2016), impinges upon the performance base specifications of concrete. Instead, performance based specifications, are the core of concrete sustainability (Hooton and Bickley, 2014).

2.5.2.2. Inventory Data

The second source of uncertainties and unreliability in LCA results after the scope definition is life cycle inventory (LCI). This is the data collection stage, in which the input and output factors, including energy, raw materials, products, and waste, are analysed for the LCA of concrete. The LCI for a concrete mix mainly include: 1) upstream processes: those involved in the production of each of the constituents and its transportation till the concrete production plant, 2) core processes which involve the energy and emissions required for mixing concrete and transportation to site, and 3) downstream processes needed for the demolition or any other end-of-life scenario (Wu et al., 2014). LCI data is a major contributor to the uncertainty in a concrete LCA study due to the following:

i. There are no standards to where and how to get LCI data for a concrete LCA. Anand and Amor (2017) stated that concrete inventory data could come from three sources: primary data from the building industry to which the user has access, accredited environmental databases such as EcoInvent, GaBi and EuGeos or EPDs. EPDs are standardized documents to communicate the environmental performance of a product (Del Borghi, 2012). Although EcoInvent and GaBi are updated annually to reflect any changes in the inventory data included, Hafliger et al. (2017) suggest that the priority in the source of upstream processes of a concrete mix is for EPDs and in the case of several EPDs, an average should be taken. The reason is that EPDs are done in accordance with the same process, an LCA, under the guidance and supervision of local authorities such as the BRE in the UK. This would contribute to standardized processes and more efficient error tracking methods in concrete LCAs. Looking at the 40 papers in this systematic review, only 20% used primary data, the rest used EcoInvent and GaBi, while only 2 used EPDs.

ii. Apart from the reliability issue of the choice of the suitable source of LCI for the data, the existing data in each of the LCI sources contain large uncertainties. Looking into the 25 papers in this systematic review scope that opted to use primary data for LCI, the GWP of OPC was found to vary between 550 kg eq CO_2/ tonne and 1750 kg eq CO_2/ tonne as shown in Figure 2.11. The reason could be that the OPC production process is different in efficiency between one producer and the other (Huntzinger and Eatmon, 2008). Also, the fact that upstream process for OPC production depend on the electricity mix of the country of origin. For example, in the US, about 8% of the OPC used is imported and the upstream inventories of the imported clinker specific to the country of origin, as well as the energy consumed in transporting the OPC to the US, would increase the resulting impact of the OPC than the local alternatives (Gursel et al., 2014). The electricity mix in China almost has twice the environmental impact as that of Malaysia, Indonesia and Thailand for example due to the higher dependency on fossil fuel in electricity generation (Gursel et al., 2016). In all cases, the variability in the upstream impact of OPC is crucial due to the directly proportional relationship between the OPC content in a mix and the resulting concrete GWP. This was established by analysing the data from 300 concrete mixes as seen in Figure 2.12.

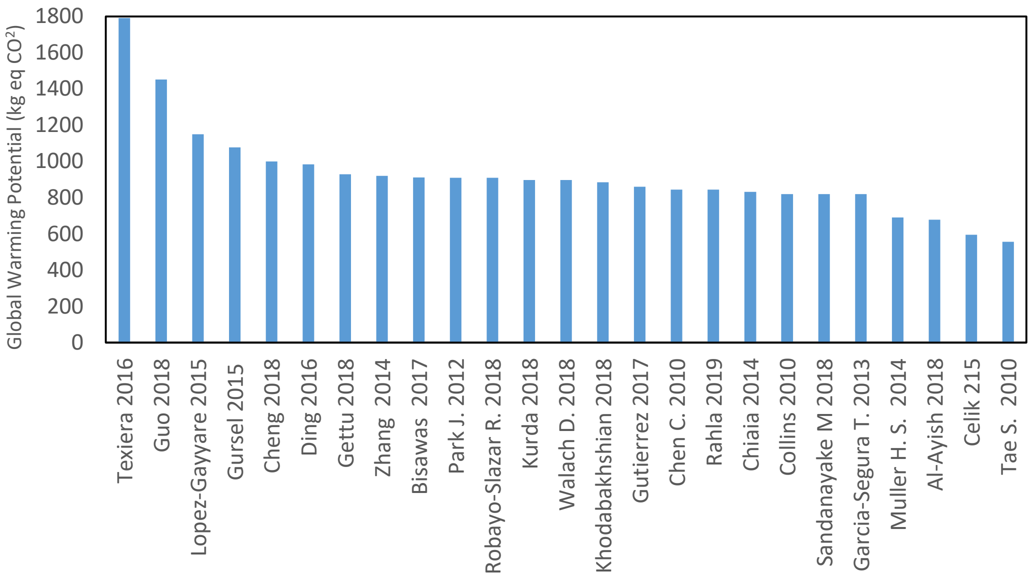


Figure 2.11: A review of the reported GWP of a tonne of OPC from 25 papers

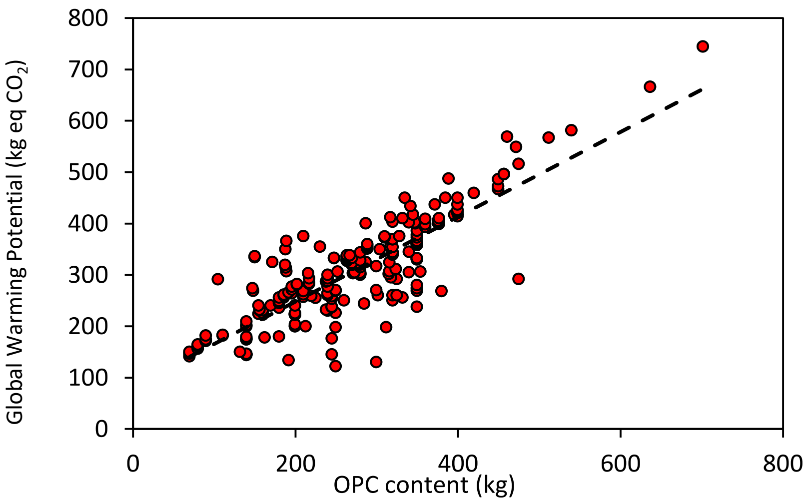


Figure 2.12: A graph correlating between GWP of 300 concrete mixes from the database in Appendix A and OPC content

iii. Another vital source of error in a LCA study that is linked to the inventory data is the impact allocation. Impact allocation is the process of portioning the environmental burden of the original process to the waste material being recycled in the product under study (Marinkovic et al., 2017). According to the EU directive 2008, waste can be considered a by-product when (i) its further use is certain, (ii) it is produced as an integral part of a production process, (iii) it can be used without any further processing other than normal industrial practice, and (iv) its further use is lawful (Chen et al., 2010). All four points apply to FA, GGBS and SF hence they should be considered as by-products not as waste. This entails including a percentage of the environmental burden of their original production process, which are coal combustion, steel production and glass manufacturing respectively (Anastasiou et al., 2015). The first impact allocation scenario is “Mass allocation” where the percentage allocation is based on the relative mass between the waste material as a by-product and the mass of the total (the effective mass of electricity + the mass of fly ash) as shown in Equation 2.1. The second scenario is “Economic allocation” in which the percentage allocated is based on the relative market value between the final product, which is FA and electricity as per Equation 2.2 (Chen et al., 2010).

$$\boldsymbol{Mass\ Allocation} \quad = \frac{(\boldsymbol{m})_{by-product}}{(\boldsymbol{m})_{main\ product}+(\boldsymbol{m})_{by-product}} \tag{2.1}$$

$$\boldsymbol{Economic\ Allocation} = \frac{(€.\boldsymbol{m})_{by-product}}{(€.\boldsymbol{m})_{main\ product}+(€.\boldsymbol{m})_{by-product}} \tag{2.2}$$

Upon reviewing the literature, it was found that out of 33 exploratory LCA studies of concrete involving SCMs, only 20% of the LCA studies included an allocation scenario. Furthermore, all of them either used or recommended an economic allocation since it is usually a lower number the mass allocation, which allows the results to be positive relative to OPC. However, fluctuation of market prices means that each LCA model would have its own value of the economic allocation. It remains a debate as to which allocation scenario is more accurate, but there is an agreement that if an SCM is involved, there needs to be some impact allocated.

2.5.2.3. Impact Assessment

The third stage of an LCA is the assessment of the impact of the concrete mix by simply multiplying the functional unit by the aggregates impact of the concrete from the 3 life phases. As seen in equations 2.3 and 2.4, the emissions and energy use are calculated by adding up all the emissions and energy use of the products and processes involved in the production, use and end-of life stages.

$$\textbf{Total emissions for mix } (\mathbf{x}) = \mathrm{FU_x} \times \textstyle\sum_{n=1}^{3} \text{emissions of all products and processes of stage n} \tag{2.3}$$

$$\textbf{Total energy use for mix } (\mathbf{x}) = \mathrm{FU_x} \times \textstyle\sum_{n=1}^{3} \text{energy use of all products and processes of stage n} \tag{2.4}$$

Contextualizing these information about the concrete mix understudy, an environmental impact indicator is needed. An impact assessment method is vital to produce judgements on the severity of the impact of concrete on the three main areas of protection: 1) ecosystem quality 2) human health and 3) natural resources (Menoufi, 2011) This is done through three steps: characterization of the impact, which is a must-do, then normalization and weighing, which are both optional (Zhang et al., 2017). According to Sayagh et al. (2010), there are two main types of indicators: mid-point indicators, which correlates the calculated impact to a specific change in the environment such as global warming potential and end-point indicators, which correlate the same increase to a further on damage in the cause-effect change such as human health. The significance of this differentiation is that the same comparison between products or processes could result in different scores if looked upon by a mid-point or an end-point indicator, due to the exaggeration of damage that happens to reach the latter (Maia de Souza et al., 2016). Hence, it could be concluded that, in line with the aforementioned sources of error, opting for an end-point indicator rather than a mid-point one would be a reliability issue resulting from users' choices. However, even with mid-point indicators, which are the most popular in the literature, there is a reliability issue in the use of mid-point indicators in concrete LCA studies. There are two famous mid-point approach methods: CML and TRACI. CML was developed in 1992 by the Institute of Environmental Sciences of the University of Leiden and it contains indicators such as: depletion of abiotic resources, land competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic Ecotoxicity, marine aquatic Ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, acidification and eutrophication. TRACI, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts, was prepared by the US Environmental Protection Agency's (US EPA's) National Risk Management Research Laboratory in 2003. It uses indicators such as: ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health non-cancer, human health criteria pollutants, eco-toxicity, and fossil fuel depletion. Within the scope of this systematic review, it was found that more than half of the studies used global warming an indicator which is a limiting judgment. For example, although AAC has 50-70% less GWP than OPC, it has 10 times more the human toxicity, fresh water ecotoxicity and ozone layer depletion (ODP) due to the use of sodium silicate and sodium hydroxide as an alkali activator (Habert et al., 2011). However, as stated by Passuello et al. (2017), the ODP impact of a kg of cement is already insignificant when contextualized to the greater environmental ecosystem since it is similar to those emitted by a single lamp operating for three years. Nevertheless, it would add to reliability of the LCA results of concrete to not depend on GWP only, but rather three or four other mid-point indicators.

2.5.3. *Quantifying economic aspects*

The cost of construction materials is the second most influential factor (after functionality) in the decision-making process regarding selection of alternatives (Kurda et al., 2019). A simple way of quantifying the economic burden of concrete is to calculate its market price and compare it to the other alternatives using equation 2.5 (Zhang et al., 2014):

$$\text{Cost of concrete alternative per unit volume }(x) = \sum_{Y=1}^{n} \text{mass of constituent Y per unit volume} * \text{price of Y per unit mass} \tag{2.5}$$

Assuming the market price of concrete is not always known possibly because it is an innovative material, Wang et al. (2017) suggested that equation 2.6 is used instead:

$$\text{Cost of concrete alternative} = \text{Cost of energy in concrete preparation} + \text{Cost of raw materials production and transportation} \tag{2.6}$$

The scope of the systematic review for the concrete LCA included 10 papers with market prices (£/unit) for 10 different concrete constituents. As expected, there are some fluctuations in the reported market prices depending on the year and country of origin as shown in Table 2.7. Unlike LCA data, these fluctuations are not necessarily a by-product of user choices or data anomalies, but rather the ruling demand and supply state of the market. Hence, it is advised to create a more comprehensive library of the market prices of the relevant products, which is updated periodically to educate the users about the economic aspects of the concrete under study. Albeit, market prices would only be suitable for a Cradle-to-Gate scope of a LCA, which was agreed as not being reliable when studying concrete. Hence, it is better to create an overlap between the service life and its cost by performing a life cycle cost analysis similar to what Navarro et al. (2018) did in comparing alternatives for a concrete bridge. This overlap between the functional aspects and economic aspects could also be achieved by multiplying the market price by the replacement factor proposed by Hafliger et al. (2017) which captures the number of times a concrete alternative would need to be replaced to fulfil the required service life. However, in all these futuristic economic assessment models, it is assumed that the prices of concrete would stay the same in the future relative to the inflation rate, which is not necessarily true. Hence, it would be advisable to include the potential difference in the forecasted market prices and inflation rates in the calculation of the economic indicator of the concrete alternative understudy. There is also an established overlap between the economic and environmental aspects of concrete in terms of economic allocation. If the user opts for an economic allocation scenario for the recycled components of the concrete alternative, the price of the original product as well as the other by-products from the same process would need to be determined.

Table 2.7: A review of the market prices for some sustainable concrete constituents from 10 papers

Paper	Country	Cement	NA Coarse	NA Fine	Water	FA	GGBS	SF	SP
Chen C. (2010)	France					20	40		
Gursel (2015)	USA							890	
Jiang (2014)	USA						74		
Khodabakhshian (2018)	Iran	100	10	10				500	4500
Li (2015)	China						20		
Navarro (2018)	Spain	88	16	14		38		1140	1380
Park (2012)	South Korea	78	31	31	7.8	33	41		62
Seto (2017)	Canada					107			
Teh (2017)	Australia					30	88		
Wang (2017)	China	40	6	4	3.2	10			265
Yuan (2017)	China	100	5.5	6.5					1700
Zhang (2014)	China	58	7	9	0.58	9			580
	Average	**77.3**	**12.6**	**12.4**	**3.9**	**32.6**	**44.5**	**843.3**	**1414.5**
	St. Dev.	**24.1**	**9.8**	**9.7**	**3.7**	**29.6**	**29.1**	**322.5**	**1640.1**

2.6. Research gaps

From the literature findings, it is apparent that:

1) There is a gap in the specifications and legislation side when it comes to the implementation of sustainable concrete strategies because there are only two theoretical decision support frameworks for concrete selection on sustainability basis. Nevertheless, a new framework is needed to build on the following identified missing elements in the existing frameworks:
    a. Methodology: The framework should include sequestered carbon as an overlap between functional and environmental aspects, the concrete replacement ratio as an overlap between functional and economic aspects and economic impact allocation as an overlap between economic and environmental aspects.
    b. Functional properties should be allowed to be predicted using models and opt to be capped to a threshold represented by the project specifications in order to achieve a performance based specification.
    c. When calculating Environmental Indicators through an LCA, it was established that:
        i. A Cradle-to-Grave scope is required.
        ii. If an SCM is being used, impact allocation is a necessity.
        iii. Primary inventory data should be prioritized.
        iv. Communicate impact assessment through several mid-point indicators.
    d. When calculating Economic Indicators, there is a need to include the total cost of the alternative including transportation, landfill taxes and if available carbon taxes. The difference between the inflation rate and the expected changes in the cost of goods need to also be considered to attribute the time value of money.
2) There are several promising concrete types that could potentially be more sustainable than concrete such as AAC valorising materials with low recyclability such as EAFS or BCC utilizing a combination of SCMs. Hence, there is a need to explore the sustainability index of these materials using the newly developed assessment framework.

Chapter 3

Developing the ECO_2 sustainability assessment framework

3.1. Introduction

Sustainability, in general, is a multi-faceted notion that outlines the nature and impact of human activity on the current and future means of life (Panesar et al., 2017). The literature review in Chapter 2 concluded that there is a growing emphasis on including sustainability as an element in policy making (Miller et al., 2016). The classical definition of sustainability dictates a combination of the environmental, economic and social aspects of the subject matter (Suarez Silgado et al., 2018). Hence, a typical sustainability assessment model should include one of more of these aspects to judge the sustainability of a certain product (Cinelli et al., 2014).

A multi-criteria decision analysis (MCDA) methodology is the main decision support technique used to evaluate alternative(s) based on a set of indicators to judge their sustainability (Wang et al., 2017). A MCDA methodology follows a standard process starting with the problem definition, then the parameters used for comparison and then assessing the studied alternatives using these parameters to help the user make a decision. Within the construction sector, the future carries alarming environmental hazards due to concrete production (Gursel et al., 2016). As established, conventional concrete, consisting primarily of OPC, is a primary contributor to waste and carbon dioxide emissions globally (Al-Ayish et al., 2018). Although several solutions are being studied and implemented to make concrete more sustainable, there is still no agreed measure to assess concrete sustainability (Kurda et al., 2019). To overcome the above issue, this chapter aims to develop and propose a new concrete sustainability framework under the title "developing ECO_2: A performance based ecological and economic framework for sustainability assessment of concrete". The chapter starts with defining the problem, which is the absence of a reliable method to quantify how sustainable a prescribed concrete mix is. Then, by following through the typical components of a MCDA, the gaps in the existing concrete sustainability frameworks from the literature are identified (section 3.2). Then, the newly developed ECO_2 framework is presented based on the gaps in existing frameworks (section 3.3). The final section (3.4) includes the proposed methods for the framework validation.

The contents of this chapter were published in the 292nd volume of the “Cleaner Production” journal on 10th April 2021 under the title “A whole life cycle performance-based ECOnomic and ECOlogical assessment framework (ECO_2) for concrete sustainability”. The paper included the following authorship responsibilities, conceptualization (Tatiana Garcia-Segura, Nadia Al-Ayish, Wai Ming Cheung, Brabha Nagaratnam, and Rawaz Kurda), data collection, data analysis, data interpretation, and writing the paper (Hisham Hafez), and revision (Tatiana Garcia-Segura, Nadia Al-Ayish, Wai Ming Cheung, Brabha Nagaratnam, and Rawaz Kurda).

3.2. Existing Concrete Sustainability Assessment Frameworks

Across the literature, several frameworks were found that used MCDA methodology for concrete sustainability assessment based on two or more pillars. In 2004, Lippiatt and Ahmed published a framework called BEES: Building for Environmental and Economic Sustainability (Lippiatt and Ahmed, 2004). After that, several researchers developed a Methodology for the Relative Sustainability Assessment of Residential Buildings (MARS-H, from the Portuguese acronym), which is another binary MCDA framework that combines economic and environmental indicators (Braganca et al., 2010). The latter was further developed to suite concrete, among other building materials, into the Method for the Relative Sustainability Assessment of Building Technologies (MARS-SC) (Mateus et al., 2013). Rahla et al. (2018) modified the MARS-SC framework to include the performance of concrete as a third pillar to concrete sustainability. Recently, another MCDA framework was developed at the Instituto Superior Técnico in Lisbon combining the environmental, economic and performance indicators of concrete, “CONCRE*Top*” (Kurda et al., 2019). Throughout the next section, the two distinguished frameworks namely MARS-SC and CONCRE*Top*, are compared against each of the components of a typical MCDA and the gaps found in them are presented.

3.2.1. Step 1: Define scope

3.2.1.1. Level 1

The goal of both MARS-SC and CONCRE*Top* is the same; to assess the sustainability of concrete. A MCDA sustainability assessment framework is typically divided into three levels as shown in Figure 3.1, the first being the sustainability index, the second represents the pillars of sustainability and the last are the indicators used to quantify each pillar (Tosic et al., 2015).

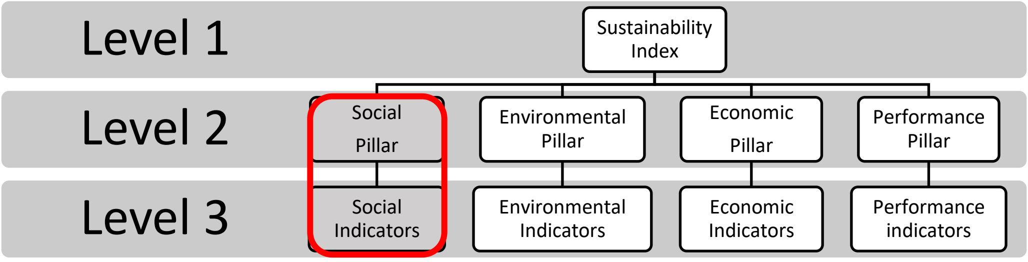


Figure 3.1: A schematic of the three levels of a typical MCDA framework scope omitting the social pillar

3.2.1.2. Level 2

Contrary to the famous triple bottom line (Social, Economic and Environmental) sustainability assessment scope agreed in the literature; most frameworks ignore the Social impact pillar. The social pillar is more popular among frameworks related to construction works in which different methods of construction would influence social indicators such as job creation and/or willingness to pay (Wang et al., 2017). However, the scope of both frameworks understudy is the sustainability of concrete as a building material. Therefore, as seen in Figure 3.1, the social pillar is considered as out of scope.

In exchange, MARS-SC and CONCRE*Top* added the "performance" of concrete alternatives as a third pillar of sustainability. As established in the literature, the extensive use of concrete in infrastructure is mainly due to its ability to fulfil in-service requirements such as constructability, strength and durability (Gettu et al., 2018). That is the reason that performance related parameters usually serve as the principal basis for concrete selection rather than environmental impact or cost (Alexander and Thomas, 2015). Hence, it is necessary to include a measure of performance, which is referred to in the MARS-SC framework in Figure 3.2 as the functional pillar (Miller et al., 2018).

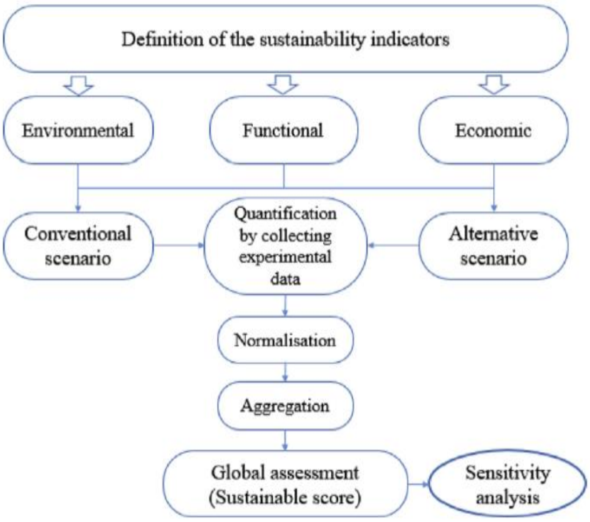


Figure 3.2: The MARS-SCMCDA framework for concrete sustainability assessment (Rahla et al., 2019)

3.2.1.3. Level 3

The third level is concerning the selected indicators for the assessment of each of the pillars. According to Mace et al. (2007), a sustainability indicator is key to the reliability of a MCDA and it should be suitable for communicating the objectives of the framework to the intended stakeholders. The calculation process of the sustainability index in both frameworks under study is the same. The environmental indicators are summed up into a single environmental indicator, as well as the functional and economic ones. The sustainability index is calculated through adding the score of all three impact categories: functional, environmental and economic. In both frameworks, this is done through a "additive-aggregation" process which means that each pillar is assigned a different weight by the user and the final sustainability index score is the weighted averaged of the individual scores.

This logic follows a compensatory rationality where, for example, an alternative x could have an overall higher sustainability index than alternative z although it had a lower environmental and economic score. The reason could be that the former scored a higher functional impact with a large enough margin than the latter that it overtook the difference in the two other pillars. However, the reason could also be that the user assigned a bigger weight to the functional indicator which enhances the slight advantage in the functional performance of alternative x compared to z.

3.2.2. Step 2: Define alternatives

In order to compare between different concrete alternatives, it is required for the user of any of the MCDA frameworks to define them. Defining a concrete alternative is done by specifying the mixing proportions of each of the constituents used in each mix. The first research gap identified in the existing frameworks is the absence of scenario analysis. As discussed in chapter 2, assuming different scenarios is vital to tackle the uncertainty in LCA of concrete. Possible scenarios include fluctuating market prices, project specifications and the weights assigned to indicators.

3.2.3. Step 3: Define LCA system boundary

The methodology used to study the economic and environmental impact is life cycle assessment (LCA). A LCA study is divided into 4 main stages: 1) Scope and goal definition, 2) Defining the inventory for the life cycle processes, 3) Characterising and measuring the life cycle impact and 4) Interpretation of results (Teh et al., 2017). The first stage, which is the definition of goal and scope, involves the system boundary and the functional unit selection. A system boundary of a concrete product could be Cradle-to-Gate, which means including all processes and emissions until the production of its different constituents or Cradle-to-Grave which includes the “Use” and “End-of-Life” phases or Cradle-to-Cradle including the negative impact from recycling a landfilled material in a new concrete. The second research gap found in both frameworks, MARS-SC and CONCRE*Top,* is that the scope specified is only Cradle-to-Gate. However, it is recommended for a reliable LCA study of concrete to be either Cradle-to-Grave or Cradle-to-Cradle (Hafez et al., 2019).

3.2.4. Step 4: Calculate LCA Functional Unit

A Functional unit (FU) is the parameter responsible for the quantification of the environmental and economic impact indicators in a LCA (Dobbelaere et al., 2016). Hence, its selection needs to be reflective of the nature of the LCA logic (Panesar et al., 2017). That is why, in the MARS-SC and CONCRETop frameworks, the functional unit is assumed as simply a unit volume of concrete (1 m^3). In both frameworks, functional indicators are quantified through a process similar to the environmental and economic indicators. This is the third research gap in this critical analysis of the frameworks because the FU used in the LCA of the MCDA should be indicative of the performance of concrete.

3.2.5. Step 5: Collect LCA Inventory Data

The second stage of a LCA study is the life cycle inventory data collection. This is the data collection stage, in which the input and output factors, such as energy, raw materials, products, and waste, are analysed for the LCA of concrete. The inventory data for a concrete mix mainly include: 1) upstream processes: those involved in the production of each of the constituents and its transportation till the concrete production plant, 2) core processes which involve the energy and emissions required for mixing concrete and transportation to site, and 3) downstream processes needed for the demolition or any other end-of-life scenario (Wu et al., 2014). Examining both frameworks from the literature, it was apparent that they only include inventory data concerning upstream processes, which is consistent with their selected Cradle-to-Gate scope but is not the best practice. This is the fourth research gap identified in this section.

The source of concrete inventory data could be: primary data from the building industry to which the user has access, accredited environmental databases such as EcoInvent, GaBi and EuGeos or Environmental Product Declarations (EPDs) (Anand and Amor, 2017). Although databases such as EcoInvent and GaBi are updated annually to reflect any changes in the inventory data included, Hafliger et al. (2017) suggest that the priority in the source of upstream processes is for EPDs of the actual constituents in the mix. The reason is that EPDs are done in accordance to the same process, an LCA, under the guidance and supervision of local authorities such as the BRE in the UK, which makes it reliable primary data. When examining MARS-SC and CONCRE*Top*, it was clear that they rely on data from a single earlier publication and an average of several publications and EPDs respectively. This is not ideal in terms of reliability of the LCA, but is also static and does not allow the user the flexibility to change it. The fifth research gap in this section is for concrete sustainability frameworks to prioritize primary data.

The third component of inventory data is impact allocation; the process of portioning the environmental burden of the original process to the waste material being recycled in the product under study (Marinkovic et al., 2017). Interpreting the EU directive 2008 conditions, FA, GGBS and SF ought to be considered as by-products not as waste (Chen et al., 2010). This means that they should be allocated a percentage of the environmental burden of their original production process, which are coal combustion, steel production and glass manufacturing respectively (Anastasiou et al., 2015). Neither MARS-SC nor CONCRE*Top* considers the impact allocation, which is the sixth research gap presented in this section.

3.2.6. Step 6: Calculate the sustainability index

The final step of the sustainability assessment process is to calculate the sustainability index. For each alternative, the functional, environmental and economic parameters are measured or deduced. Using the weights of each, the average value between them is calculated as the sustainability index. Both frameworks followed the same calculation method. However, according to Cinelli et al. (2014), a sustainability framework should have a user-friendly tool in order to allow users to apply it to the objective alternatives. Hence, the seventh and final research gap found in MARS-SC and CONCRE*Top* is the fact that there were no tools available for users to apply.

3.2.7. *Summary of gaps in existing frameworks*

The summary of the gaps found in the two frameworks, MARS-SC and CONCRE*Top* reviewed are:

i. Allowing for different scenarios for comparison between alternatives.
ii. The scope specified for the LCA study should be either Cradle-to-Grave.
iii. Functional parameters should be integrated in the LCA as the functional unit.
iv. The LCA inventory data should include upstream and downstream data.
v. Primary sources should be prioritized as a source of inventory data.
vi. Impact allocation for SCM based concrete should be included.
vii. There are no tools for users to apply the frameworks.

3.3. The ECO$_2$ sustainability assessment framework

Before introducing the features of the new framework that builds on the identified gaps in the existing ones, it is necessary to explain the core of its logic. The ECO$_2$ is primarily a performance based framework for concrete sustainability assessment. The term performance based is associated with a trend in specifying concrete durability called performance based specifications. For years, concrete durability was determined using prescriptive specifications –sometime referred to as deemed to satisfy specifications, which included constraints such as minimum cement content, maximum SCM use and maximum water to binder ratio (Alexander et al., 2010). Standards such as ACI 308-01 ensure an optimum concrete performance by restricting these ratios to certain ranges. However, this rigid nature of the prescriptive based specifications is not ideal when it comes to sustainability. Due to the wide range of performance requirements in concrete applications, specifications for concrete should be flexible and focusing on the intended project application (Hooton and Bickley, 2014). The definition of performance based specifications given by the Canadian standard CSA-A23.1 is “A specification method in which the final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods. The processes, materials or activities used by the contractors, subcontractors, manufacturers and material suppliers are then left to their discretion” (Lobo et al., 2006).

An example of the sustainability potential of both specifications is when a contractor is required to cast a pavement for a homeowner. The only requirement given by the engineer is a minimum compressive strength of 30 MPa. Knowing that the pavement is exposed to de-icing salt and carbonation, the contractor needs to make sure the reinforcing concrete pavement resists the deterioration against both mechanisms. If the contractor is to follow a prescriptive specification method, there would be a cap on the allowed % replacement of cement by an SCM and minimum cement content per cubic meter. It was established that cement is the main contributor to the economic and environmental impact of concrete in earlier sections. Hence, the contractor would follow the standards and increase the cement content resulting in a concrete pavement of a high environmental and economic impact. On the other hand, had the contractor designed a mix that utilized a higher % of SCM or a less cement that would be modelled to satisfy the performance based specifications, the final concrete pavement would have been more sustainable significantly.

The same concept is applied to the sustainability assessment frameworks. As shown in section 3.3, both MARS-SC and CONCRE*Top* include the functional properties of concrete as a separate pillar of sustainability. This means that, similar to the durability prescriptive specifications, this sustainability pillar is quantified regardless of the intended application of the concrete alternative. This is manifested clearly in the static assessment criteria set by both frameworks. According to Rahla et al. (2019), a project that requires a concrete with a minimum strength of 30 MPa and service life of 50 years. There means that, for this project, 3 concrete mixes who exhibit strength of 30, 40 and 60 MPa respectively would be assessed using the MARS-SC framework with a normalized impact of 1/2: 2/3: 1, respectively. This means that the extra environmental and economic impact invested in making alternatives 2 and 3 of higher strength would be rewarded, which is not the best practice for sustainability. According to Muller et al. (2016), using concrete with superior functional properties than the project requirement is a waste of resources and should be penalized rather than rewarded when assessing the sustainability.

This is the core of the logic behind the ECO_2 framework. As seen in Figure 3.3, the framework overcomes the third gap from the reviewed frameworks concerning accounting for the performance of concrete alternatives in a prescriptive method. Instead, the ECO_2 framework includes user-defined project specifications as the basis for assessing the functional impact. This means that for the aforementioned example of the 3 concrete mixes of compressive strength equals to 30, 40 and 60 MPa, they would all be considered equal since the project only requires 30 MPa. Nevertheless, the functional impact of the studied concrete alternatives is then translated into the functional unit to be used for the LCA study. The first step in using the framework, building on the first gap identified in the reviewed frameworks, the ECO_2 allows users to define several scenarios that could be used to compare the alternatives under study. A scenario analysis between varying project requirements and weights of indicators –for example- is a step towards decreasing the uncertainty in the LCA results. The second step after defining the potential scenarios and alternatives under study is to perform the LCA using the functional parameters as a FU. After that, the environmental and economic impact assessment is quantified, aggregated and normalized for every alternative and comparisons done. The word ecological is used as a synonym to environmental just to allow for the acronym ECO_2 to be representative of the included pillars: ECOnomic and ECOlogical as well as indicating a relevance to CO_2 which is vital to the impact assessment process. Finally, a sensitivity analysis is prepared to determine the critical variables in the assessment process of every alternative.

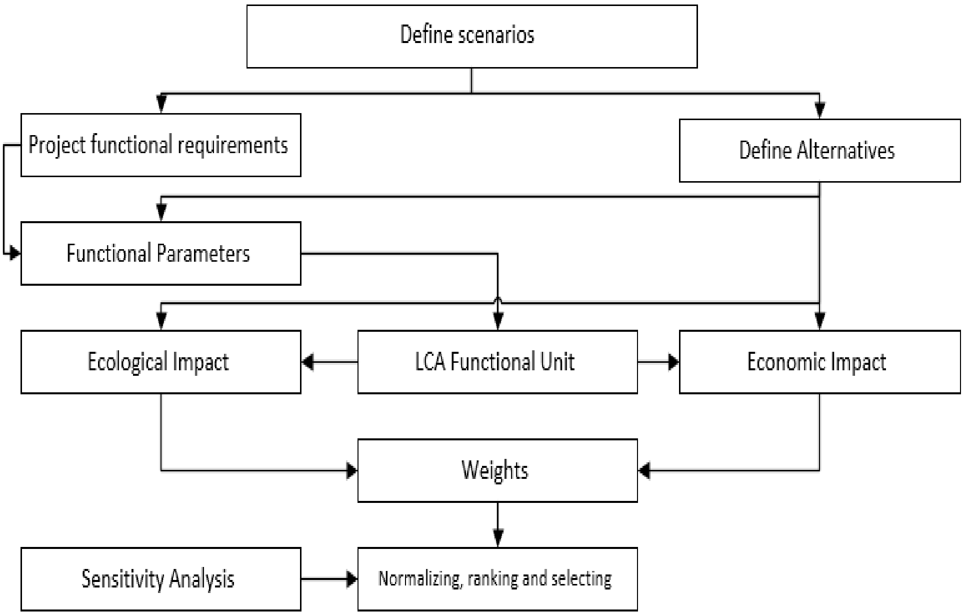


Figure 3.3: A schematic of the logic followed by the ECO_2 sustainability assessment framework

3.3.1. *Step 1: Define scope*

Similar to that of both reviewed frameworks, the goal of ECO_2 is the sustainability assessment of concrete. The ECO_2 users could be anyone with the objective of assessing a set of concrete alternatives against project specifications. The selected sustainability indicators for each of the frameworks understudy as well as that of ECO_2 could be summarized in Table 3.1. As explained in the introduction, the functional indicators in ECO_2 are not included in the aggregated sustainability score. Following the best practice for sustainability assessment, they are rather translated into the functional unit of the LCA for the environmental and economic impact. Although the indicators used for environmental impact in ECO_2 are less than MARS-MOD, it is established by the literature that these are the most reliable and indicative mid-point indicators (Kurda et al., 2019). A new indicator, Y, was developed in ECO_2 to measure the ecological impact combining the normalized values of the selected mid-point indicators based on the performance based functional unit. Also, the economic impact according to ECO_2 is calculated using a new indicator, Z, that is based on a whole life cycle cost assessment which is more reliable than the baseline cost of the concrete alternative (Panesar et al., 2013). Finally, the ECO_2 index is the third indicator that was developed in the framework to combine Y and Z for a given alternative.

Table 3.11: A Table summarizing the selected indicators of the ECO_2 framework compared to MARS-SC and CONCRE*Top*

Sustainability Pillars	Indicators	Previous frameworks		Proposed framework
		MARS-SC	CONCRE*Top*	ECO_2
Functional	Slump	-	√	√*
	Compressive Strength	√	√	√*
	Resistance to Chloride Penetration	√	√	√*
	Carbonation	√	√	√*
	Modulus of Elasticity	-	√	-
	Permeability to Water	√	-	-
Environmental	Global Warming Potential	√	√	√
	Ozone Depletion Potential	√	-	√
	Acidification Potential	√	-	√
	Eutrophication Potential	√	-	√
	Abiotic Depletion Potential	√	-	√
	Photochemical Ozone Creation Potential	√	-	√
	Cumulative Energy Consumption	-	√	√
	Fresh Water Net Use	-	-	√
	Human Toxicity Potential	√	-	-
	Freshwater Aquatic Ecotoxicity Potential	√	-	-
	Marine Aquatic Ecotoxicity Potential	√	-	-
	Terrestrial Ecotoxicity Potential	√	-	-
	Y – Combined ecological impact	-	-	√
Economic	Base cost of concrete	√	√	-
	Z - Net present value	-	-	√

*the functional indicators in ECO_2 are not directly included in the aggregated sustainability score

3.3.2. *Step 2: Define alternatives*

As agreed in chapter 2, in order to reduce the systematic uncertainty of LCA, it is recommended to perform scenario analysis (Wu et al., 2014). Hence, the first significant feature of the ECO_2 framework is allowing the user to define the following scenarios:

a. Number and location of the project.
b. The project's functional requirements. The user needs to register the minimum required service life, slump, and 28 days compressive strength for each scenario.
c. Type of concrete (plain or reinforced) for functional indicators purpose.
d. Total concrete volume. One of the sustainability assessment parameters is the level of detail (LoD) of the project which will house the concrete. The volume could be that of the whole structure, an element or just a unit volume.

3.3.3. *Step 3: Define LCA system boundary*

Following the second gap identified in section 3.2, the ECO_2 framework was designed to have a Cradle-to-Grave scope. As Figure 3.4 shows, the study would include the "Production", "Use" and "End-of-Life" phases. The first assumption in the framework is that the "Use" phase would not include the energy and emissions resulting from the maintenance of concrete while in service. The reason is that according to Hafez et al. (2019), the values for the maintenance are variable largely, which would add randomness to the study. Hence, any concrete alternative is expected to perform in a perfect manner throughout their predicted service life and are to be replaced (N) times whenever appropriate to fulfil the required service life. The second assumption is that the operational energy is not included as a parameter in the assessment. The reason is that structural concrete contributes minimally to the operational energy consumption of a building compared to other building components (less than 3%) according to Gursel et al. (2014). Aside from that, the ECO_2 framework assumes the following:

- The transportation distances entered by the user or averaged from secondary sources are the actual geographic distances. They are multiplied by 1.7 in environmental impact calculations to account for the return trip.
- The user-input mixing proportions follow the logical boundaries by totalling to the equivalent of unit volume.

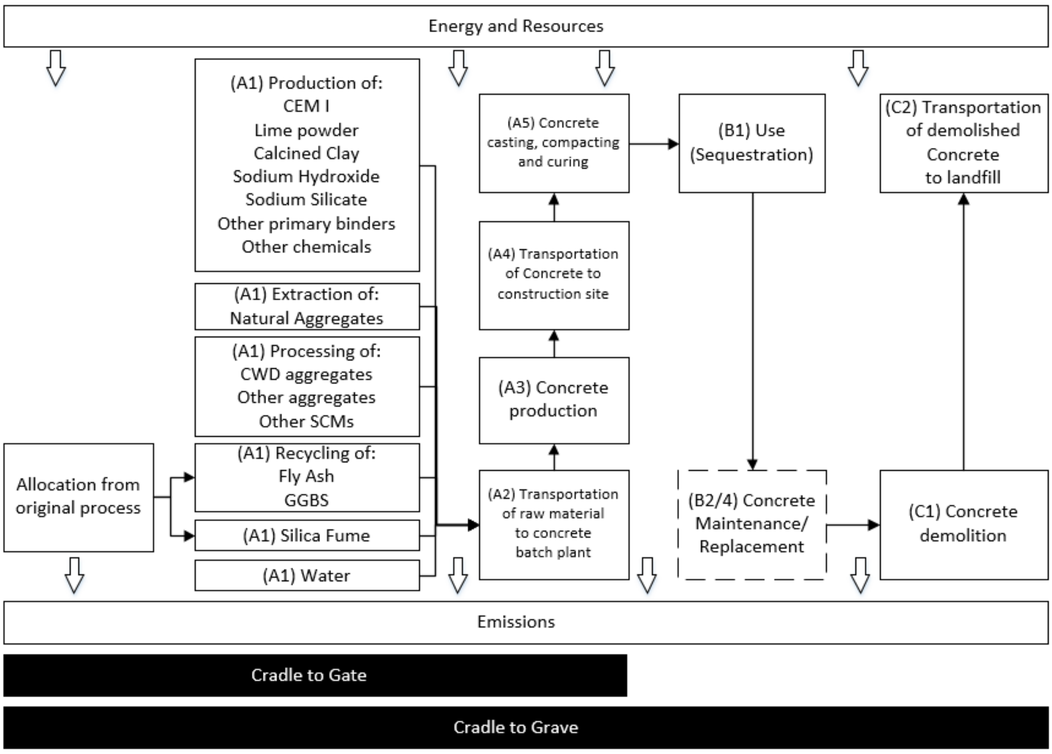


Figure 3.4: A schematic of the Cradle to Grave system boundary selected for the ECO_2 framework

3.3.4. Step 4: Calculate LCA Functional Unit

Calculating the FU according to the ECO_2 framework is done through two stages:

3.3.4.1. Predicting the functional indicators

The indicators are divided into two groups: the first is the minimum requirements which are the workability and strength and the second is the service life indicators. Service life of concrete is the time needed till it reaches the ultimate limit of deterioration under specific exposure conditions and upon which either repair or replacement is needed (Garcia-Segura et al., 2014). If the alternative under study is reinforced concrete, corrosion of the steel reinforcement is the main deterioration mechanism, which makes resistance to chloride penetration and resistance to carbonation the main indicators of durability (Tang et al., 2015). For each indicator, the user is given the option of inputting primary data in the form of results of standardized tests as shown in Figure 3.5. If primary data is not available, the framework includes some empirical models to predict these indicators from some concrete types. The standard tests and prediction models are summarized as follows:

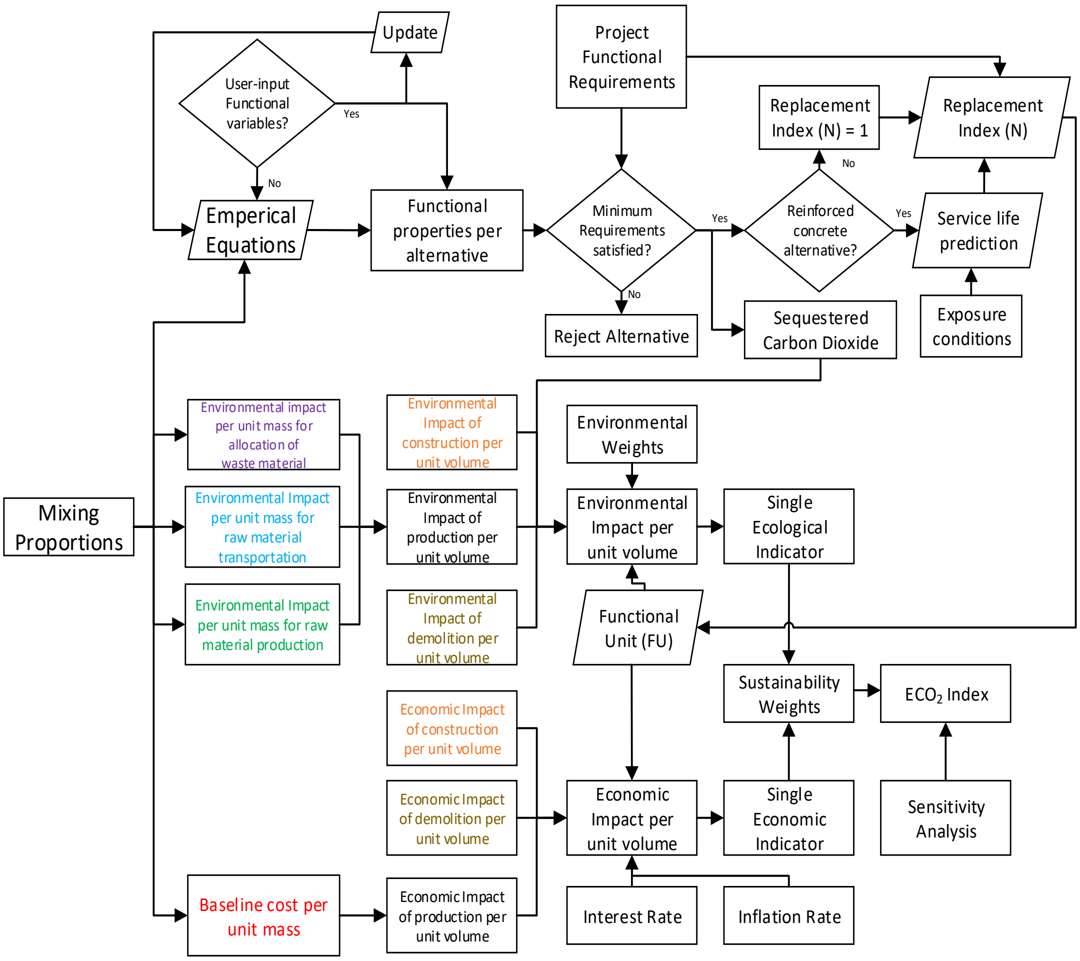


Figure 3.5: The ECO_2 algorithms for calculating the economic and ecological impact of concrete alternatives

i. Workability is vital for concrete construction, and it is largely attributed to the available free water in the concrete mix, which is dependent on the ratio between the volume of the paste and the volume of the aggregates (Chandwani et al., 2015). The most agreed upon indication of workability is the standard cone slump test (according to BS EN 12350-2 for example), which is why the functional parameter is directly referred to in the tool as “Slump”. The expected values for the test vary between 0 and 300mm and are normalized according to the classification listed in EN 206-01 as S1 (0-40 mm), S2 (50-90 mm), S3 (100-150 mm), S4 (160-210 mm) and S5 (220-300 mm). If primary data is not accessible to the user, according to Hoang and Pham (2016), the slump value Y (mm) for OPC based concrete could be predicted using equation 3.1. where the symbols of $x1$, $x2$, $x3$, $x4$, $x5$, and $x6$ represent the amount of cement, natural sand, crushed sand, coarse aggregate, water, and superplasticizer within the concrete mix, respectively.

$$Y_{slump}(mm) = 36.22 - 12.47 * C - 27.03 * AF_1 - 24.56 * AF_2 - 7.39 * AC - 3 * W - 1.18 * SP \quad (3.1)$$

ii. Compressive strength is a time dependant property that increases as concrete ages. Hence, it could have been more encouraging to rely on the compressive strength performance of concrete at 90 days especially when concrete with sustainable potential such as BCC are considered. However, the agreed indicator for strength for the ECO_2 framework is the 28 days compressive strength which could be tested according to BS EN 12390-3 (Felekoglu et al., 2006). The reason is that it is the curing period considered in most standards and to always allow for the worst case scenario when assessing concrete performance. Compressive strength is affected by more factors than slump such as curing age, curing conditions, binder composition and water to binder ratio and is dependent on the characteristics of the mortar, coarse aggregates, and the interface between them (Wu et al., 2001). In case primary data was not found, several prediction model found in the literature. An example for predicting 28 days compressive strength of blended cement concrete containing only OPC, silica fume and fly ash is presented in equation 3.2, where W, C, S and F stand for the mass content in kg per unit volume of water, OPC, silica fume and fly ash, respectively (Papadakis and Tsimas, 2002).

$$Y_{c.strength}(MPa) = 17.08 * \left(\frac{W}{C+0.77*S+0.385*F}\right)^{-1.119} \quad (3.2)$$

iii. Chloride penetration is the primary mechanism for the corrosion of steel reinforcement in reinforced concrete. For the corrosion to be initiated, which means the compromise of the concrete cover, which occurs when the chloride concentration penetrating the concrete cover reach a threshold identified as the chloride threshold (Garcia et al., 2013). The chloride threshold potential of a concrete mix is dependent on a set of exposure conditions such as temperature, RH and % of free chlorides as well as intrinsic variables such as the concrete type and w/b ration (Lars-Olof et al., 1996). A standard test to measure the resistance of a concrete mix to chloride penetration is called Rapid Chloride Penetration Test (RCPT) according to ASTM C1202–18 (Mahima et al., 2018). In order to predict the value for the chloride diffusion coefficient D_{nssm}, the following data in Table 3.2 was extracted from the literature.

Table 3.2: A summary of the values for resistance to chloride penetration coefficients from the literature

Source	W/B ratio	% replacement of OPC					Electrical Resistivity (Couloumb)
		FA	GGBS	SF	CC	LP	
Burden	0.4						6158
Karahan	0.35	90%					2800
Karahan	0.35	70%					600
Dhanya	0.4	50%					1000
Dhandapani	0.45	30%					1600
Inthata	0.3	10%					1687
Karahan	0.35		90%				400
Akhter uz Zaman	0.25		70%				339
Dhanya	0.4		50%				390
Buss	0.35		35%				1800
Mary and Kishore	0.45		10%				3500
Mohamed	0.35			15%			280
Akhter uz Zaman	0.25			10%			216
Kou	0.5					15%	3600
Kavita	0.38					10%	500

iv. Resistance to Carbonation. A standard method of calculating Kn, the natural carbonation rate of concrete, is to plot the carbonation depth versus the duration of exposure, then calculate the slope of the best fit curve (Van den Heede and De Belie, 2018). The depth of carbonation could be measured from a natural carbonation test or the standard accelerated test LNEC E 391:1993 that is then correlated using equation 3.3 Where K_a is the accelerated carbonation rate, CC_n is the CO_2 % concentration in the environment and CC_a is that in the accelerated carbonation chamber. In case primary data is not available, major discrepancies were found in reported carbonation rates of the same concrete type as shown in Table 3.3. The reason could be that, even if they were the same concrete type, having a mix of lower w/b ratio would have a higher resistance to carbonation (Silva et al., 2015). Another reason is the difference between accelerated and natural carbonation testing. Van den Heede et al. (2019) showed that testing high volume FA BCC using an accelerated carbonation setup would overestimate the carbonation rate predicted.

$$K_n = K_a\sqrt{\frac{CC_n}{CC_a}} \qquad (3.3)$$

It is important to note that, similar to compressive strength, the resistance of concrete to chloride penetration and carbonation is a time dependant characteristic. Hence, it is an underestimation to use the tests performed on samples cured for only 28 days. However, this assumption is a normal practice in concrete standards and is considered as one of the limitations of the performance assessment within the ECO_2 framework.

Table 3.3: A summary of the values of the natural carbonation rate from the literature

Source	W/B ratio	% replacement of OPC					Natural Carbonation rate (mm/sqrt year)
		fly ash	GGBS	SF	CC	LP	
Alhassan and Ballim	0.50						2.20
Atis	0.29	0.70					9.90
khunthongkeaw	0.50	0.50					6.13
Newlands	0.45	0.30					1.02
khunthongkeaw	0.40	0.10					1.18
McNally amd Sheils	0.45		0.70				2.86
Collepardi	0.40		0.50				4.50
Lofgren	0.40		0.30				0.97
Gettu	0.50		0.15				2.70
Sanjuan	0.36			0.10			4.00
San Nicolas	0.45				0.25		3.97
Eguchi	0.50				0.20		0.60
Collepardi	0.50					0.25	6.90
Collepardi	0.40					0.15	1.20
Kaewmanee	0.55					0.10	1.61

3.3.4.2. Calculating the functional unit:

First, for every alternative (i) if Yslump (i) < Yslump (r) or Ystrength (i) < Y strength (r), the alternative is rejected. After that, if the concrete alternative is plain concrete, FU is equals to 1 m^3 of concrete. If it is reinforced, in order to account for the durability of the concrete alternative and its ability to sustain its functionality throughout the required service life of the project, a replacement factor N was development. Scenarios in which the user selects a plain concrete type, the value of N = 1 as shown in the algorithm in Figure 3.5. It is established that plain concrete types are assumed to be durable enough to sustain any service life requirements. For every reinforced concrete scenario, the user would have registered a value for the required service life (SL_R). The mechanism by which this carbonation could prove detrimental to the concrete durability by inducing corrosion to the reinforcement is chemical de-passivation. The dissolved carbon dioxide from the environment reacts with the calcium hydrate phases of the concrete binder. The process reduces the pH of the carbonated depth of concrete (X_c), which de-passivates the protection layer against corrosion of the steel reinforcement. It is then assumed, in the simple model proposed by Jiang et al. (2000), that the durability of a concrete alternative against carbonation is a measure of the time at which the depth of carbonated concrete (X_c) is equal to that of the concrete cover (X, in cm). Given that the values for the natural carbonation rate ($K_{n,}$ in cm per year^{-1}), the predicted service life ($SL_{P\text{-}Cr}$, in years) for carbonation could be calculated as per equation 3.4:

$$SL_{P-Cr} = \left(\frac{X}{K_n}\right)^2 \tag{3.4}$$

Service life predictions against chloride-induced corrosion are defined in standards as the duration that takes the chloride content at the surface of the steel reinforcement to reach the chloride threshold (Srubar, 2014). According to Markeset and Kioumarsi (2017), the most significant parameters in the DuraCrete model of service life prediction against chloride penetration are: D, which is the chloride diffusion coefficient (m^2/s) and C_{cr}, which is the chloride threshold level (%). The model, which is developed based on Fick's 2nd law of diffusion, predicts the service life $SL_{p\text{-}cl}$ as per equations 3.5 and 3.6 as the time when C(x,t) is equal to C_{cr}:

$$C(x,t) = C_o * erfc(\frac{x}{2*\sqrt{D_t * t}}) \tag{3.5}$$

$$D_t = D(\frac{t_o}{t})^{\propto} \tag{3.6}$$

Where, C_o is the chloride concentration on the concrete surface estimated at 0.5-1%, X is the concrete cover, α is an aging factor and t is the service life expected for the durability against chloride penetration $SL_{R\text{-}Cl}$, in years. After determining the expected service life for every reinforced concrete alternative according to both mechanisms of deterioration: $SL_{P\text{-}Cr}$ and $SL_{P\text{-}Cl}$ in years, the replacement ratio N would be calculated as per equation 3.7 and the FU would be calculated as per equation 3.8:

$$N = \frac{SL_R}{\min(SL_{P-Cr}, SL_{P-Cl})} \tag{3.7}$$

$$FU_i = N_i * 1m^3 \tag{3.8}$$

The variable N is devised to complement the potential deficiency in the durability of a concrete mix. If a mix is expected to live shorter than the required service life in the defined scenario, the environmental and economic impacts are rightfully multiplied by N. However, if the opposite occurs and the mix is expected to live beyond the required service life, then N is assumed as 1. The decision to have a minimum value of 1 for N is to not reward the unnecessarily higher performance of concrete. This resourceful perspective to sustainability assessment complies with the principles of performance based specifications and avoiding the gaps in existing frameworks.

3.3.5. Step 5: Collect LCA Inventory Data

In return, building on the aforementioned gaps in the existing frameworks, the ECO_2 framework first includes inventory data for upstream, core and downstream processes. As shown in Figure 3.6, the framework includes the production, construction, demolition and the transportation from the source to the batch plant then to the construction site as well as that to the landfill. Secondly, the framework allows the user the option to enter site-specific primary data for all processes as well as EPDs for the constituents used in concrete. However, if not available, the framework includes a database of more than 250 data points from published articles, EPDs and extracts from the ECOinvent database from which the inventory data for the processes understudy can be extracted. The summary of the database could be found in Appendix B.

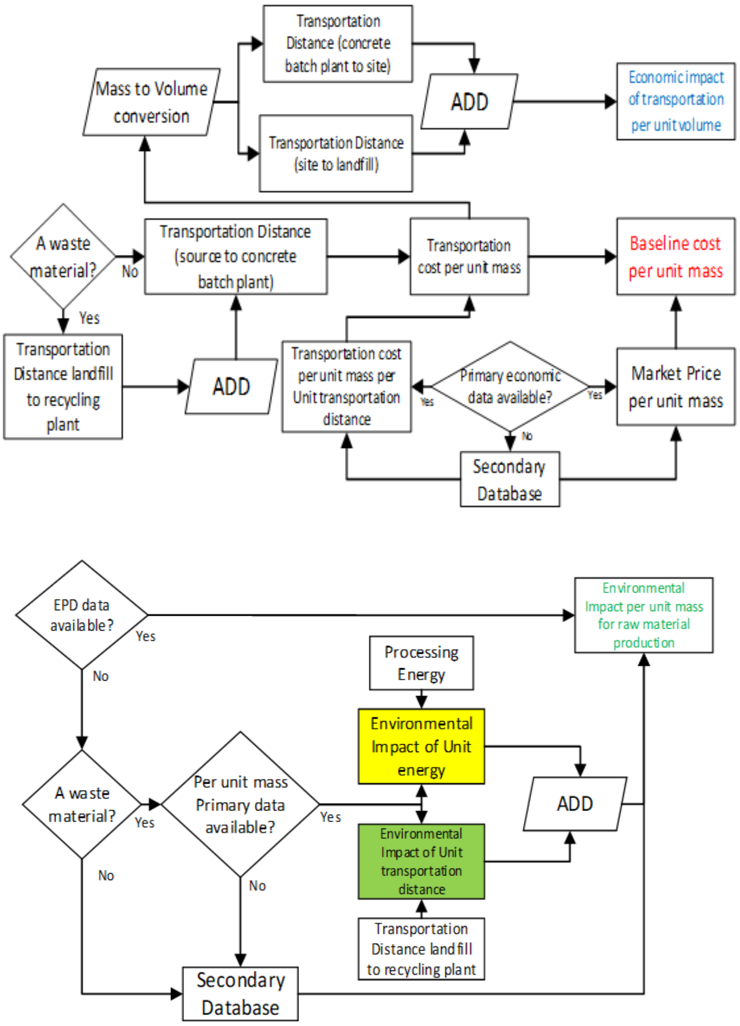


Figure 3.6: Two flowcharts showing the method of calculating the inventory data per unit mass for material production and transportation

Finally, the ECO$_2$ framework calculates the impact allocated to FA, GGBS and SF if included in the alternative. This is through either mass allocation as shown in Equation 3.9 or "economic allocation" in which the percentage allocated is based on the relative market value between the final product, which is electricity, as per Equation 3.10 (Chen et al., 2010).

$$\text{Mass Allocation} \quad = \frac{(\mathrm{m})_{\text{by-product}}}{(\mathrm{m})_{\text{main product}} + (\mathrm{m})_{\text{by-product}}} \tag{3.9}$$

$$\text{Economic Allocation} = \frac{(€.\mathrm{m})_{\text{by-product}}}{(€.\mathrm{m})_{\text{main product}} + (€.\mathrm{m})_{\text{by-product}}} \tag{3.10}$$

Although economic allocation is dependent on the time-dependant market prices of the raw materials, it is the most preferred in the literature. According to Marinkovic et al. (2017), in case the difference between the price of main and secondary process generating the SCM product is more than 25%, economic allocation should be applied. Once the percentage allocation is calculated, the allocated impact per unit mass is equal to the same percentage from the impact of the original process, which is either user-input or extracted from the ECO$_2$ database.

3.3.6. *Step 6: Calculate the sustainability index*

3.3.6.1. **Environmental Impact Assessment**

The environmental impact per unit volume is calculated using the aforementioned eight mid-point indicators for each concrete alternative (i) understudy as shown in equation 3.11. For every environmental impact indicator V, the impact per unit volume is multiplied by the functional unit calculated in 3.4.3.

$$V_i(per\ functional\ unit) = V_i(per\ m^3) * FU_i(calculated\ in\ 3.8) \qquad (3.11)$$

The per unit volume impact indicator V is calculated according to equation 3.12 giving an example with the GWP indicator. The upstream unit mass impact of each raw material j is multiplied by the mass per unit volume proportion of j in the mix specified for alternative i and the total impact from the n number of raw materials per alternative is added to the per unit volume impact for construction and demolition. For the GWP indicator only, the per unit volume expected sequestered carbon dioxide is deducted from the total.

$$\frac{GWP_i}{m^3} = \sum_{j=1}^{n}\left(\frac{GWP_{j\ upstream}}{kg} * \frac{kg_j}{m^3}\right) + \frac{GWP_i construction}{m^3} - \frac{GWP_i sequestered}{m^3} + \frac{GWP_i\ demolition}{m^3} \qquad (3.12)$$

$$\frac{GWP_{j\ upstream}}{kg} = \frac{GWP_j production}{kg} + \frac{GWP\ transportation}{kg.km} * 1.7 * D_j\ (km) + GWP_j allocated \qquad (3.13)$$

Where D_j is the distance between the source of the raw material (j) and the concrete batch plant (in kilometres)

For every raw material (j) included in the concrete mix of this alternative, the value of the upstream impact indicators per unit mass is the addition of that from its production process, transportation and allocation (if applicable) as shown in equation 3.14. As agreed for all ECO_2 operations, the values for this inventory data are either user-input using the relevant EPD or estimated as an average from the database.

$$GWP_i\ core = \frac{GWP_i construction}{m^3} - \frac{GWP_i sequestered}{m^3} \qquad (3.14)$$

$$\frac{GWP_i construction}{m^3} = \frac{GWP\ transportation}{m^3.km} * 1.7 * D_{i1}\ (km) + \frac{GWP\ energy_1}{m^3.kWh} * E_{i1}\ (kWh) \qquad (3.15)$$

The first element of the core processes; the impact of concrete construction, is a summation of: 1) the energy required for the mixing, pumping, compacting and curing of concrete whether done on site or in a prefabricated concrete plant and 2) the energy and emissions of transporting concrete the distance D1, which is 170% the geographic distance between the concrete batch plant and site, which could be equal to zero in case the concrete is produced on site.

The second is the carbon sequestration, which is the term used to describe how much carbon dioxide is absorbed by concrete from the environment. There are 2 ways for concrete to absorb CO_2 through carbonation process. The first, labelled as carbon utilization methods, are usually executed by injecting pressurized CO_2 either in aggregates (Tam et al., 2020), the production process of special types of cement (Vance et al., 2015) or in the concrete mixer (Monkman et al., 2016). The second is by natural exposure to the CO_2 in the environment throughout its service life. Concrete is able to re-absorb 13-48% of the production phase CO_2 through carbonation (Collins et al., 2010). Since it is only CO_2, the carbon sequestration only affects the GWP environmental indicator. The magnitude of the sequestered carbon is dependent on: exposure conditions and intrinsic variables that dictate the theoretical limit of carbonate-able chemical phases in a concrete mix. The exposure conditions are the exposed surface area of the concrete member, the CO_2 concentration in the environment, the humidity and temperature as well as the exposure time. The intrinsic variables affecting the carbon sequestration potential are the type of binder and the total binder content per unit volume (Souto-Martinez et al., 2017). Hence, the exposure conditions are assumed the same for all alternatives under the same scenario, while the intrinsic variables depend on the mixing proportions and type of cement replacement if any in each alternative. The user can opt to enter primary data for the exposure conditions per scenario or rely on the assumed default values obtained from the literature in Table 3.4.

Table 3.4: Secondary exposure conditions from the literature in the ECO_2 framework

Concrete Cover (X)	30	mm
Thickness of concrete members	250	mm
Exposed area of concrete	4	m^2/m^3
Average Temperature yearly	23	°C
Average Humidity yearly	60	%
Average Carbon Concentration	0.04	%
Average Surface Chloride Content yearly	0.05	(% by weight of concrete)

There are several models available to predict the amount of carbon sequestered U_{CO_2} of a given concrete alternative after (t) days, which is equivalent to the required service life (SL_R). One of the simplistic models is as shown in equation 3.16 based on Yang et al. (2014):

$$U_{CO_2}(t) = a_{CO_2}(t) * A * X_c * t \ (grams/m^3) \qquad (3.16)$$

The equation is simplifies because it assumes a constant rate of carbonation and subsequently a static chemical reaction for the carbon absorption, which is not suitable to the time-variable carbonation property of concrete. However, the following equation 3.17 could still used with care as a simplified method of calculating the amount of absorbed CO_2 where A is the exposed surface area of concrete (in cm^2), X_c is the carbonation depth (in cm) and $a_{CO_2}(t)$ is the amount of absorbable CO_2 in g/cm^3 at time t, for an alternative of a total binder content B (grams) and Water (grams):

$$a_{CO_2}(t) = 366 * 10^{-6} * B * \frac{t}{2+t} * \frac{W/_B}{W/_B + 0.194} \qquad (3.17)$$

The environmental impact from the downstream processes would be the addition of the energy required to demolish a unit volume of concrete as well as that from transporting it from the site to the landfill. Equation 3.18 shows how the calculation is done.

$$\frac{GWP_i \ demolition}{m^3} = \frac{GWP \ transportation}{m^3.km} * 1.7 * D_{i2} \ (km) + \frac{GWP \ energy_2}{m^3.kWh} * E_{i2} \ (kWh) \qquad (3.18)$$

3.3.6.2. Economic Impact Assessment

The economic impact per unit mass of the production and transportation of each raw material are summed together as per equation 3.19 to produce the baseline cost (C_b) of each alternative (i).

$$C_b = \sum_{j=1}^{n} \left(\frac{(C_p + (C_t * D_j))}{kg} * \frac{kg_j}{m^3} \right) \tag{3.19}$$

The unknowns in equation 3.19 are: C_p and C_t are the market price per unit mass and the transportation cost per unit mass and unit distance of each raw material, respectively. D_j is the transportation distance, which equals the geographic distance between the source of the raw material and the concrete batch plant. Unlike the transportation distance input in the environmental impact assessment, this distance is not doubled under the assumption that the return trip is accounted for as a part of the charged cost of transportation. Kg_j/m^3 describes the value of the mixing proportion for this raw material j in the alternative i. Similar to the process of environmental impact assessment, the value for C, the economic impact per unit volume of alternative (i) is calculated using equations 3.20, 3.21 and 3.22. It should be noted that C_c and C_d stands for the cost per unit volume of the construction and demolition processes respectively, while C_e is the cost per unit energy. Also, D_{i1} and D_{i2} are the distances (geographic) in km between the construction site and the concrete batch plant and landfill, respectively. Finally, E_{i1} and E_{i2} stands for the amount of energy required for the construction and demolition processes respectively.

$$C_c = (C_t * D_{i1}) + (C_e * E_{i1}) \tag{3.20}$$

$$C_d = (C_t * D_{i2}) + (C_e * E_{i2}) \tag{3.21}$$

$$C_i = C_b + C_c + C_d + C_x \tag{3.22}$$

C_x is an indicator of another unique feature in the ECO_2 framework; the ability to account for the economic consequences of carbon policies. In order to meet their environmental goals, several countries are implementing economic policies attempting to cut down their carbon emissions. Carbon taxation, a tax on carbon emissions from burning fossil fuels, is a famous and straight forward example. Imbabi et al. (2013) argue that a carbon tax of £30 per tonne of CO_2 would push cement producers to utilize non-fossil fuel and reduce the environmental impact by at least 10%. C_x could be indicative of another carbon control economic policy, carbon savings incentives, which would then be associated with a negative sign decreasing the cost of concrete. Di Filipo et al. (2019) argue that, although it would require governments to secure the funding for these incentives beforehand, this could be potentially means to encourage contractors and concrete producers to rely on low-carbon concrete alternatives to make use of the incentives. Shima et al. (2004) mentioned the possibility of the Japanese government offering the equivalent of £6 per m^3 of concrete if it proves to be "Green". Of course, the critical factor in such a case would be the definition of the cut-off for the criteria upon which the concrete alternative would prove worthy of such incentives. That is why frameworks, such as ECO_2, are significant to provide a clearer indication of how sustainable a concrete alternative is. For the MARS-SC and CONCRE*Top* frameworks, the economic impact indicator is simply the baseline cost. However, this is not representative of the whole service life cost of the concrete since this baseline cost is repaid every time the reinforced concrete alternative is to be replaced in the case the predicted service life falls short of the required one. Hence, the ECO_2 framework presents an economic index, Z, representing the net present value of the expected cash flow of the concrete alternative i. According to Panesar et al. (2013), in order to calculate Z, the real interest rate F_r needs to be derived by setting the interest rate F_i to negate an inflation rate F_f as in equations 3.23 and 3.24.

$$F_r = \frac{1+F_i}{1+F_f} - 1 \tag{3.23}$$

$$Z_i = \frac{C_i}{(1+F_r)^t} \tag{3.24}$$

3.3.7. *Step 7: Impact normalization and aggregation*

The final component of a typical MCDA prior to judging the set of alternatives studied under a certain scenario is normalization (Zhang et al., 2017). Normalization is the step at which the score of each indicator is scaled to a benchmark value (Kim et al., 2017). According to Cinelli et al., it is vital to benchmark sustainability indicators against a "local" value by comparing to the highest value of the studied alternatives and a "global" one such as an established standard (2014). In the MARS-SC framework, only local benchmarking was found, while CONCRE*Top* did both. As explained in the introduction, the ECO_2 tool is not intended for LCA experts. Hence, in order for the user to interpret the values of the environmental and economic indicators, its needs to be normalized to local and global benchmarks. First, the global benchmarks for only four indicators were found and adopted from Kurda et al. (2019) as shown in Table 3.5. As per the standard local normalization procedure, all the indicators are ranked highest to lowest, and the normalized value for both V_i and Z_i would be calculated as shown in equation 3.25.

$$V_i' = \frac{max\ (V_i) - V_i}{max\ (V_i) - min\ (V_i)} \tag{3.25}$$

Table 3.5: Local Benchmarking values for 3 out of the 9 indicators used in the ECO_2 framework

	Total cost (£/m^3)	GWP (kg eq CO_2/m^3)	CED (MJ / m^3)	
Local Benchmarking	>82	>522	>3388	**Very High**
	75-82	392-522	2541-3388	**High**
	69-75	354-392	2299-2541	**Normal**
	62-69	224-354	1452-2541	**Low**
	<62	<224	<1452	**Very Low**

A normalized value for each indicator would be a value ranging from 0 to 1 in ascending order, which means 0 and 1 are the worst and best normalized scores for an indicator, respectively. After that, the normalized value of the single score ecological impact (Y) for each alternative (i) is calculated as per equation 3.26 where W_v is the variable representing the weight given for each mid-point environmental indicator V and subsequently its normalized value V'. These weights are either user-input according to the user's preference or would be assume equal as shown in Table 3.6.

$$Y_i = \sum V_i' * W_v \tag{3.26}$$

Table 3.62: An extract of the sustainability weights from the secondary database of the ECO_2 tool

Weight of sustainability Indicators (default)	GWP	ODP	AP	EP	ADPE	POCP	CED	FW
	13%	13%	13%	13%	13%	13%	13%	13%
	Ecological W_{E1}	Economic W_{E2}						
	50%	50%						

Finally, ECO_2, which is the single sustainability assessment index that combines is calculated. According to the equation 3.27, ECO_2 is calculated for each alternative (i) by combining the single ecological (Y_i) and economic (Z_i) indicators together based on their weights W_{E1} and W_{E2}. Following the same normalization order, the normalized value for ECO_2 ranges from 0 to 1 in ascending order, which means 0 and 1 are the worst and best normalized scores, respectively.

$$ECO_{2_i} = Y_i * W_{E1} + Z_i * W_{E2} \tag{3.27}$$

3.3.8. Limitations to the ECO_2 framework

The objective of creating the ECO_2 framework was to create a reliable concrete sustainability assessment framework through covering the identified gaps in the existing ones, but this does not mean that it is a perfect solution. Among the identified limitations in the ECO_2 framework is that, similar to any LCA study, there is no method to validate that the data provided is logical. The inventory data, especially if it is primary, could deviate from the median of the secondary database by several magnitudes of scale and there are no checks within the framework to alarm the user and ensure the results are logical. The second limitation is related to the methodology of calculating N, the replacement rate of the concrete's service life. The existing models to predict the service life of concrete against the steel corrosion whether through carbonation or chloride penetration could generally be described as simple. Both parameters of concrete performance vary widely depending on the details of the exposure conditions, the maturity of the concrete binder at the time of exposure and both factors are time dependant. Hence, it is acknowledged that the principle of predicting the service life of the concrete alternative in order to compare it with the required service life contains a large uncertainty. However, this is not a problem in the logic of the framework, but rather the current methods used in its application. This limitation would be easily tackled in the near future by updating the service life prediction models used to the more accurate ones expected to be released soon building on the works of Xuan-Dong et al. (2021) and (Pathan et al. (2021) for example. The same applies for carbon sequestration. Although the concept of including the potential of absorbing CO_2 as a positive environmental impact is one of the principles of the ECO_2 framework, the models used to predict the amount of sequestered carbon are still primitive. The solution to that would be to also include the more developed model in the future for the framework development.

3.4. Validating the ECO_2 framework

After demonstrating the methodology of the ECO_2 framework building of the gaps in existing ones from the literature, it is fit to investigate possible methods of validating it. The validation applies to two components separately, the selected sustainability indicators and the framework as a whole. According to De Neufville (1978), a sustainability indicator does not have validity in itself but only insofar as it matches the user's understanding and purpose. Hence, it should be judged based on its ability to serve the intended function which is in the case of this project, quantifying the sustainability of concrete. According to Sala et al. (2015), a standard method of validating sustainability indicators is a combination of scientific soundness and social appeal. In most cases, a questionnaire is prepared with the indicators explained and delivered to experts and stakeholders. In the case of the two novel indicators developed within ECO_2, Y and Z, it was not seen as necessary since the indicators were both building on gaps from existing literature as explained in earlier sections. Concerning validating the framework as a whole, Qureshi et al (1999) defines a method with three components:

- Sensitivity analysis: examines the extent of variation in predicted performance when parameters are systematically varied; ensures the stability of the model. As seen in Figures 3.3 and 3.5, this framework already allows a user to do a sensitivity analysis.
- Self-validation: the developers of the framework ensure data, conceptual and operational validity to the intended purpose. This is explained in section 3.4.1.
- Verification: ensures the model has been developed properly; conceptual and mathematical. Verification ensures that the model has been developed in a formally correct manner in accordance with a specified methodology.

3.4.1. Self-Validation of the ECO_2 framework

Similar to the methodology adopted in validating the indicators developed within ECO_2, the following summary of the features of the framework in terms of logic and application act as a self-validation method. As explained in section 3.3, these features were developed based on an identified gap in the previous concrete SA frameworks namely: MARS-SC and CONCRE*Top*:

i. <u>An LCA functional unit representative of performance-based specifications:</u>

The main feature in the ECO_2 framework is in fact a paradigm shift. Following the recommendations from the literature, the framework introduces a novel perspective to functional indicators. Rather than combining it with environmental and economic indicators, the ECO_2 framework uses performance based specifications as the basis for calculating the FU of the LCA. As explained in section 3.3.4, the FU is then used to calculate the environmental and economic impact indicators. This allows the stakeholders to build a more reliable judgment on the sustainability of the concrete alternatives under study.

ii. Including the whole life cycle boundary system of concrete:

As opposed to all other frameworks which assume a Cradle-to-Gate system boundary, the ECO_2 framework assumes a Cradle-to-Grave one. This, in return, allow for the inclusion of significant LCA features such as adding the impact resulting from the use and demolition of concrete.

iii. Deducting the sequestered carbon dioxide:

The predicted values for the sequestered carbon dioxide of every concrete alternative under study either through carbon utilization processes during production or natural exposure to carbonation throughout the required service life. This impact is deducted from the GWP indicator making the calculations more reliable based on literature recommendations.

iv. The framework is dynamic and includes a learning dimension:

Both frameworks being compared in this chapter to the newly developed ECO_2 framework, namely CONCRE*Top* and MARS-SC are static. This means that the framework does not develop. ECO_2 tool to be introduced includes a database of secondary data obtained from public databases and peer-reviewed articles that is continuously updated based on the primary data entered by the user.

v. Prioritize the use of primary data as inventory for LCA:

However, following the recommendations of the LCA best practice, the framework allows the user the flexibility to enter primary data for all variables of the study, which makes it more reliable.

vi. Include the environmental impact allocation for industrial by-product:

For the first time in a concrete SA framework, ECO_2 is mandating the inclusion of the upstream environmental impact of the industrial processes that generated materials such as FA, SF and GGBS. This feature assures a more accurate estimate of the LCA results, but will also mean that the interdependency between the economic and environmental impact is considered. Since in most cases the economic allocation scenario is followed, any variation in the market price of the SCM would have an impact on the environmental impact allocated.

vii. The economic impact is based on a whole life cycle:

As opposed to calculating the economic impact of concrete alternatives based on the market price according to CONCRE*Top* and MARS-SC, the ECO_2 framework predicts a whole life cycle cost of concrete taking into consideration the time value of money. This allows the economic indicator to include, potentially, carbon savings incentives. Also, depending on the possibility of replacing the concrete to meet the service life requirement, the cost of the alternative is decided.

viii. Allow for optimization based on scenario analysis:

ECO_2 recommends a specific scenario analysis that allows for optimization of concrete projects as a whole. The level of detail in a concrete structure is a unit volume or a building element such as a column or a beam or the whole structure. The volume of concrete in each of these LOD is non-linearly proportional with its assumed compressive strength. Hence, several scenarios could be assumed in which these two parameters and the sustainability index would then be optimized accordingly.

3.4.2. *Comparing ECO_2 to existing frameworks*

After explaining the distinctive features of the ECO_2 framework, it is necessary to observe how different the new logic is compared to both existing frameworks, MARS-SC and CONCRE*Top*. In order to clarify the differences, the comparison is done between 3 concrete mixes under 2 different scenarios. The hypothetical case study assumes a construction project requires 2 concrete mixes: a plain concrete one and another reinforced. The minimum required slump, 28 days compressive strength and service life are 200mm, 30 MPa and 50 years respectively. The mixing proportions for the three mixes under study are shown in Table 3.7.

Table 3.7: The mixing proportions of the three alternatives under study

Mix	1	2	3		
CEM I	250	125	125		Mixing Proportions (kg/m^3)
FA	0	125	0		
GGBS	0	0	125		
Coarse Agg	1050	1050	1050		
Fine Agg	950	950	950		
Water	165	165	165		
Superplasticizer	2.5	2.5	2.5		
Slump	200	280	220	mm	Fresh and mechanical properties prediction
28 days c. Strength	40	35	30	MPa	
Carbonation	100	20	40	Years	Service life prediction
Chloride penetration	100	150	200	Years	
Basic Unit cost	90	80	70		\$/m^3

The functional performance of the three mixes is not realistic. The values are assumed as such to guarantee a discrepancy of the values for the variable N. Hence, the results should only be perceived relatively between the 3 frameworks not in an absolute manner. The remaining assumptions of this case study are as follows:

- The concrete cover is assumed as 50mm for the service life calculations.
- The environmental indicators selected for the comparison between the frameworks are the global warming potential (GWP) and cumulative energy demand (CED). The reason is that these are the only two considered in the CONCRE*Top* framework.
- The average values for the LCI data were obtained from the ECO_2 database and summarized in Table 3.8 including the cost and transportation distances of the raw materials.
- The economic impact allocation for FA and GGBS from electricity and steel production are selected as 2% and 1%, respectively which are the average values from the literature.

Table 3.8: Inventory data for the hypothetical case study

Component	Unit	GWP kg eCO_2/unit	CED MJ/unit	Transportation Distance km
CEM I	kg	0.896	4.193	152
FA (no allocation)	kg	0.006	0.438	446
GGBS (no allocation)	kg	0.040	0.685	564
Coarse aggregates	kg	0.010	0.072	184
Fine aggregates	kg	0.007	0.058	184
Superplasticizer	kg	0.908	19.822	539
Transportation by truck	t.km	0.290	3.148	
Energy grid use	kWh	0.037	0.830	
Electricity from coal	kWh	0.319	0.001	
Steel production	kg	1.473	20.187	

As sections 3.2 and 3.3 demonstrated, the main difference in the logic of the ECO_2 framework than MARS-SC and CONCRE*Top* is the functional assessment of concrete. According to both reviewed frameworks, the functional impact of an alternative is calculated based on the local comparison of the alternatives in terms of measured performance regardless of the project specifications. Hence, the functional impact of alternatives 1, 2 and 3 would be calculated as follows:

Table 3.9: Functional Impact Calculations for the three reviewed frameworks

Mix	1	2	3	
Slump	200	280	220	mm
28 days c. Strength	40	35	30	MPa
Carbonation	100	20	40	Years
Chloride penetration	100	150	200	Years
Slump	1.0	0.0	0.8	normalized
28 days c. Strength	0.0	0.5	1.0	
Carbonation	0.0	1.0	0.8	
Chloride penetration	1.0	0.5	0.0	
Functional performance	0.5	0.5	0.625	MARS-SC and CONCRE*Top*
Required service life	50	50	50	ECO_2
minimum service life	100	20	40	
FU (PC scenario)	1	1	1	
FU (RC scenario)	1	2.5	1.25	

On the other hand, ECO_2 consider the functional performance compared to the project requirements by integrating it into the functional unit calculations for the LCA. As explained in section 3.2, the three mixes pass the minimum requirements since the slump and strength are higher than the project requirement. Hence, the functional unit of each alternative is calculated as shown in Table 3.9. Furthermore, the environmental impact assessment is calculated per unit volume of concrete by multiplying the inventory data of each mix constituent by its mixing proportion in each alternative. The three sustainability assessment frameworks being compared, MARS-SC, CONCRE*Top* and ECO_2 all have a similar process for the production impact per unit volume as shown in Table 3.10. However, since it considers a whole life cycle scope, the ECO_2 adds the impact of allocation, transportation, sequestration and construction and demolition. Hence, the impact assessment of each alternative according to the ECO_2 is always higher in absolute values with 10-20% than that calculated using MARS-SC and CONCRE*Top* as in Figure 3.7.

Table 3.10: Environmental impact of whole life cycle of concrete per functional unit as per ECO_2 framework

Mix		Functional performance	Environmental performance	Economic performance	Sustainability Index
1	MARS-SC and CONCRETop	0.5	0	0	0.17
	ECO_2 (PC scenario)	-	1	0	0.50
	ECO_2 (RC scenario)	-	0.81	1	0.91
2	MARS-SC and CONCRETop	0.5	0	0.5	0.33
	ECO_2 (PC scenario)	-	1	0.5	0.75
	ECO_2 (RC scenario)	-	0.72	0	0.36
3	MARS-SC and CONCRETop	0.625	1	1	0.88
	ECO_2 (PC scenario)	-	0.75	1	0.88
	ECO_2 (RC scenario)	-	0	0.8	0.40

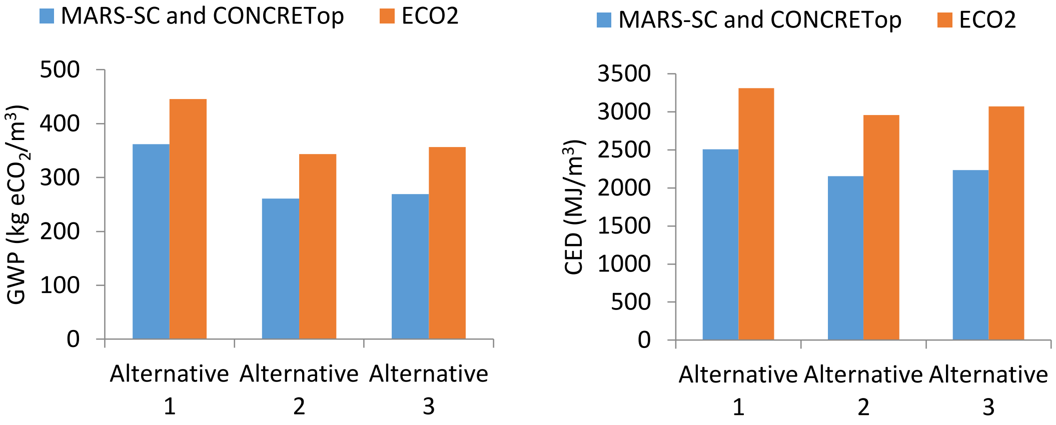


Figure 3.7: Comparison between the values of environmental impact indicators GWP (left) and CED (right) of the reviewed frameworks and ECO_2

Regarding the third pillar, the economic impact assessment, the reviewed frameworks simply compare the basic cost per unit volume of the concrete mixes. This means that since alternatives 1, 2 and 3 costs 90, 80 and 70 £/m^3 respectively, the score would be 0, 0.5 and 1. On the other hand, ECO_2 builds on a more reliable economic measure, which is the net present value of each alternative. For plain concrete, since the alternatives are expected to fulfil their service life requirement, the net present value is similar to the total cost, but the costs of transportation, construction and demolition are added as shown in Table 3.11. Moreover, assuming an interest rate 0.5% and an inflation rate of 2%, for the reinforced concrete scenario, the NPV of alternatives 1, 2 and 3 would be 105, 220 and 130 £/m^3.

Table 3.11: The economic impact assessment as per the MARS-SC and CONCRE*Top* frameworks and ECO_2

production cost	90	80	70	$\$/m^3$
Total cost	90	80	70	MARS-SC and CONCRE*Top*
Economic impact score	0	0.5	1	
Transportation, construction and demolition costs	15	15	15	$\$/m^3$
Net present value (PC scenario)	105	95	85	
Net present value (RC scenario)	105	220	130	
Economic impact score (PC scenario)	0	0.5	1	ECO_2
Economic impact score (RC scenario)	1	0	0.8	

Finally, the sustainability assessment index is generated by calculating a weighted average between all normalized indicators. The normalization of both environmental and economic indicators follows an ascending logic, which means that 1 is the highest value and 0 is the lowest. The results in Table 3.12 shows that although the values obtained from MARS-SC and CONCRE*Top* are different than that obtained from ECO_2, the judgment/ranking of the alternatives is the same. In the PC scenario, mix 3 with the GGBS is the best, followed by the FA mix and finally the CEM1 mix. This could be attributed to the fact that the SCMs have lower environmental impact and are cheaper than CEM1. However, in case of RC concrete (scenario 2), due to the higher service life expected for the CEM I mix, mix 1 ranks the most sustainable, followed by the GGBS alternative and finally the FA one.

Table 3.12: Single index sustainability score of the alternatives using MARS-SC, CONCRE*Top* and ECO_2 frameworks

Mix		Functional performance	Environmental performance	Economic performance	Sustainability Index
1	MARS-SC and CONCRETop	0.5	0	0	0.17
	ECO_2 (PC scenario)	-	1	0	0.50
	ECO_2 (RC scenario)	-	0.81	1	0.91
2	MARS-SC and CONCRETop	0.5	0	0.5	0.33
	ECO_2 (PC scenario)	-	1	0.5	0.75
	ECO_2 (RC scenario)	-	0.72	0	0.36
3	MARS-SC and CONCRETop	0.625	1	1	0.88
	ECO_2 (PC scenario)	-	0.75	1	0.88
	ECO_2 (RC scenario)	-	0	0.8	0.40

3.4.3. Verification of the ECO_2 framework

In order to verify that the framework serves the purpose it was designed for, a tool was developed using Ms-excel that follows the logic explained in the previous sections. The tool will be implemented on three different case studies in the next chapters. This would be the test that the framework is implementable, accurate and can provide a better judgement on how certain concrete alternatives measure in terms of ECO_2 sustainability index under specific scenario.

Chapter 4

Case study #1: Assessing the sustainability potential of alkali activated concrete from electric arc furnace slag using the ECO_2 tool

4.1. Introduction

As mentioned in the previous chapters, the sustainability potential of any non-conventional concrete type can be assessed only after optimizing them based on their technical properties, EI and cost simultaneously. For that purpose, this study developed a newly advanced ECO_2 framework (Chapter 3) to optimize concrete with non-conventional ingredients based on the mentioned categories. The aim of the current chapter is to validate the mentioned method using experimental data and results from the literature.

The literature review in Chapter 2 concluded that there is a possibility to produce sustainable concrete by alkali activating recycled industrial by-products as cement-free binders. Hence, as part of a collaboration with the civil engineering research and innovation centre for sustainability (CERIS) at the University of Lisbon, an experimental based case study was prepared for a novel alkali activated concrete (AAC) type. The industrial by-products, namely electric arc furnace slag (EAFS) and fly ash (FA) were used as a precursor to develop the cement-free binder for the AAC. Primary data required to calculate the sustainability index using the ECO_2 tool were collected including functional, environmental and economic parameters. Accordingly, this chapter first describes the case study and then presents the background on EAFS based AAC. After that, the data collection process is evaluated including all the experimental and analytical methods. Finally, the data was fed into the ECO_2 tool developed in chapter 3 in order to judge the sustainability of the novel concrete mixes. The results are later discussed and summarized.

In this work, the general background of the ACC based EAFS was first shown to understand the functional, environmental and economic parameters of this concrete that will be a first case study for the mentioned method (section 4.2), and also to show that judgement of any materials in terms of a single direction (e.g., environmental and economic impact) may not be reliable. Then, details on the selected case study were shown in section 4.3. Section 4 dedicated to the data collection, especially the details on the experimental work. After that, the main goal of this work was considered, namely applying the ECO_2 tool on the case studies (section 4.5). At the end, the outputs were discussed by considering the sensitive analysis (section 4.6).

The contents of this chapter were published in the 281st volume of the "Construction and Building materials" journal on 26th April 2021 under the title "Assessing the sustainability potential of alkali-activated concrete from electric arc furnace slag using the ECO_2 framework". The paper included the following authorship responsibilities, Conceptualization and preliminary analysis (Rui Vasco Silva), Data collection (Hisham Hafez, Dany Kassim), Data analysis (Hisham Hafez), Data interpretation (Hisham Hafez, Rawaz Kurda), Writing the paper (Hisham Hafez), Revision (Jorge de Brito), and Submission (Hisham Hafez).

4.2. Background

4.2.1. Sustainability Potential of AAC

Since the early work of Purdon and Glukhovzky in the 1940s and 1960s respectively till the recent 2020 such as RILEM technical report by Provis et al., (2020), AAC has been regarded as a potential for producing sustainable concrete. The core attribute of the sustainability of AAC is that it valorises industrial by-products of low recyclability into the precursor of the binder. This combines the merits of totally eliminating the impact of using cement as well as reducing the impact of landfilling these by-products. According to Jiang et al. (2014), the embodied carbon of an AAC mix is around 50% less than that with OPC. Nevertheless, industrial by-products are usually cheaper than OPC which enhances the sustainability potential of AAC even more (Provis et al. 2014). However, the mentioned fact may not be generalized on the environmental and economic impact of all AAC alternatives. The reason is that sodium silicate (SS) and sodium hydroxide (SH), the main components of the alkaline activator solutions in AAC, are expensive and energy intensive in production (Garcia-Lodeiro et al., 2014). Another reason is that in several cases, some energy is required to either prepare the industrial by-product by crushing and milling or in the heat curing of the AAC (Komljenovic et al., 2013). The use of SS and SH also causes a 10 times increase in the human toxicity, fresh water Ecotoxicity and ozone layer depletion (ODP) of the resulting AAC mix (Habert et al., 2011). However, the ODP impact of a kg of cement is already insignificant when contextualized to the greater environmental ecosystem since it equals the impact of the average household lighting in months (Passuello et al., 2017). According to the statement given above, the judgement on the environmental and economic impact of AAC, although shows a positive prospect, is not clear. This is one of the issues that will be resolved through the tool developed in chapter 3 (ECO_2 tool).

Apart from environmental and economic impact, the functional properties (the third pillar of sustainability according to the ECO_2 tool) of AAC also vary on a large scale. The strength and durability of an AAC is highly dependent on the quality of the binder produced, which was found to be correlated to three main aspects (i-iii).

i. First, the reactivity of the precursor, which has some correlation to the following three factors:
  - The hydration modulus HM= $(CaO+MgO+Al_2O_3)/(SiO_2)$. The more hydraulic it is (HM > 1.4), the easier it is activated (Law et al., 2011);
  - The microstructure. According to Wang et al. (1994), a material that is more crystalline is less reactive than the amorphous one;
  - The particle size of the material. The smaller it is, the larger the surface area of the material and thus it becomes more reactive (Nassir Amin et al., 2017).

ii. The second aspect that determines the quality of the binder in an AAC mix is the chemical compatibility of the reactants. As agreed, a precursor is a material with an abundance of either calcium, aluminium or silicon oxide as shown in Figure 4.1. It was found that the following four ratios are critical to the functional properties of the AAC mix (Provis et al., 2019):
  - The mass ratio of solution to the precursor;
  - The Si/Al ratio of the chemical composition of the precursor;
  - The concentration of the alkali activating solution (Na_2O %);
  - The ratio between SiO_2/Na_2O in the alkali activator (MS).

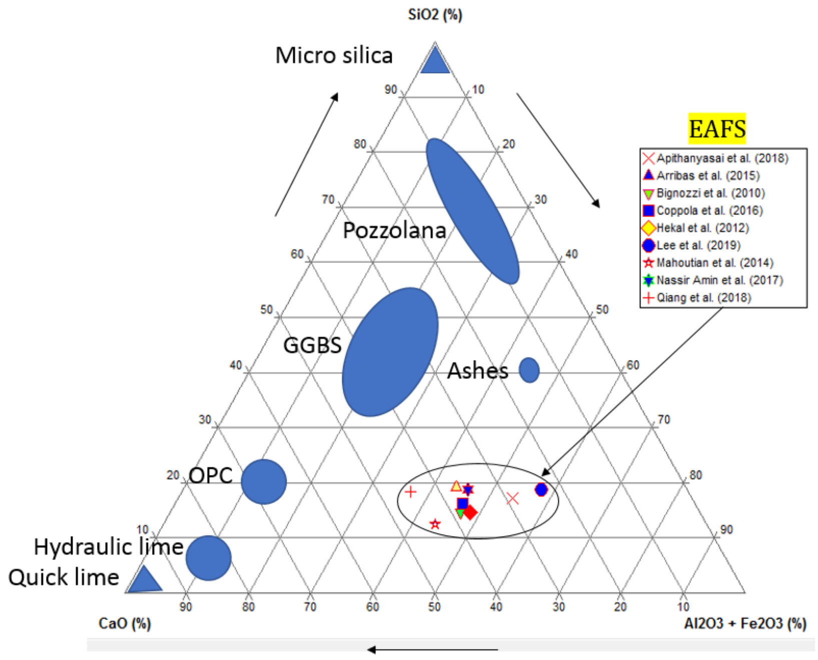


Figure 4.3: A ternary diagram for the chemical composition of possible precursors for AAC

iii. The third and final aspect that affects the functional properties of an AAC mix is the curing method. Palacios and Puertas (2011) argued that dry sealed curing optimizes the properties of AAC, while Mohammad Nassir et al. (2017) emphasized the significance of heat curing for AAC especially that with FA as a precursor for the first 24 hours.

As agreed in chapter 3, the selected functional parameters for the ECO_2 framework are the workability, strength and durability against chloride penetration and carbonation. First, most AAC mixes have higher workability than OPC concrete according to Puertas et al. (2014), but it is more susceptible to decrease after short periods of time depending on how high the SiO_2/Na_2O ratio is. However, AAC is not compatible with most of the commercially available water reducing agents which is fundamental in increasing the workability beyond a certain threshold of the solution to precursor ratio (Rashad, 2013). Secondly, the compressive strength of an AAC mix could be higher than that of OPC concrete but the higher the solution concentration (Na_2O %), the higher the strength of the FA based AAC (Kumar et al., 2007). Regarding the GGBS based AAC mixes, Duxson et al. (2005) confirmed that the silica modulus is an essential parameter for optimizing the mechanical properties of the resulting AAC. Regarding the resistance to chloride penetration, AAC is typically more durable than OPC concrete, but is also highly dependent on the SiO_2/Na_2O ratio in the activator as well as the ratio of activator: precursor (Ravikumar and Neithalath, 2013). Finally, Bernal et al. (2015) concluded that generally most AAC mixes are less durable to carbonation than OPC concrete, but are still highly dependent on the optimization of the chemical ratios as discussed before.

4.2.2. Literature review on EAFS

Normally, for one tonne of steel, 7-15% of non-hazardous slag is produced with the potential of being recycled in different applications such as ground granulated blastfurnace slag (GGBS) and EAFS (Buchart-Korol, 2013). GGBS is a by-product from blast furnace based steel making processes, has almost 97% recyclability potential as a SCM due to its highly pozzolanic nature (Dhir et al., 1996). However, most of the steel production worldwide is shifting towards electric arc furnaces (EAF) because it requires less energy and cost (Jiang et al., 2018). For this fact, EAF production technique took over 55% of the market in the US in 2006 (Jiang et al., 2018). Considering that fifty million tonnes of EAF steel are produced worldwide, around 5 million tonnes of EAFS are generated in the process (Bignozzi, 2010). Contrary to GGBS, only 20% of the produced EAFS is recycled as low value road embankments while the rest are landfilled (Adsenaya, 2018). Hence, there is a significant potential for recycling EAFS as a precursor in AAC. In order to assess the suitability of recycling EAFS in binders, the following factors were found in the literature.

- The chemical composition: Due to the variability in the raw materials used for steel manufacturing through EAF, the chemical composition of EAFS shown in figure 4.1 was found to vary widely (Coppola et al., 2016). It mainly consists of 25-40% of iron oxides, 25-40% of calcium oxides, 10-30% of silicon oxides and 5-15% of aluminium oxides (Figure 4.1).

This means that there is abundance in aluminosilicate qualifying it as a precursor. However, the presence of some free CaO in the chemical composition of EAFS provides a threat to its potential integration within concrete due to risk of volumetric instability (Arribas et al., 2015).

- The minerology: The main mineral composition of EASF consists of calcium di and tri silicates (C_2S, C_3S), the same abundant minerals in cement, which means there is a possibility of integrating EAFS as a supplementary cementitious material (Qiang et al., 2013). However, the physical characterization of EAFS without treatment shows almost fully crystalline microstructure which indicates low reactivity (Choi et al., 2016). The reason is that the molten slag is dumped upon formation and is allowed to air cool over a long time.

As received EAFS is dark in colour, with angular shaped fractions of a hard and rough surface which makes it for use as an aggregate in concrete (Jiang et al., 2018). The density of EAFS varies between 3000 and 3500 kg/m^3, which is 20-30% higher than that of natural aggregates due to the presence of iron and iron oxides (Coppola et al., 2016). Concrete mixes; in which EAFS was incorporated as coarse aggregates, were found to exhibit a decrease in compressive strength (Arribas et al., 2015). The higher replacement level of coarse natural aggregates with EAFS, the less the workability and the higher the shrinkage of concrete (Gonzales-Ortega et al., 2019) can be seen. This is because EAFS absorbs 20-30% more water than that of the natural aggregates (Faleschini et al., 2015). However, the concrete mixes where EAFS was used as aggregates were found to be compatible regarding resistance to freeze-thaw and sulphate attacks (Manso et al., 2016). Studies showed that integrating EAFS as a partial replacement of OPC up to 20% in blended cement concrete would yield the same compressive strength (Parron-Ribio et al., 2018; Qiang et al., 2013). For higher replacement ratio, the strength and durability of the BCC decrease due to the established low pozzolanic activity (Hekal et al., 2012). However, further mechanical activation of EAFS; which can be achieved through grinding it to a d90=11 micrometres, can increase the replacement ratio up to 30% (Nassir Amin et al., 2017). The energy required to grind the landfilled EAFS to the required particle sizes was reported to be 68 kWh/tonne according to Adolfsson et al. (2011). Also, re-melting and then quenching of the EAFS would result in a more amorphous microstructure which would enhance the pozzolanic properties of the slag (Mumoud et al., 2009). However, the initial idea behind recycling EAFS into concrete was to decrease the environmental impact, therefore special attention is needed when energy-intensive processes as such are required. When it comes to alkali activated binders, only few references (Apithanyasai et al., 2018; Ozturk et al. 2019) that attempted to utilize EAFS as a precursor were found. Apithanyasai et al. (2018) prepared an alkaline solution using 10 M concentration and a silica modulus of 2.5 and the solution: precursor ratio was 0.9. The compressive strength of the EAFS based alkali activated paste was 30% less than the control OPC paste but the water absorption and shrinkage were compatible. Also, Ozturk et al. (2019) ran an optimization scheme on several mortar mixes and concluded that the optimum mixes for compressive strengths were obtained when the sodium oxide concentration, silica modulus and early age curing temperature were set at 6%, 2 and 80

◦C, respectively. Apithanyasai et al., (2018) reported that the EAFS was supplied for free by steel factories, so it would probably carry no economic impact allocation from the original steel manufacturing process unlike GGBS. This shows sustainability potential in terms of economic and environmental impact when recycled as a precursor for AAC. However, the functional parameters are still uncertain, given the variability in the chemical composition of EAFS and the scarce publications on this regard. Hence, it is advisable to use an established AAC precursor such as FA as a reference for functional parameters due to high number of studies since FA based AAC could show satisfactory performance in terms of functional impact depending on the optimized mix design parameters.

4.2.3. Summary of literature

The following literature data in Table 4.1 summarizes the effect of certain factors of the mix on the sustainability parameters of the AAC using EAFS as a precursor.

4.3. Description of the case study

It is now established that industrial wastes of low recyclability could present a sustainable alternative for OPC in concrete through alkali activation. The environmental motive behind considering EAFS as a precursor in this study is that around 0.5 million tonnes of EAFS are produced in Portugal every year (Statista, 2019) and currently it is all just landfilled. This sustainability of the resulting concrete is significantly dependent on other constituents and the concrete mixing proportions, as explained in section 4.2. Another factor is the availability of industrial waste in proximity to the concrete production facility. Transporting the waste for long distances could counteract the positive and environmental gains attained from the recycling process (Hafez et al., 2020).

This case study, done in collaboration with the University of Lisbon, investigated the possibility of recycling EAFS as a precursor in AAC. The slag was obtained from Siderurgia Nacional, the main steel manufacturer in Portugal. The case study had the following objectives:

- Design and prepare several promising mixes based on approximations from the literature for EAFS based AAC;
- Prepare AAC mixes based on FA as a reference;
- Collect the necessary inventory data for the environmental and economic impact of all the mix constituents as per the LCA scope in the ECO_2 framework;
- Test the fresh, hardened and durability properties as required by the ECO_2 framework of the designed mixes of AAC;
- Apply the ECO_2 tool on all prepared mixes and discuss the obtained results compared to the literature.

Table 4.1: A summary of the effect of critical parameters of the mix design of AAC on sustainability indicators

Parameter	**Interpretation**	**Action**	**Predicted effect on the AAC sustainability parameters**				
			Functional			**Environmental**	**Economic**
			Workability	Strength	Durability		
Chemical composition of precursor	The higher the hydration modulus the more reactive	None	NA	NA	NA	NA	NA
Particle size of the precursor	To less it is the higher the reactivity	Mechanical activation	NA	⇧	⇧	⬆	⬆
Mineral characteristics of precursor	The more amorphous, the more reactive	Re-melting and quenching	NA	⇧	⇧	⬆	⬆
Alkalinity of Precursor (Kb)	If >1, a base. optimum Ms = 1.00-1.5 If < 1, an acid optimum Ms = 0.75-1.25	The more sodium silicate used, the higher the Ms	⬇	⇧	⇧	⬆	⬆
Silica Modulus (Ms) = SiO_2/Na_2O	-						
Alkaline concentration = Na_2O %	-	The more SH used, he higher the% of sodium oxide in the solution	NA	⇧	⇧	⬆	⬆
Solution : Precursor Ratio	Optimum ratio around 0.4	Decrease the ratio	⬇	⇧	⇧	⇩	⇩
EAFS / FA ratio	% replacement of FA by EAFS as a precursor	Increase the ratio	⇧	⇧	⇧	⬆	⬆

Improve ⇧⇩ Deteriorate ⬆⬇

NA (Non applicable) = the change in this variable is not necessarily correlated with a change in this indicator

4.4. Data collection

4.4.1. Functional Properties:

4.4.1.1. Materials:

- Electric Arc Furnace Slag:

The slag was acquired from the Siderurgia Nacional company, Portugal with a particle size of around 40-50 mm as seen in Figure 4.2a. In order to obtain an average particle size equivalent to that of cement, 3 stages of mechanical activation were followed. In the first stage, the slag was crushed using a Los Angeles abrasion testing machine, then using a jaw crusher and a ball mill . After the three stages, the slag were sieved to ensure 99% of it passes sieve #120 as in Figure 4.2b.The detailed procedure will be explained in section 4.4.2 along with the energy required for the treatment and transportation processes. The chemical characterization was done using X-ray fluorescence on different sizes of EAFS as well as FA and the results are summarized in Table 4.2.

Table 4.2: The XRF results for the chemical composition of EAFS and FA

Chemical composition	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)
EAFS	25.5	16.0	9.16	25.7	5.12	0.3	0.17	0.03
FA	3.6	57.8	20.9	7.4	1.0	0.6	1.0	1.7

Figure 4.2: A picture showing the EAFS as-received (a- left) and after milling to the required size for use as a precursor in concrete (b-right)

- Fly Ash:

FA was acquired from a local supplier in Lisbon. Details around the price and transportation distances were shown in section 4.4.2. The FA as received had a nominal particle size of 99% passing sieve #120. The chemical composition of the FA was provided by the supplier as shown in Table 4.2.

- Alkaline Solution:

To prepare the alkaline solution, pure SH pellets (99% purity) were acquired from a local supplier in Lisbon. For water reduction purposes, a commercial superplasticizer (SP) that consists of a β-naphthalene sulfonic acid formaldehyde condensate was acquired from a local supplier in Lisbon. Details concerning the price and transportation distances of both materials were shown in section 4.4.2. In addition, drinking (tap) water from the public water network was used for the mixture.

- Aggregates:

Five grades of natural aggregates were quarried from different local sources. Two sizes of natural silica sand were used as fine aggregates and 3 sizes of crushed limestone were used as coarse aggregates. The decision to select five different sizes of aggregates was aimed at optimizing the gradation curves compared to the ASTM C33 as shown in Figure 4.3.

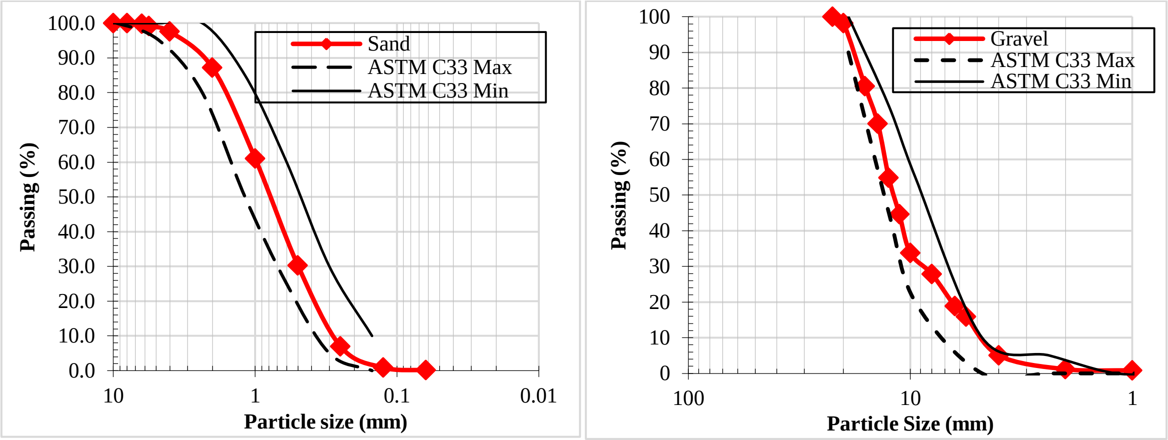


Figure 4.3: Gradation curves of the coarse (left) and fine (right) aggregates used in the concrete mixes

The aggregates were stored in a dry area to guarantee saturated surface dry conditions. The particle sizes and proportions, as well as the water absorption percentages, of each of the 2 types of aggregates are summarized in Table 4.3. Similarly, to other materials, details concerning the price and transportation distances of the aggregates were shown in section 4.4.2.

Table 4.3: Characterization of the aggregates used in the concrete mixes

Aggregates	**Nominal size**	**Oven-dried density**	**Water absorption**	**Mass ratio**	General size
	mm	(kg/m^3)	%	%	
Fine sand	0/1	2637	0.4	30	Fine aggregates
Coarse sand	0/4	2617	0.5	70	
Rice grain gravel	2/5.6	2600	1	15	Coarse aggregates
Fine gravel	5.6/11.2	2600	1.2	25	
Coarse gravel	10/20	2600	1.4	60	

4.4.1.2. Concrete mixes:

In order to assess the functional properties of the EAFS based AAC, an experimental program was developed for the mixes shown in Table 4.4. Mixes 1-3 consist of precursors of 100% FA as a reference AAC, while mixes 7-9 are based on 100% EAFS precursors. The reason the FA based alternatives were used as a control is due to fact that the FA AAC is established in the literature. To gain the co-benefits from the aforementioned types of mixes, mixes 4-7 were attempted with proportions of 50% FA and 50% EAFS as precursors. The recommended optimum mixture for AAC using EAFS was reported in the literature to be 6% alkaline concentration and a silica modulus of 2 (Ozturk et al., 2019). However, it was decided to use an alkaline solution with a concentration of 10%, and no sodium silicate in order to reduce the severe environmental and economic impact associated with the latter. The water to precursor ratio was chosen to vary between 0.30, 0.40 and 0.50 and the dosage of SP was varied accordingly based on trial mixes to target an S2/S3 slump classes. The proportions per m^3 of each mix are summarized in Table 4.5.

Table 4.4: The mix design for mixes 1-9

Mixes	Effective water/ precursor (mass)	SP/ precursor (%)	FA (%)	EAFS (%)	Na_2O/ precursor (%)
M1	0.30	1.50	100	0	10
M2	0.40	0.50			
M3	0.50	0.00			
M4	0.30	1.50	50	50	
M5	0.40	0.50			
M6	0.50	0.00			
M7	0.30	1.50	0	100	
M8	0.40	1.00			
M9	0.50	0.50			

Table 4.5: The mixing proportions for mixes 1-9

Raw materials	Mass of each component per AAC mix (kg/m^3)								
	M1	M2	M3	M4	M5	M6	M7	M8	M9
FA	299	292	284	150	146	142	0	0	0
EAFS	0	0	0	167	163	158	334	325	316
SP	4	1	0	5	1	0	5	3	2
Water	104	131	155	104	131	155	104	130	155
NaOH	39	38	37	41	40	39	43	42	41
Fine sand $_{0/1}$	265	258	251	265	258	251	264	257	250
Coarse sand $_{0/4}$	613	597	581	613	597	581	612	595	579
Sand-Gravel $_{2/5.6}$	174	169	165	174	169	165	174	169	164
Fine gravel $_{5.6/11.2}$	290	282	275	290	282	275	290	282	274
Coarse gravel $_{10/20}$	696	678	660	696	678	659	695	676	658

4.4.1.3. Concrete mixing:

Following the standard procedure for AAC, the alkaline solution was prepared by dissolving the SH pellets in water gradually and then left to cool down for 24 hours. On the mixing day, the solution was added first in the vertical mixer (wetted initially to avoid water absorption) along with the SP and the precursor then mixed for 5 minutes. After that, the mixer was stopped until the aggregates were added and then all the components were mixed together for another 5 minutes. After the slump test was carried out, the steel moulds were sprayed from the inside with paraffin to act as a release agent. Subsequently, the concrete was manually casted with the required dimensions. Steel moulds were used instead of plastic moulds due to the sticky nature of AAC that would make its demoulding process more difficult. A needle vibrator was used to vibrate the concrete upon casting for 30 seconds placed 20 mm off the floor of the mould according to NP EN 12390-2. After finishing the surface of the AAC moulds with a trowel, the specimens were wrapped with thin plastic film for sealing as shown in Figure 4.4 then placed in the oven. Following the recommendations from the literature, each specimen was cured for the first 24 hours in an oven at 70◦C. Although FA based AAC is established to achieve adequate strength at 28 days of curing under room temperature (Criado et al., 2010), all samples were subjected to heat curing in order to allow for a fair comparison in terms of the energy demand. Afterwards, the specimens were demoulded and left to cure in a temperature of 23 ± 2◦C and a relative humidity of 100% till testing day. Direct water contact with the specimens was prevented to avoid efflorescence. The energy requirements in all the concrete construction processes were discussed in section 4.4.2.

Figure 4.4: A picture of the casted AAC samples with the plastic wrap prior to thermal curing

4.4.1.4. Concrete testing procedure:

- Slump:

The standard slump cone test was performed on each fresh mix according to the EN 12350-2 standard. Mixes with a slump less than 100 mm were rejected and the SP was changed to obtain the target slump.

- Compressive Strength:

After 28 days of curing, cubic samples of 150mm per side were tested for compressive strength according to the NP EN 12390-3 standard. Three cubes from each mix were tested using a TONI PACT 3000 universal testing machine with a loading rate of 12 KN/s.

- Chloride Ion Penetration:

After 28 days of curing, for each concrete mix, three cylindrical specimens of 100 mm in diameter and 50 mm in thickness were cut from the casted cylinders. According to the BUILD NT 492 standard, the specimens were placed in a clean and dry desiccator and air vacuumed for 3 hours. After that, the samples were vacuumed in a lime solution for 1 hour then left for 20 more hours to saturate in the lime solution. On testing day, the specimens were placed in sealed rubber forms and placed in the rapid chloride ion penetration testing (RCPT) apparatus as shown in Figure 4.5a. Inside the apparatus, two solutions were added, the cathodic solution with salt and water and the anodic solution with SH and water. Measurements were taken for the temperature of the anodic solution and the calibrated voltage then the samples were left for the designated testing period (24 hours). After the testing period ended, the temperature of the anodic solution and the voltage by the apparatus were logged again and the samples were broken in halves. By spraying each half using silver nitrate solution and leaving it to set for 24 hours, the depth of penetration was measured using a vernier calliper across 7 equally spaced intervals along the cross section of the specimen as seen in Figure 4.5b. The chloride penetration resistance of each specimen D_{nssm} was calculated using equation 4.1.

$$D_{nssm} = \frac{0.0239 * L * \ (273 + T)}{t * (U - 2)} * \left(X_d - 0.0238 * \sqrt{\frac{L * \ X_d * (273 + t)}{U - 2}} \right) \qquad (4.1)$$

Where T is the average temperature of the solution in ◦C, U is the voltage in volts set for the test, t is the testing duration in hours, L is the specimen thickness in mm and X_d is the average depth of chloride penetration measured in mm.

Figure 4.5: The picture on the left (a) is for the RCPT machine and on the right (b) is for a broken sample while measuring the depth of chloride penetration

- Carbonation:

After 21 days of curing, three cylindrical specimens of 100 mm diameter and 30 mm thickness were cut from the originally cast samples of each mix based on the LNEC E391 standard. The specimens were painted with insulating rubber on both sides allowing the carbonation only along the periphery. At 28 days, the specimens were placed in a carbonation chamber with a CO_2 concentration of 5 ± 0.1%, temperature 23 ± 3◦C and relative humidity of 60 ± 5% for 14 days as seen in Figure 4.6. After the exposure period ended, the samples were broken into four pieces and sprayed with phenolphthalein. The depth of carbonation was then measured using a Vernier calliper across each face of the broken fraction of each sample and averages were recorded for every mix. Although it is established in the literature that, for the carbonation results of AAC to be representative, the CO_2 concentration in the carbonation chamber should be < 1% (Criado et al., 2017), the facilities did not allow for a change in the existing set level of CO_2 due to the ongoing experiments in the chamber. Hence, the carbonation results are not considered as conclusive of the carbonation performance of the mixes, but rather a relative performance measure across them.

Figure 4.6: Samples in the carbonation chamber

4.4.1.5. Concrete testing results

The results of the experimental work explained in section 4.4.1.4 are summarized in Table 4.6. Generally, the standard deviation of all results are small, and there were not any outlying results. In the following paragraph, the output of each studied test, namely (i) slump, (ii) compressive strength, (iii) chloride penetration resistance, (iv) accelerated carbonation rate and are showed. The results were discussed in section 4.4.1.6.

Table 4.6: A summary of the results for the conducted tests on the AAC mixes in this study

Tests	**Mixes**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Slump (mm)	Actual value	105	200	180	110	190	170	140	190	210
28 days Compressive Strength (MPa)	Actual value	23.7	18.8	14.0	12.7	10.8	10.3	1.9	1.5	1.7
		22.7	18.1	13.2	11.8	11.1	9.2	1.9	1.7	1.4
		24.3	19.4	13.2	11.9	10.5	9.7	1.8	1.6	1.4
	Average	23.6	18.8	13.5	12.1	10.8	9.7	1.9	1.6	1.5
	St. Dev.	0.8	0.7	0.5	0.5	0.3	0.5	0.1	0.1	0.2
28 days resistance to chloride penetration D_nssm (*10-12 m2/s)	Actual value	16.79	17.77	18.35	9.08	10.36	11.95	16.97	15.93	18.18
		16.79	18.26	17.41	9.08	10.62	11.75	17.25	16.39	19.17
		17.54	17.28	17.16	8.94	10.91	11.32	17.87	15.99	19.16
	Average	17.0	17.8	17.6	9.0	10.6	11.7	17.4	16.1	18.8
	St. Dev.	0.4	0.5	0.6	0.1	0.3	0.3	0.5	0.2	0.6
Accelerated carbonation rate (mm/year$^{1/2}$)	Actual value	81	86	94	97	96	92	111	114	127
		75	85	87	92	97	100	112	115	118
		84	89	87	92	93	97	111	120	122
	Average	80	87	89	94	95	96	111	116	122
	St. Dev.	5	2	4	3	2	4	1	3	5

i. The higher the water to precursor ratio is, as expected, the higher the workability of the mix. However, the slump results show no clear correlation between the changes of the precursor from FA to EAFS.

ii. The 28 days compressive strength results show that replacing FA with EAFS as a precursor for the AAC resulted in a decrease in strength as seen in Figure 4.7. Note that the values of strength for mixes 7, 8 and 9 where EAFS was solely used (as a 100% precursor) as a precursor were very weak (almost 1 MPa). It was also noticed that, among the 100% FA mixes (M1-3), the higher the water: precursor ratio, the lower the strength.

iii. In terms of resistance to chloride penetration, there was no clear correlation between the results for the RCPT test and any of the 2 variables understudy (water/precursor ratio and FA/EAFS ratio).

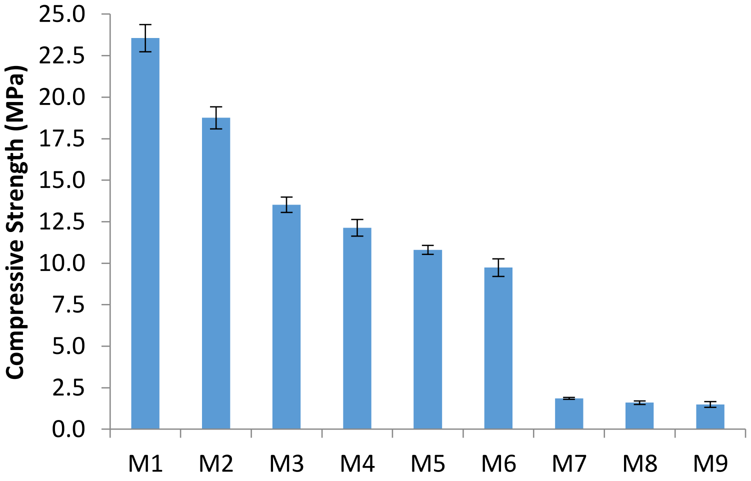


Figure 4.7: A graph showing the compressive strength of the AAC mixes tested

Finally, in order to calculate the resistance to carbonation, the carbonation depth of each mix was measured after the accelerated test. The depth of carbonation is then divided by the period of exposure to calculate the carbonation rate. In order to convert the accelerated carbonation rate K_a to natural carbonation rate K_n, the following equation 4.2 is used, where CC_n is the natural carbon concentration which is assumed as and CC_a is the carbon concentration is the testing chamber (%).

$$K_n = K_a\sqrt{\frac{CC_n}{CC_a}} \tag{4.2}$$

As seen in Figure 4.8, the higher the water/precursor ratio, the higher the natural carbonation rate was found to be. The same applies for replacing FA with EAFS as a precursor, the higher the replacement ratio, the lower resistance the AAC mix is to carbonation. Although the carbonation experimental setup was, as established in the previous section, not suitable to the nature of AAC, the relative performance between the mixes follows the expected trends in the literature.

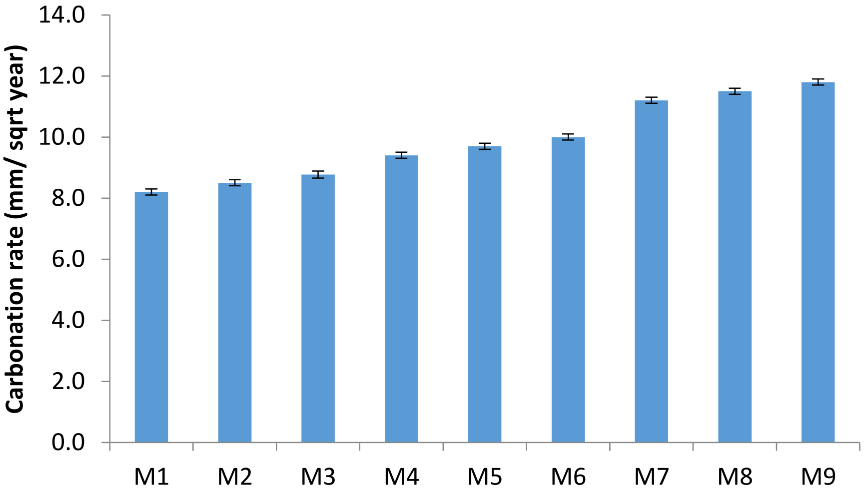


Figure 4.8: A graph showing the natural carbonation rate of the AAC mixes tested

4.4.1.6. Discussing concrete testing results:

It is not within the scope of this chapter, or the project as a whole to extensively investigate the reasons behind the functional properties of concrete mixes. As far as the ECO_2 framework is concerned, the functional properties are an input similar to other inventory data. The accuracy and reliability of this data is dependent on the accuracy of the literature review had it been secondary or on the user in case of primary data. Hence, in this case study, the experimental results were discussed to validate the mix designs and methodology.

The results clearly indicate that the use of EAFS as a 100% precursor with the proposed alkaline activator; which has a modulus of silica equals 0 yields a very weak binder. The literature suggested that the optimum activator for a slag would have a modulus of silica close to 2. However, the logic behind the selection of this alkaline activator is to avoid including SS to maintain a low level of the economic and environmental impacts.

4.4.2. Environmental and Economic Data

4.4.2.1. Production of raw materials

The selling prices of all the raw materials could be summarized in Table 4.7. The energy requirements for the quarrying of the aggregates and water were not available so it was assumed to be equal to the average in the ECO_2 database. The same applies for the SH and SP. For the impact allocation of the FA, since the difference between the price of electricity and FA in Portugal is >25%, economic impact allocation scenario was followed as per equation 4.3.

$$\text{Economic Allocation} = \frac{(\text{€.m})_{\text{FA}}}{(\text{€.m})_{\text{electricity}} + (\text{€.m})_{\text{FA}}} = 3\% \qquad (4.3)$$

The EAFS was assumed to have zero impact allocated since no economic value or established recycling protocol were associated with it. However, in order to prepare the slag to be of the adequate particle size, it went through a lengthy process. For every 20kg, the LA abrasion testing machine was used for 2 hours, then the jaw crushing machine was used for 1 hour and finally the ball milling machine was used for 2 hours. The power input for each of these machines are 800W, 500W and 1200W, respectively. Hence, the energy demand allocated for the production of each kg of EAFS is calculated as follows:

Slag processing energy = (2h*0.8kW + 1h*0.5kW + 2h*1.2kW) / 20kg = 83 kWh/tonne (4.4)

Table 4.7: Summary of the primary inventory data for the raw materials used in this study

Materials	Unit	Energy Demand (kWh/unit)	Price (£/unit)	Transport Distance (km)
Aggregates	Tonne	-	11.77	15
Water	Tonne	-	2.77	0
SH	Tonne	-	507	100
Plasticizer	Tonne	-	1433	20
FA	Tonne	-	36.22	60
Electricity	KWh	-	0.10	-
EAFS	Tonne	83	0.00	30

4.4.2.2. Transportation of raw materials

All materials were produced in Portugal and transported locally to the University of Lisbon's labs where the testing was done. The means of transportation was assumed to be a 20 tons lorry and the return trip was accounted for by adding 70% to the distance travelled. The cost of transportation is assumed to be 0.0485 £/km/tonne as per the average in the ECO_2.

4.4.2.3. Impact of concrete production

The construction of concrete includes the process of mixing, vibrating and curing. As explained in section 4.3, the curing method followed for all AAC mixes within the scope of this experimental campaign included 24 hours in the oven. The oven, operating at 70◦C used a heat gun with input power equals to 2000W. The oven has a capacity of approximately 25 cubes (150mm a side) which means that the energy required for curing could be calculated as follows:

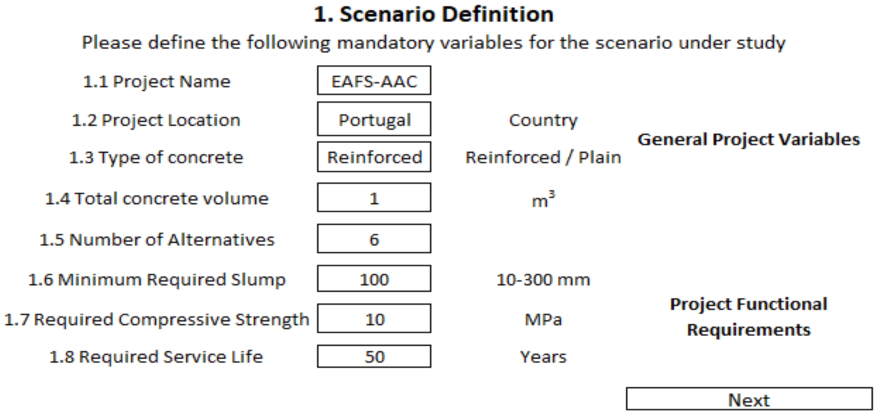
$$\text{Concrete curing energy} = 2\text{kW}*24\text{h}/\ (25\text{cubes}*0.15\text{m}*0.15\text{m}*0.15\text{m}) = 20\ \text{kWh/m}^3 \quad (4.5)$$

4.5. Applying the ECO_2 tool

As discussed in chapter 3, the ECO_2 tool is applied in five steps: First, the scenarios are set, then the alternatives are defined, and their functional unit are calculated. After that, using the primary inventory data, all impacts (environmental and economic) are calculated. Finally, the ECO_2 index is evaluated in an attempt to optimize the alternatives. In the next subsections, these steps will be followed and data from the case study will be utilized to validate the tool development and conclude the optimum AAC mix in terms of economic and environmental sustainability.

4.5.1. Define scenario

To account for uncertainty as per the LCA recommendations from Chapter 3, two scenarios were defined: a reinforced concrete scenario (S1) and a plain/mass concrete scenario (S2). The former would account for the durability of concrete alternatives understudy, while the latter, would assume the AAC fulfils the service life requirements. Since the EuroCode-2 specifies a minimum of 10 MPa for the characteristic compressive strength from cubic specimens, this value was set as the required compressive strength (threshold value) of both concrete scenarios. Considering the very low strength values obtained from testing mixes 7, 8 and 9 (around 1 MPa), they would not fulfil the basic project requirements and hence as excluded from the comparison. As seen in Figure 4.9, the comparison between the remaining 6 alternatives (M1-M6) was based on a unit volume of concrete that has a minimum slump of 100mm and a targeted service life of 50 years.



1. Scenario Definition

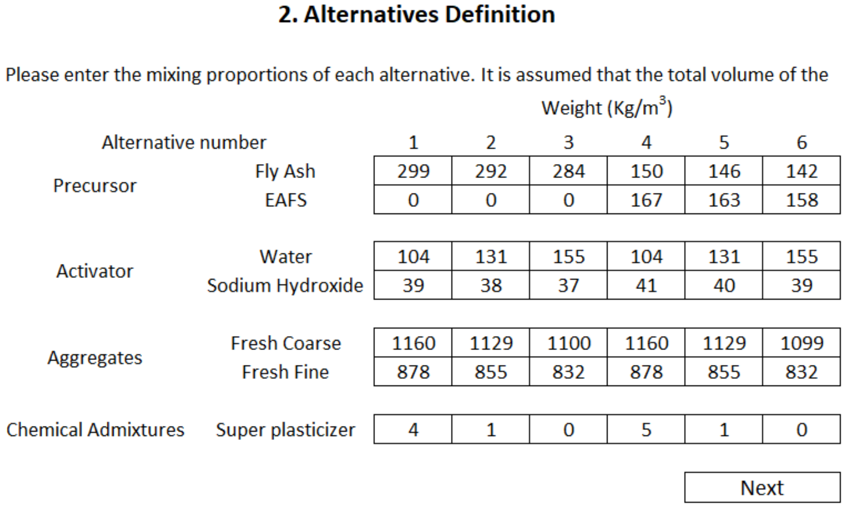
Please define the following mandatory variables for the scenario under study

1.1 Project Name	EAFS-AAC		General Project Variables
1.2 Project Location	Portugal	Country	
1.3 Type of concrete	Reinforced	Reinforced / Plain	
1.4 Total concrete volume	1	m^3	
1.5 Number of Alternatives	6		
1.6 Minimum Required Slump	100	10-300 mm	Project Functional Requirements
1.7 Required Compressive Strength	10	MPa	
1.8 Required Service Life	50	Years	

Figure 4.9: A screenshot of the 1st step of the ECO_2 tool: Scenario Definition

4.5.2. *Define alternatives*

The next step would be to enter the mixing proportions of each mix (conventional and non-conventional/alternative mixes) per cubic meter. As seen in Figure 4.10, the Table is identical to the mix design Table 4.4. This would then serve as the basis for quantifying the environmental and economic impact of each alternative as per the ECO_2 logic.



2. Alternatives Definition

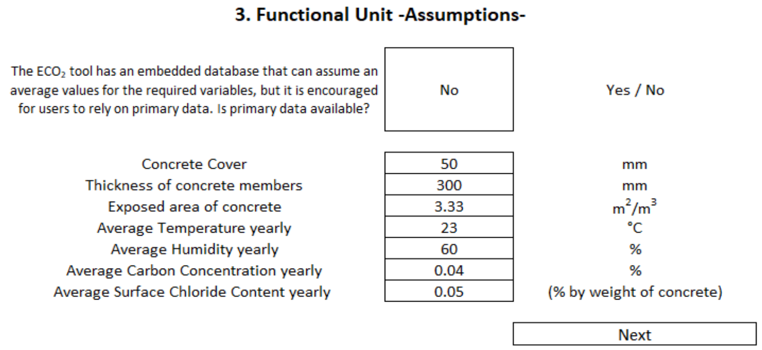
Please enter the mixing proportions of each alternative. It is assumed that the total volume of the

		Weight (Kg/m^3)					
Alternative number		1	2	3	4	5	6
Precursor	Fly Ash	299	292	284	150	146	142
	EAFS	0	0	0	167	163	158
Activator	Water	104	131	155	104	131	155
	Sodium Hydroxide	39	38	37	41	40	39
Aggregates	Fresh Coarse	1160	1129	1100	1160	1129	1099
	Fresh Fine	878	855	832	878	855	832
Chemical Admixtures	Super plasticizer	4	1	0	5	1	0

Figure 4.10: A screenshot of the 2nd step of the ECO_2 tool: Defining all alternatives

4.5.3. *Define functional unit calculations assumptions*

In this third step, the user must specify the assumptions upon which the functional parameters are calculated. If not, the tool assumes average values based on the database. In this case study, there was no investigation on the environmental conditions (temperature and humidity) of Portugal, so the values for the assumptions were assumed as shown in Figure 4.11.



3. Functional Unit -Assumptions-

The ECO_2 tool has an embedded database that can assume an average values for the required variables, but it is encouraged for users to rely on primary data. Is primary data available? No Yes / No

Concrete Cover	50	mm
Thickness of concrete members	300	mm
Exposed area of concrete	3.33	m^2/m^3
Average Temperature yearly	23	°C
Average Humidity yearly	60	%
Average Carbon Concentration yearly	0.04	%
Average Surface Chloride Content yearly	0.05	(% by weight of concrete)

Figure 4.11: A screenshot of the 3rd step of the ECO_2 tool: defining the FU calculations assumptions

4.5.4. Calculate functional unit

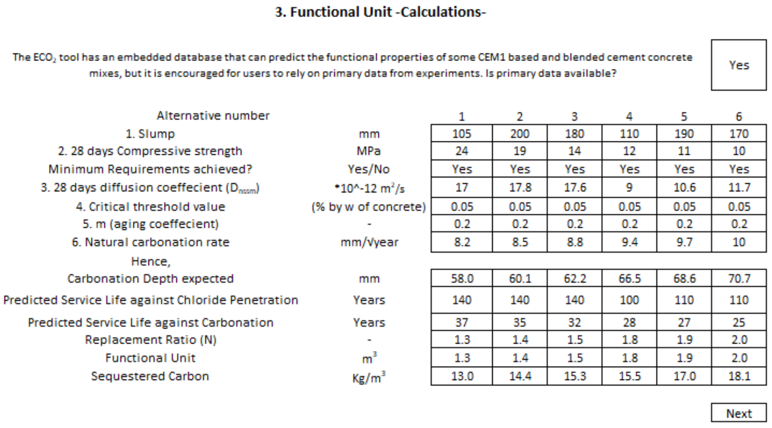
After stating the assumptions, the fourth step is to calculate the functional unit for each alternative under study. As explained in chapter 3, for plain concrete alternatives, the value of N, which is the replacement rate over the targeted service life of the project, is assumed as 1. This means that for scenario 2; where the concrete is assumed to be plain, the functional unit is equals 1 m^3 for all six alternatives. Regarding the 1st scenario, where the concrete is designed to be reinforced the replacement rate is calculated depending on the durability properties of each mix. The ECO_2 tool calculates the expected service life of each alternative relying on the value of the natural carbonation rate as per equation 4.6 depending on the assumed concrete cover. Using equations 4.7 and 4.8, the value for "$SL_{p\text{-}cl}$" (the service life against chloride penetration) is predicted. For each alternative, the service life selected is then the least of both values and the replacement factor N is calculated. It appears that the FA based mixes (M1-M3) are more durable and hence exhibit a lower replacement rate than the rest of the mixes as seen in Figure 4.12.

$$SL_{P-Cr} = \left(\frac{X}{K_n}\right)^2 \tag{4.6}$$

$$C(x,t) = C_o * erf\left(\frac{x}{2 * \sqrt{D_t * t}}\right) \tag{4.7}$$

$$D_t = D\left(\frac{t_o}{t}\right)^{\propto} \tag{4.8}$$

$$\mathrm{N} = \frac{\mathrm{SL_R}}{\min(\mathrm{SL_{P-Cr}}, \mathrm{SL_{P-Cl}})} \tag{4.9}$$



3. Functional Unit -Calculations-

The ECO_2 tool has an embedded database that can predict the functional properties of some CEM1 based and blended cement concrete mixes, but it is encouraged for users to rely on primary data from experiments. Is primary data available? Yes

Alternative number		1	2	3	4	5	6
1. Slump	mm	105	200	180	110	190	170
2. 28 days Compressive strength	MPa	24	19	14	12	11	10
Minimum Requirements achieved?	Yes/No	Yes	Yes	Yes	Yes	Yes	Yes
3. 28 days diffusion coeffecient (D_{nssm})	*10^-12 m^2/s	17	17.8	17.6	9	10.6	11.7
4. Critical threshold value	(% by w of concrete)	0.05	0.05	0.05	0.05	0.05	0.05
5. m (aging coeffecient)	-	0.2	0.2	0.2	0.2	0.2	0.2
6. Natural carbonation rate	mm/√year	8.2	8.5	8.8	9.4	9.7	10
Hence,							
Carbonation Depth expected	mm	58.0	60.1	62.2	66.5	68.6	70.7
Predicted Service Life against Chloride Penetration	Years	140	140	140	100	110	110
Predicted Service Life against Carbonation	Years	37	35	32	28	27	25
Replacement Ratio (N)	-	1.3	1.4	1.5	1.8	1.9	2.0
Functional Unit	m^3	1.3	1.4	1.5	1.8	1.9	2.0
Sequestered Carbon	Kg/m^3	13.0	14.4	15.3	15.5	17.0	18.1

Figure 4.12: A screenshot of the FU calculations for each mix (alternative) based on the 1st scenario

One of the unique features of the ECO_2 framework is accounting for the sequestered carbon dioxide throughout the “use” phase. However, the existing model that calculates the amount of CO_x uptake is not very accurate when applied to AAC (Zhang et al., 2018). Hence, similar to the carbonation rate disclaimer, the values of sequestered carbon dioxide measured according to equations 4.10 and 4.11 below are to be interpreted only in the context of the ECO_2 index calculations and not as an absolute measure.

$$\mathrm{U_{CO_2}(t) = a_{CO_2}(t) * A * X_c * t\ (grams/m^3)} \tag{4.10}$$

$$\mathrm{a_{CO_2}(t) = 366 * 10^{-6} * B * \frac{t}{2+t} * \frac{W/_B}{W/_B + 0.194}} \tag{4.11}$$

Where, “A” is the exposed surface area of concrete (in cm^2), $\mathrm{X_c}$ is the carbonation depth (in cm) and $\mathrm{a_{CO_2}(t)}$ is the amount of absorbable CO_2 in g/cm^3 at time t for each alternative of a total binder content B (grams) and Water (grams).

4.5.5. Input inventory data

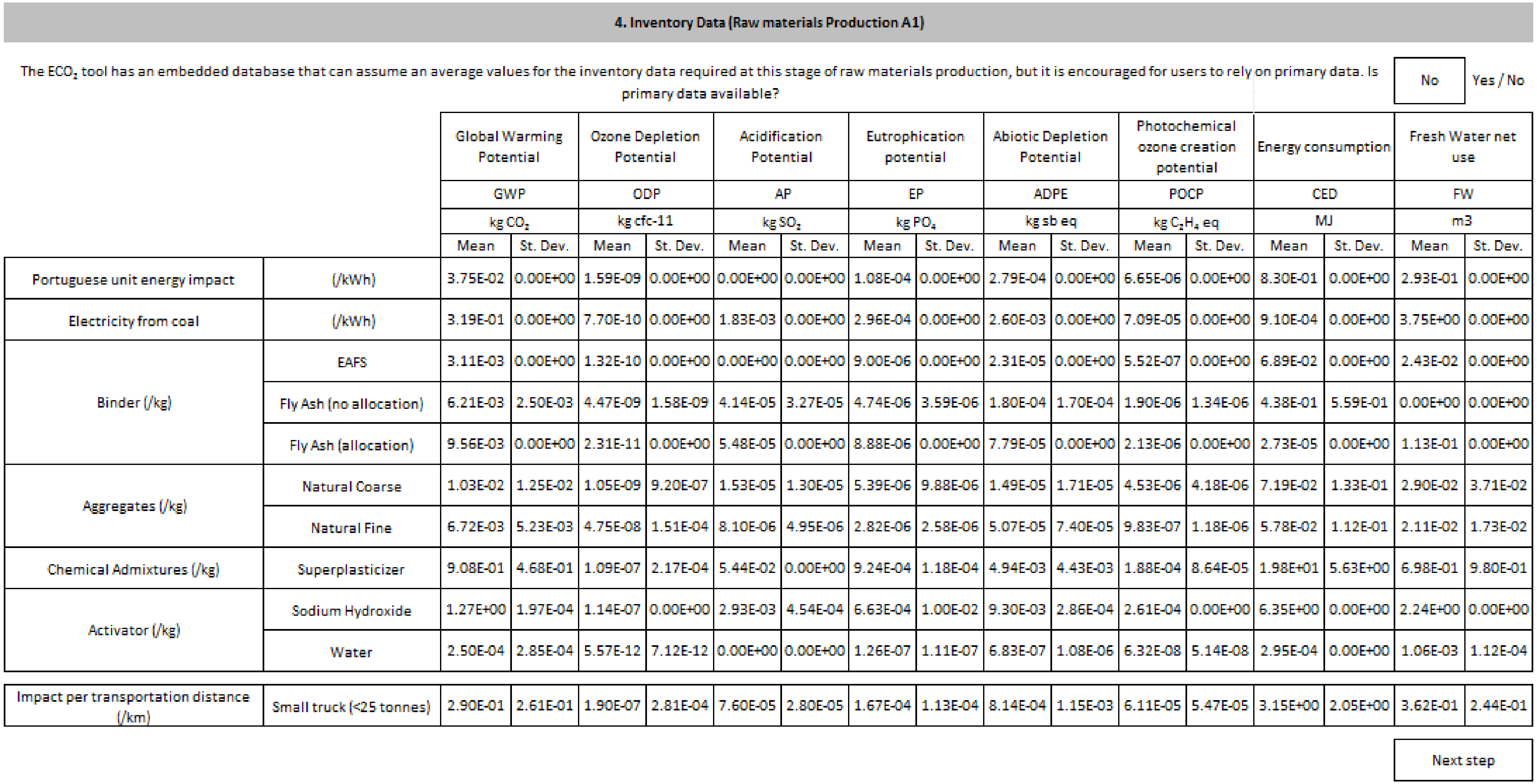
The fifth step in the ECO_2 tool is to decide on the inventory data values. The inventory data is divided into two groups; the environmental impact calculations group and another one for the economic impact calculations. Concerning the environmental impact inventory data, the data is divided into the following processes (sections 4.5.5.1-4.5.5.4).

4.5.5.1 Raw materials production

The only primary data collected for this study is the energy required for EAFS processing, which was estimated to be 83 kWh/tonne as discussed section 4.4.2. This is translated to the environmental indicators by multiplying it to the average impact per unit energy of the Portuguese energy grid, which was extracted from the Ecoinvent database. The value of the country specific energy mix among the remaining impact per unit mass of the other raw materials used in this study were extracted from the ECO_2 database as seen in Figure 4.13.

4.5.5.2 Raw materials transportation

As agreed in section 4.4.2, all materials were produced in Portugal and transported locally using a small truck. An extra 70% of the impact is added to account for the return ride. According to the transportation distances summarized in Table 4.8, the impact resulting from transporting the raw materials in this study was calculated in the ECO_2 tool as shown in Figure 4.14 by multiplying the impact from the previous subsection (unit transportation via small truck) by the distances.



4. Inventory Data (Raw materials Production A1)

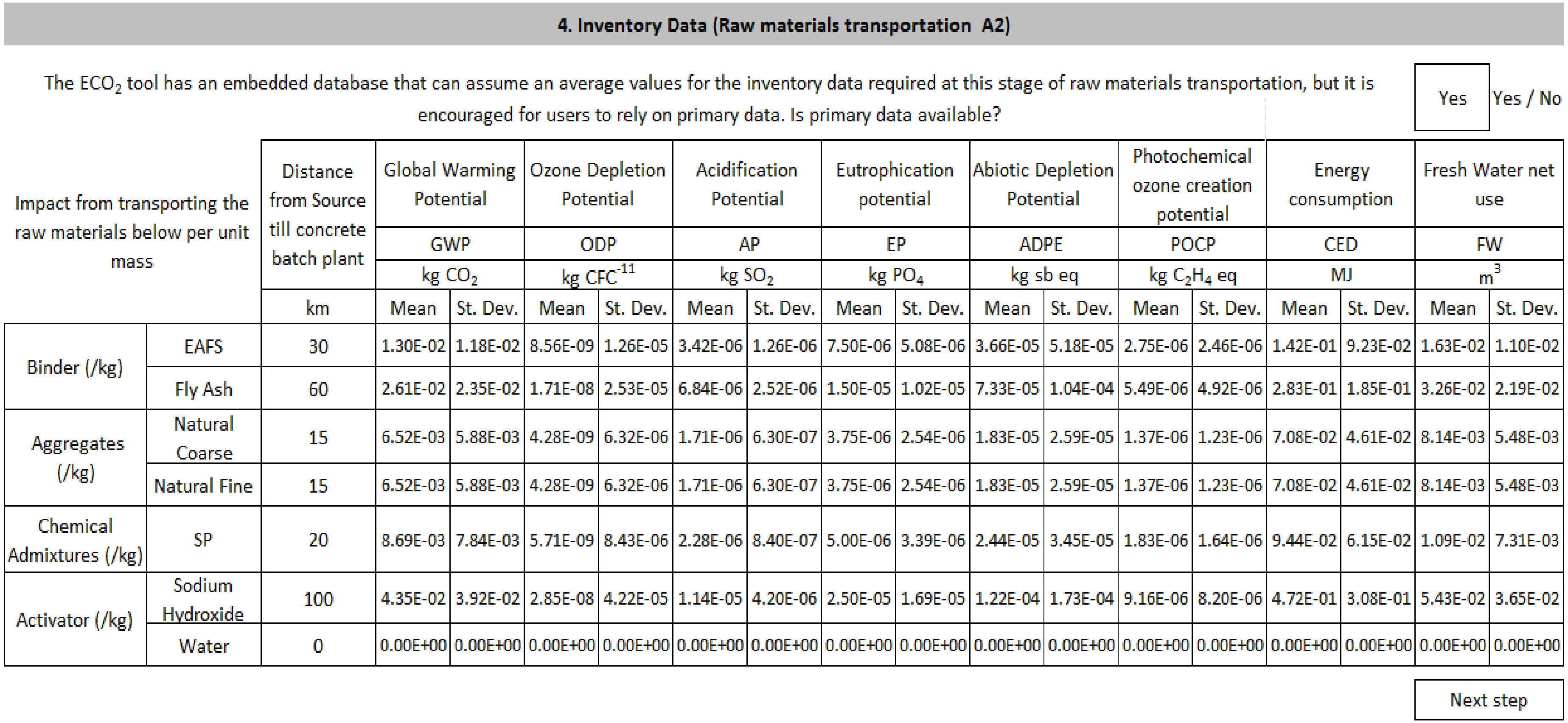
The ECO_2 tool has an embedded database that can assume an average values for the inventory data required at this stage of raw materials production, but it is encouraged for users to rely on primary data. Is primary data available?

No — Yes / No

		Global Warming Potential		Ozone Depletion Potential		Acidification Potential		Eutrophication potential		Abiotic Depletion Potential		Photochemical ozone creation potential		Energy consumption		Fresh Water net use	
		GWP		ODP		AP		EP		ADPE		POCP		CED		FW	
		kg CO_2		kg cfc-11		kg SO_2		kg PO_4		kg sb eq		kg C_2H_4 eq		MJ		m3	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Portuguese unit energy impact	(/kWh)	3.75E-02	0.00E+00	1.59E-09	0.00E+00	0.00E+00	0.00E+00	1.08E-04	0.00E+00	2.79E-04	0.00E+00	6.65E-06	0.00E+00	8.30E-01	0.00E+00	2.93E-01	0.00E+00
Electricity from coal	(/kWh)	3.19E-01	0.00E+00	7.70E-10	0.00E+00	1.83E-03	0.00E+00	2.96E-04	0.00E+00	2.60E-03	0.00E+00	7.09E-05	0.00E+00	9.10E-04	0.00E+00	3.75E+00	0.00E+00
Binder (/kg)	EAFS	3.11E-03	0.00E+00	1.32E-10	0.00E+00	0.00E+00	0.00E+00	9.00E-06	0.00E+00	2.31E-05	0.00E+00	5.52E-07	0.00E+00	6.89E-02	0.00E+00	2.43E-02	0.00E+00
	Fly Ash (no allocation)	6.21E-03	2.50E-03	4.47E-09	1.58E-09	4.14E-05	3.27E-05	4.74E-06	3.59E-06	1.80E-04	1.70E-04	1.90E-06	1.34E-06	4.38E-01	5.59E-01	0.00E+00	0.00E+00
	Fly Ash (allocation)	9.56E-03	0.00E+00	2.31E-11	0.00E+00	5.48E-05	0.00E+00	8.88E-06	0.00E+00	7.79E-05	0.00E+00	2.13E-06	0.00E+00	2.73E-05	0.00E+00	1.13E-01	0.00E+00
Aggregates (/kg)	Natural Coarse	1.03E-02	1.25E-02	1.05E-09	9.20E-07	1.53E-05	1.30E-05	5.39E-06	9.88E-06	1.49E-05	1.71E-05	4.53E-06	4.18E-06	7.19E-02	1.33E-01	2.90E-02	3.71E-02
	Natural Fine	6.72E-03	5.23E-03	4.75E-08	1.51E-04	8.10E-06	4.95E-06	2.82E-06	2.58E-06	5.07E-05	7.40E-05	9.83E-07	1.18E-06	5.78E-02	1.12E-01	2.11E-02	1.73E-02
Chemical Admixtures (/kg)	Superplasticizer	9.08E-01	4.68E-01	1.09E-07	2.17E-04	5.44E-02	0.00E+00	9.24E-04	1.18E-04	4.94E-03	4.43E-03	1.88E-04	8.64E-05	1.98E+01	5.63E+00	6.98E-01	9.80E-01
Activator (/kg)	Sodium Hydroxide	1.27E+00	1.97E-04	1.14E-07	0.00E+00	2.93E-03	4.54E-04	6.63E-04	1.00E-02	9.30E-03	2.86E-04	2.61E-04	0.00E+00	6.35E+00	0.00E+00	2.24E+00	0.00E+00
	Water	2.50E-04	2.85E-04	5.57E-12	7.12E-12	0.00E+00	0.00E+00	1.26E-07	1.11E-07	6.83E-07	1.08E-06	6.32E-08	5.14E-08	2.95E-04	0.00E+00	1.06E-03	1.12E-04

Impact per transportation distance (/km)	Small truck (<25 tonnes)	2.90E-01	2.61E-01	1.90E-07	2.81E-04	7.60E-05	2.80E-05	1.67E-04	1.13E-04	8.14E-04	1.15E-03	6.11E-05	5.47E-05	3.15E+00	2.05E+00	3.62E-01	2.44E-01

Figure 4.4: A screenshot of the values for the environmental inventory data of the raw materials production



4. Inventory Data (Raw materials transportation A2)

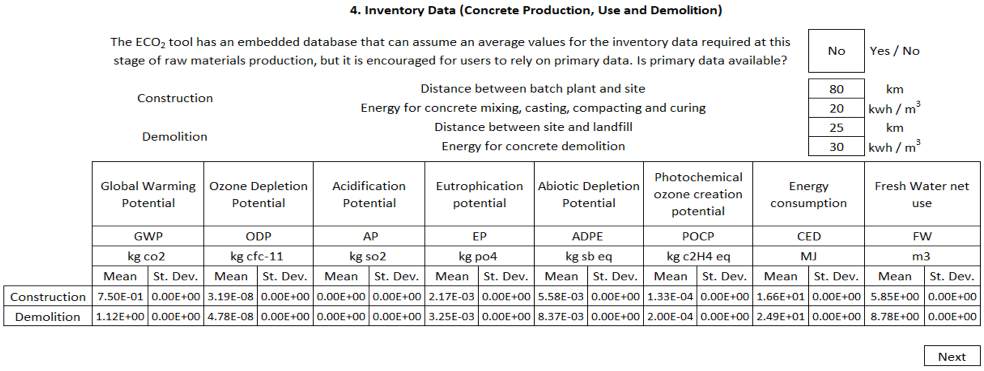
The ECO_2 tool has an embedded database that can assume an average values for the inventory data required at this stage of raw materials transportation, but it is encouraged for users to rely on primary data. Is primary data available? Yes | Yes / No

Impact from transporting the raw materials below per unit mass		Distance from Source till concrete batch plant	Global Warming Potential		Ozone Depletion Potential		Acidification Potential		Eutrophication potential		Abiotic Depletion Potential		Photochemical ozone creation potential		Energy consumption		Fresh Water net use	
			GWP		ODP		AP		EP		ADPE		POCP		CED		FW	
			kg CO_2		kg CFC^{-11}		kg SO_2		kg PO_4		kg sb eq		kg C_2H_4 eq		MJ		m^3	
		km	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Binder (/kg)	EAFS	30	1.30E-02	1.18E-02	8.56E-09	1.26E-05	3.42E-06	1.26E-06	7.50E-06	5.08E-06	3.66E-05	5.18E-05	2.75E-06	2.46E-06	1.42E-01	9.23E-02	1.63E-02	1.10E-02
	Fly Ash	60	2.61E-02	2.35E-02	1.71E-08	2.53E-05	6.84E-06	2.52E-06	1.50E-05	1.02E-05	7.33E-05	1.04E-04	5.49E-06	4.92E-06	2.83E-01	1.85E-01	3.26E-02	2.19E-02
Aggregates (/kg)	Natural Coarse	15	6.52E-03	5.88E-03	4.28E-09	6.32E-06	1.71E-06	6.30E-07	3.75E-06	2.54E-06	1.83E-05	2.59E-05	1.37E-06	1.23E-06	7.08E-02	4.61E-02	8.14E-03	5.48E-03
	Natural Fine	15	6.52E-03	5.88E-03	4.28E-09	6.32E-06	1.71E-06	6.30E-07	3.75E-06	2.54E-06	1.83E-05	2.59E-05	1.37E-06	1.23E-06	7.08E-02	4.61E-02	8.14E-03	5.48E-03
Chemical Admixtures (/kg)	SP	20	8.69E-03	7.84E-03	5.71E-09	8.43E-06	2.28E-06	8.40E-07	5.00E-06	3.39E-06	2.44E-05	3.45E-05	1.83E-06	1.64E-06	9.44E-02	6.15E-02	1.09E-02	7.31E-03
Activator (/kg)	Sodium Hydroxide	100	4.35E-02	3.92E-02	2.85E-08	4.22E-05	1.14E-05	4.20E-06	2.50E-05	1.69E-05	1.22E-04	1.73E-04	9.16E-06	8.20E-06	4.72E-01	3.08E-01	5.43E-02	3.65E-02
	Water	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure 4.5: A screenshot of the values for the environmental inventory data of the raw materials transportation

4.5.5.3 Concrete construction and Demolition

The energy and emissions involved in the concrete construction phase are the combination of that resulting from mixing, transporting to site, casting and curing. As agreed in section 4.4.2, since the curing routine chosen for this AAC study is heat curing, the energy required for this process is estimated at 20 kWh/m^3 of concrete. The remaining processes, as well as the data for demolition and waste transportation to the nearest landfill, are estimated from the ECO$_2$ tool database. Similar to the calculation method in 4.5.5.2, the impact from transportation is the result of multiplying the impact per unit tonne per km times the distance assumed to be travelled by the small truck. The same assumption regarding the return journey extra 70% also applies. The values could be seen in Figure 4.15.



4. Inventory Data (Concrete Production, Use and Demolition)

The ECO$_2$ tool has an embedded database that can assume an average values for the inventory data required at this stage of raw materials production, but it is encouraged for users to rely on primary data. Is primary data available? No Yes / No

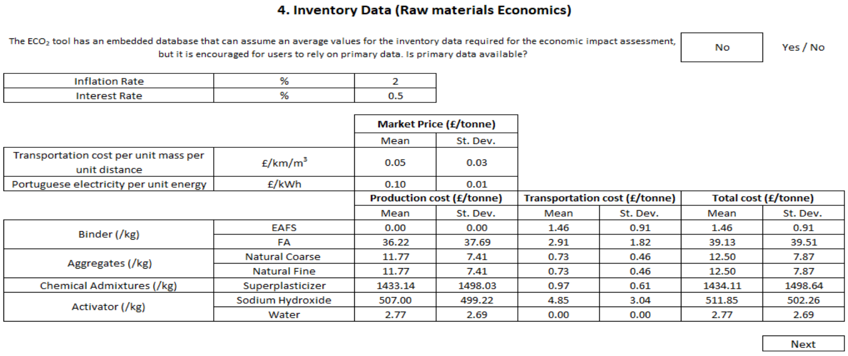
Construction	Distance between batch plant and site	80	km
	Energy for concrete mixing, casting, compacting and curing	20	kwh / m^3
Demolition	Distance between site and landfill	25	km
	Energy for concrete demolition	30	kwh / m^3

	Global Warming Potential		Ozone Depletion Potential		Acidification Potential		Eutrophication potential		Abiotic Depletion Potential		Photochemical ozone creation potential		Energy consumption		Fresh Water net use	
	GWP		ODP		AP		EP		ADPE		POCP		CED		FW	
	kg co2		kg cfc-11		kg so2		kg po4		kg sb eq		kg c2H4 eq		MJ		m3	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Construction	7.50E-01	0.00E+00	3.19E-08	0.00E+00	0.00E+00	0.00E+00	2.17E-03	0.00E+00	5.58E-03	0.00E+00	1.33E-04	0.00E+00	1.66E+01	0.00E+00	5.85E+00	0.00E+00
Demolition	1.12E+00	0.00E+00	4.78E-08	0.00E+00	0.00E+00	0.00E+00	3.25E-03	0.00E+00	8.37E-03	0.00E+00	2.00E-04	0.00E+00	2.49E+01	0.00E+00	8.78E+00	0.00E+00

Figure 4.15: A screenshot of the values for the environmental inventory data of concrete construction and demolition

4.5.5.4 Economic Inventory Data

The primary data provided from the suppliers for the purchasing prices of all constituents of the AAC studied was inputted to the ECO$_2$. The remaining data required for the calculation of the economic impact of the resulting concrete, such as the market inflation rate and the interest rates were assumed as the average value found in the literature. The cost of transporting the raw materials to the concrete batch plant was calculated based on an average unit price for transportation from the ECO$_2$ database. It is important to note that, unlike the environmental impact calculations, the return distance was not accounted for because it is assumed to be already included in the price. The summary of the data is found in Figure 4.16.



4. Inventory Data (Raw materials Economics)

The ECO$_2$ tool has an embedded database that can assume an average values for the inventory data required for the economic impact assessment, but it is encouraged for users to rely on primary data. Is primary data available? No Yes / No

Inflation Rate	%	2
Interest Rate	%	0.5

		Market Price (£/tonne)	
		Mean	St. Dev.
Transportation cost per unit mass per unit distance	£/km/m^3	0.05	0.03
Portuguese electricity per unit energy	£/kWh	0.10	0.01

		Production cost (£/tonne)		Transportation cost (£/tonne)		Total cost (£/tonne)	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Binder (/kg)	EAFS	0.00	0.00	1.46	0.91	1.46	0.91
	FA	36.22	37.69	2.91	1.82	39.13	39.51
Aggregates (/kg)	Natural Coarse	11.77	7.41	0.73	0.46	12.50	7.87
	Natural Fine	11.77	7.41	0.73	0.46	12.50	7.87
Chemical Admixtures (/kg)	Superplasticizer	1433.14	1498.03	0.97	0.61	1434.11	1498.64
Activator (/kg)	Sodium Hydroxide	507.00	499.22	4.85	3.04	511.85	502.26
	Water	2.77	2.69	0.00	0.00	2.77	2.69

Figure 4.16: A screenshot of the values for the economic inventory data of the raw materials construction and transportation

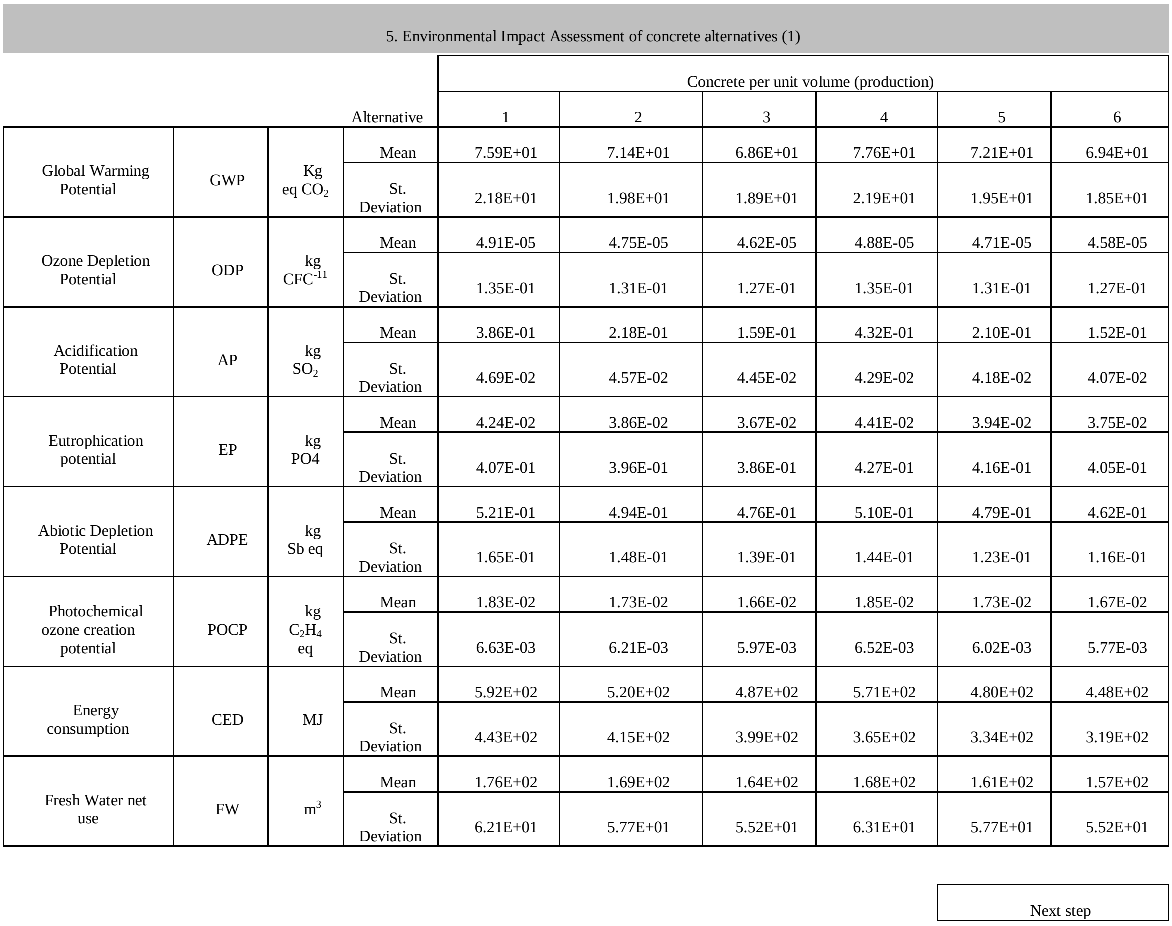
4.5.6. *Calculate the ecological impact*

In order to quantify the environmental impact of each alternative, two steps are done. First, the impact of producing concrete is calculated per unit volume by multiplying the impact of producing every constituent by its mixing proportion for every alternative. After that, it is added to the impact of transporting every constituent as seen in Table 4.8. The second step is to calculate the total impact of the concrete using the selected mid-point indicators in ECO_2, which is done by adding the impact from construction and demolition as equation 4.12 below suggests.

$$\frac{GWP_i}{m^3} = \sum_{j=1}^{n}\left(\frac{GWP_{j\ upstream}}{kg} * \frac{kg_j}{m^3}\right) + \frac{GWP_i construction}{m^3} - \frac{GWP_i sequestered}{m^3} + \frac{GWP_i\ demolition}{m^3} \qquad (4.12)$$

In case of the global warming potential indicator only, the sequestered carbon is deducted for each alternative. The total impact per unit volume is then multiplied by the functional unit for each alternative which was calculated earlier in 4.5.4. Once the total impact per functional unit is calculated for each alternative, it is then normalized, with the alternative with the lowest impact in each indicator getting a value of 1 and that with the highest impact getting a value of 0. Finally, the single environmental indicator, which is called the ecological indicator according to the ECO_2 algorithm, is calculated based on the weighted average of all indicators.

Table 4.8 The ECO_2 tool calculation method for the environmental impact per unit volume



5. Environmental Impact Assessment of concrete alternatives (1)

				Concrete per unit volume (production)					
			Alternative	1	2	3	4	5	6
Global Warming Potential	GWP	Kg eq CO_2	Mean	7.59E+01	7.14E+01	6.86E+01	7.76E+01	7.21E+01	6.94E+01
			St. Deviation	2.18E+01	1.98E+01	1.89E+01	2.19E+01	1.95E+01	1.85E+01
Ozone Depletion Potential	ODP	kg CFC^{-11}	Mean	4.91E-05	4.75E-05	4.62E-05	4.88E-05	4.71E-05	4.58E-05
			St. Deviation	1.35E-01	1.31E-01	1.27E-01	1.35E-01	1.31E-01	1.27E-01
Acidification Potential	AP	kg SO_2	Mean	3.86E-01	2.18E-01	1.59E-01	4.32E-01	2.10E-01	1.52E-01
			St. Deviation	4.69E-02	4.57E-02	4.45E-02	4.29E-02	4.18E-02	4.07E-02
Eutrophication potential	EP	kg PO4	Mean	4.24E-02	3.86E-02	3.67E-02	4.41E-02	3.94E-02	3.75E-02
			St. Deviation	4.07E-01	3.96E-01	3.86E-01	4.27E-01	4.16E-01	4.05E-01
Abiotic Depletion Potential	ADPE	kg Sb eq	Mean	5.21E-01	4.94E-01	4.76E-01	5.10E-01	4.79E-01	4.62E-01
			St. Deviation	1.65E-01	1.48E-01	1.39E-01	1.44E-01	1.23E-01	1.16E-01
Photochemical ozone creation potential	POCP	kg C_2H_4 eq	Mean	1.83E-02	1.73E-02	1.66E-02	1.85E-02	1.73E-02	1.67E-02
			St. Deviation	6.63E-03	6.21E-03	5.97E-03	6.52E-03	6.02E-03	5.77E-03
Energy consumption	CED	MJ	Mean	5.92E+02	5.20E+02	4.87E+02	5.71E+02	4.80E+02	4.48E+02
			St. Deviation	4.43E+02	4.15E+02	3.99E+02	3.65E+02	3.34E+02	3.19E+02
Fresh Water net use	FW	m^3	Mean	1.76E+02	1.69E+02	1.64E+02	1.68E+02	1.61E+02	1.57E+02
			St. Deviation	6.21E+01	5.77E+01	5.52E+01	6.31E+01	5.77E+01	5.52E+01

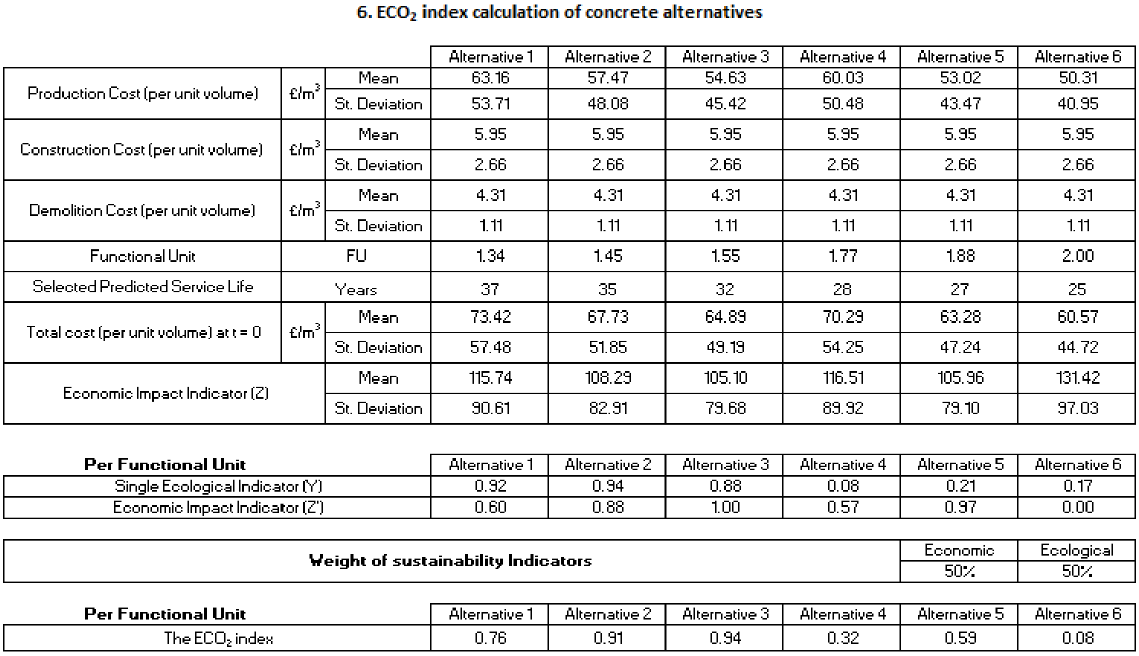
4.5.7. Calculate the ECO_2 index

After calculating the single ecological indicator for each alternative, the single economic indicator is calculated as such. First, using the economic inventory data, the per unit volume total cost of each alternative is calculated by summing up the cost of production, construction and demolition. After that, depending on the functional unit of each alternative, the single economic indicator Z is calculated using the equation below which accounts for the time value of money and real interest rate F as seen in equations 4.13 and 4.14.

$$F_r = \frac{1+F_i}{1+F_f} - 1 \tag{4.13}$$

$$Zi = \frac{C_i}{(1+F_r)^t} \tag{4.14}$$

As seen in Figure 4.17, after normalizing both indices, the single ECO_2 index is then deduced by calculating a weighted average of the single ecological indicator and the single economic one. It appears that, using the ECO_2 index as a bases for judgment, the ranking of the optimized AAC mixes would be: mix 3, mix 2, mix 2 then mix 5, mix 4 and finally mix 1. This shows that given the chosen alkaline activator, using 100% FA as a precursor is preferable and that 0.5 water: precursor ratio is the optimum one.



6. ECO_2 index calculation of concrete alternatives

			Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
Production Cost (per unit volume)	£/m³	Mean	63.16	57.47	54.63	60.03	53.02	50.31
		St. Deviation	53.71	48.08	45.42	50.48	43.47	40.95
Construction Cost (per unit volume)	£/m³	Mean	5.95	5.95	5.95	5.95	5.95	5.95
		St. Deviation	2.66	2.66	2.66	2.66	2.66	2.66
Demolition Cost (per unit volume)	£/m³	Mean	4.31	4.31	4.31	4.31	4.31	4.31
		St. Deviation	1.11	1.11	1.11	1.11	1.11	1.11
Functional Unit	FU		1.34	1.45	1.55	1.77	1.88	2.00
Selected Predicted Service Life	Years		37	35	32	28	27	25
Total cost (per unit volume) at t = 0	£/m³	Mean	73.42	67.73	64.89	70.29	63.28	60.57
		St. Deviation	57.48	51.85	49.19	54.25	47.24	44.72
Economic Impact Indicator (Z)		Mean	115.74	108.29	105.10	116.51	105.96	131.42
		St. Deviation	90.61	82.91	79.68	89.92	79.10	97.03

Per Functional Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
Single Ecological Indicator (Y)	0.92	0.94	0.88	0.08	0.21	0.17
Economic Impact Indicator (Z')	0.60	0.88	1.00	0.57	0.97	0.00

	Economic	Ecological
Weight of sustainability Indicators	50%	50%

Per Functional Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
The ECO_2 index	0.76	0.91	0.94	0.32	0.59	0.08

Figure 4.17: A screenshot of the ECO_2 tool calculation method for the economic and single sustainability index per alternative

4.6 Discussion of results

4.6.1. Case study results

Running the six selected AAC mixes using ECO_2 showed the following findings. First, The higher the water to precursor ratio, the lower the strength and durability (service life) of the AAC mixes can be seen (Figure 4.18). Mixes 3 and 6, which are the ones with the highest (0.5) ratio in both families, exhibited approximately 20% less strength and service life that Mixes 1 and 4 with the lowest (0.3) W/C ratios. Since mixes 4-6 showed around 30% less strength and durability than mixes 1-3 on average, this shows that replacing FA with EAFS as a precursor affects the functional parameters negatively. The reason behind this is that, according to the literature recommendations, the optimum activators for slag based precursors require a silica modulus between 1 and 2. However, this would have meant adding sodium silicate and increase the environmental and economic impact. Both of these observations are consistent with the hypothesis provided in Table 4.1.

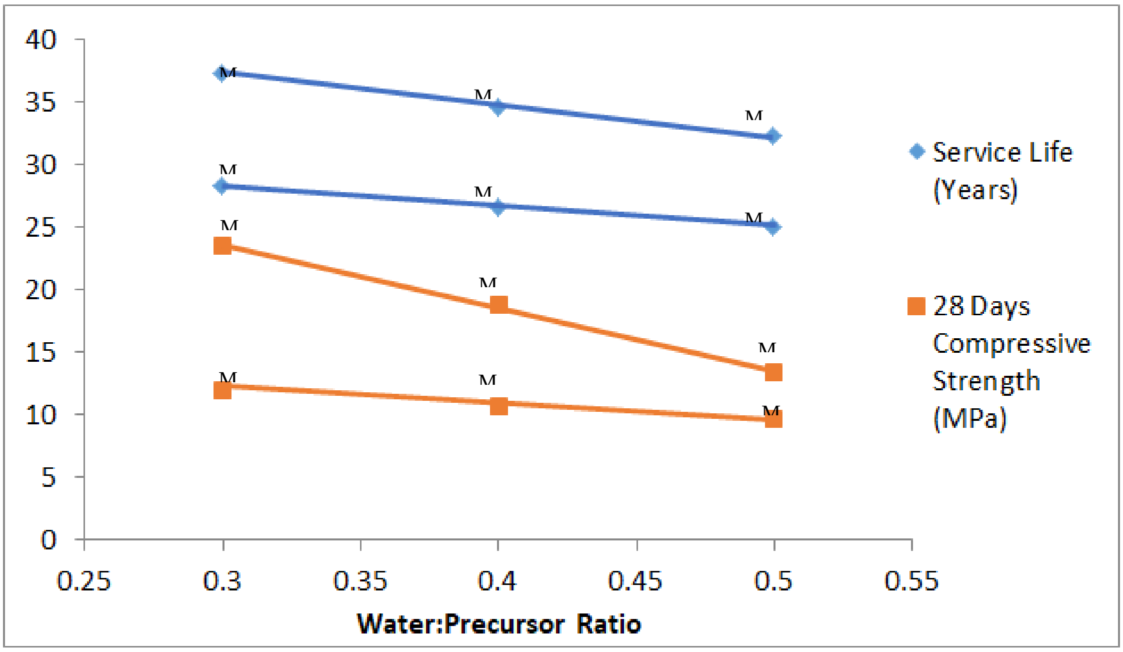


Figure 4.18: A graph showing the effect of the water: precursor ratio on the functional properties of mixes 1-6

Secondly, In terms of environmental impact assessment per unit volume of AAC, replacing FA with EAFS reduce every impact category by an average of 10% at a fixed water to precursor W/P ratio. As seen in Figure 4.19, reducing the W/P as well reduces all impact categories by approximately 10% for every 0.1.

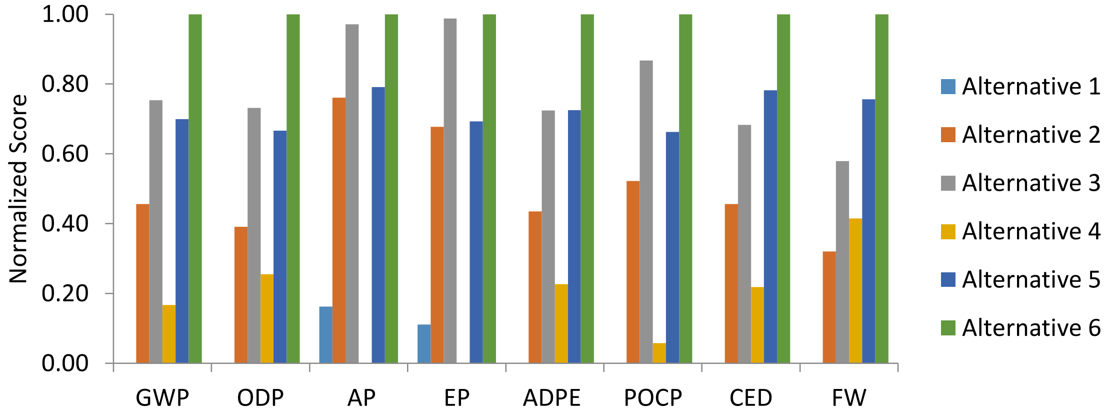


Figure 4.19: A graph showing the normalized environmental impact values of each alternative

Thirdly, Figure 4.20 show the analysis of the single ecological and economic indicator across the six mixes understudy. Alternatives 1, 2 and 3 appear to have far superior ecological performance due to the fact that the small advantage in the environmental impact for mixes 4-6 was overshadowed by the major disadvantage in the functional unit. Alternatives 2, 3 and 5 scored the best results for the single economic indicator due to the high cost of the superplasticizer and the functional unit multiplier.

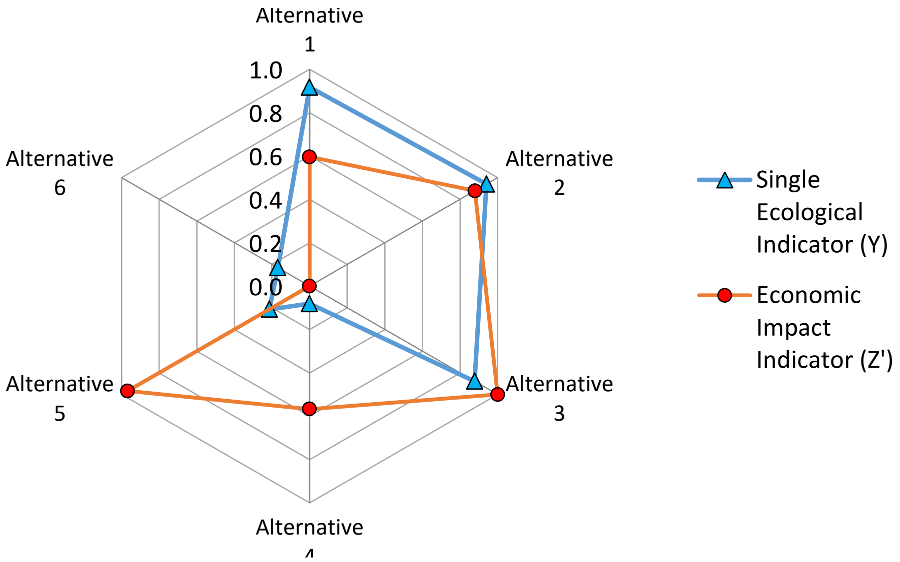


Figure 4.20: A Figure showing the single ecological and economic impact indicator for the 6 alternatives

Fourthly, One of the drawbacks of using the ECO_2 tool to quantify the sustainability index is that it only compares the performance of the alternatives understudy locally. This means that no comparisons are drawn between these alternatives and the population concrete mixes. Hence, the values were compared against threshold values for GWP, CED and basic cost per cubic meter that were obtained from the CONCRE*Top* framework (Kurda et al., 2019) as seen in Table 4.9. Accordingly, all the 6 mixes in this case study appear to have “very low” global warming potential and cumulative energy demand. The costs of all mixes are also “low” except for mixes 1 and 4.

Table 4.9: A comparison between the GWP, CED and cost of the studied alternatives against global thresholds based on the CONCRE*Top* framework (Kurda et al., 2019)

	Global Warming Potential **kg eq CO_2/m^3**	**Energy consumption** **MJ/m^3**	**Total cost** **$£/m^3$**
Alternative 1	87.71	841.61	73.4
Alternative 2	81.11	761.47	67.7
Alternative 3	76.80	721.49	64.9
Alternative 4	85.29	803.23	70.3
Alternative 5	77.59	704.13	63.3
Alternative 6	73.23	665.84	60.6
Very High	>522	>3388	>82
High	392-522	2541-3388	75-82
Normal	354-392	2299-2541	69-75
Low	224-354	1452-2541	62-69
Very Low	<224	<1452	<62

4.6.2. Sensitivity analysis

In order to account for the uncertainty of the data, it is recommended to perform a sensitivity analysis on significant input variables of the study. In this study, there were two main variables in the mix design, the w/p ratio and the % replacement of FA with EAFS as a precursor. Hence, a sensitivity analysis was designed to calculate the effect of changing the transportation distance and market price of the FA and slag on the resulting ECO_2 index score. For each parameter of change, the whole ECO_2 sustainability assessment procedure was repeated using the new values, whether +50% or -50% and the ECO_2 index of each alternative recalculated. As seen in Table 4.10, varying each of the three chosen variables by ±50% resulted in minimal (1-2%) impact on the ECO_2 index score of the studied variables, which shows that consolidates the results and conclusions in 4.6.1.

Table 4.10: Sensitivity analysis of the effect of the transport distance and price of FA and EAFS on the ECO_2 index

		EAFS transportation distance	FA transportation distance	FA selling price
Alternative 1	-50%	0.754	0.760	0.781
	0	0.756	0.759	0.759
	+50%	0.759	0.757	0.641
Alternative 2	-50%	0.908	0.913	0.919
	0	0.910	0.911	0.911
	+50%	0.911	0.906	0.789
Alternative 3	-50%	0.936	0.946	0.941
	0	0.939	0.941	0.941
	+50%	0.941	0.930	0.821
Alternative 4	-50%	0.326	0.315	0.276
	0	0.324	0.321	0.321
	+50%	0.321	0.333	0.347
Alternative 5	-50%	0.598	0.576	0.519
	0	0.591	0.584	0.583
	+50%	0.584	0.601	0.604
Alternative 6	-50%	0.087	0.082	0.082
	0	0.085	0.082	0.082
	+50%	0.082	0.083	0.082

4.6.3. Scenario analysis

Another recommendation to reduce the uncertainty in the MCDA as per the ECO_2 framework recommendation is to perform a scenario analysis. The main assumption on the basic scenario simulated in this case study is that the 6 mixes under comparison will be used as reinforced concrete. This resulted in a large discrepancy in the calculated functional unit between them (Mix 1 has a FU of 1 while mix 6 has a FU of 2) as seen in Figure 4.21 which significantly favoured the FA based mixes. Another scenario is assumed in this section where the mixes will be used as plain concrete. Hence, as explained in chapter 3, all mixes are assumed to fulfil the service life requirements and have an equal FU of 1. These parameters were simulated again using the ECO_2 tool and the results show that the original assumptions are valid in the case of plain concrete scenarios. Due to the higher ecological and economic impact of SH and FA compared to water and EAFS, increasing the W/P ratio and replacing FA with EAFS as precursors yields a binder with a better (higher) sustainability index. As seen in Figure 4.21, mixes 4-6 with 50% EAFS showed 60-70% better sustainability scores on average compared to mixes 1-3 with 100% FA. The same fact is observed for mixes 3 and 6 with a W/P of 0.5 compared to mixes 1 and 4, respectively.

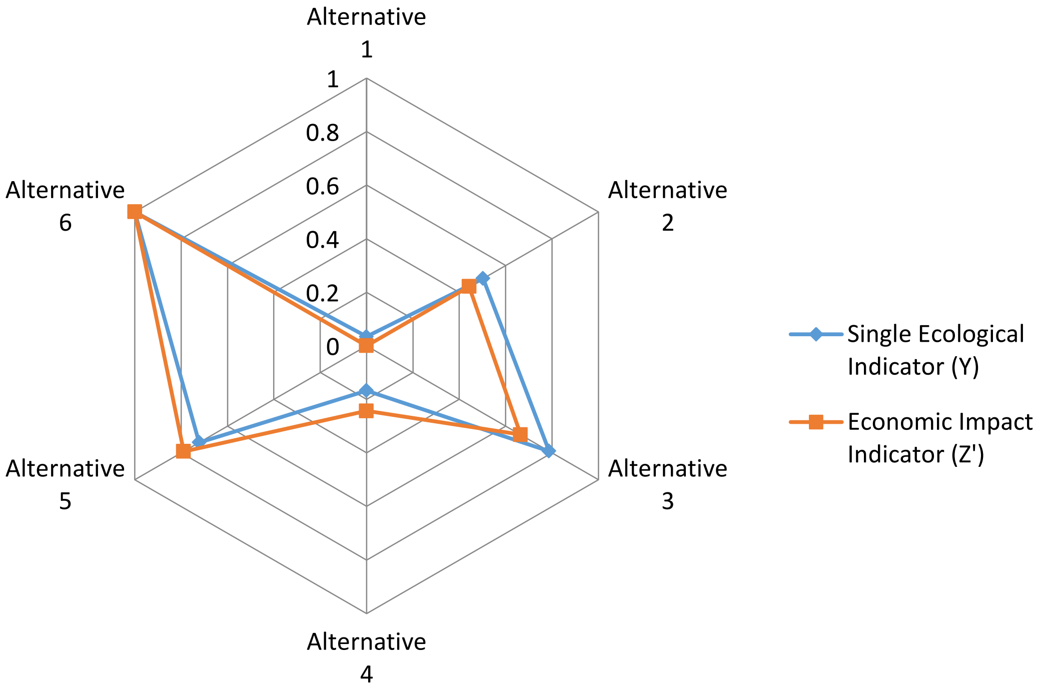


Figure 4.21: A Figure showing the single ecological and economic impact indicator for the 6 alternatives as per the plain concrete scenario

4.7 Summary

This chapter includes the first case study in which the novel ECO_2 tool was applied. As explained in the summary of Chapter 3, performing a case study primarily serves the purpose of validating the ECO_2 tool. Moreover, this case study serves also as an opportunity to judge the sustainability of a promising concrete alternative, namely EAFS based AAC. Preliminary investigation of the available literature showed that there are scarce studies performed on the performance of the material and none on the environmental and economic impact. Hence, this chapter targeted the assessment of several EAFS AAC alternatives through the ECO_2 framework. This was then used to optimize the mixing proportions of this sustainable concrete alternative based on the sustainability score. The literature review indicated a high sustainability potential of the use of EAFS as a precursor in an AAC compared to the more established FA. An experimental program was put in place and then environmental and economic analyses were done to assess whether the ECO_2 tool can generate a converging judgement that is comparable to the hypothesis from the literature. Several AAC mixes were designed to test the effect of changing the precursor from FA to EAFS and changing the water: precursor ratio on the three sustainability pillars: performance, environmental and economic impact In order to do so, an experimental rig was put in place at the University of Lisbon in Portugal and all the necessary material was procured locally. Tests performed on the AAC mixes were slump, strength, chloride penetration and carbonation.

It is important to note that in regards to the carbonation rate results and the prediction of the CO_2 uptake during the service life of each mix, the study in this chapter was only limited to the relative, not the absolute, performance across the mixes. The reason, as explained in the chapter, lies in the absence of a carbonation chamber with a capacity to provide a <1% CO_2 concentration for the accelerated carbonation testing and the absence of accurate prediction models for CO_2 uptake in AAC.

The preliminary conclusion was that due to the deteriorated functional properties of the EAFS based AAC mixes, the optimum mixes were that of only FA. However, this was only valid in terms of reinforced concrete, because when a scenario with plain concrete was assumed, the EAFS based mixes exhibited a significantly improved sustainability potential using the ECO_2 index. In both cases, the original hypothesis concerning the effect of W/P ratio was proven and the results from both scenarios were run against the sensitivity of some input data and showed minimal effect. Due to the complexity of the sustainability assessment calculations, it would not have been easy for users to analyse the optimum mix based on the combined functional, environmental and economic impacts. Hence, the use of the ECO_2 tool was critical to make this assessment easier and allow for the optimization of the mixing proportions of AAC mixes with a target of the highest achievable single sustainability score. Nevertheless, this case study was a proof on the applicability, flexibility, scientific rigour and reliability of the ECO_2 tool and the next two case studies will aim at generalizing these acclaimed features across other concrete types.

Chapter 5

Case Study #2: Using non-linear machine learning regression models to predict the functional properties of binary and ternary blended cement concrete mixes and optimizing their sustainability potential based on the ECO_2 framework

5.1. Introduction

As established from the literature review in Chapter 2, blended cement concrete (BCC) is one of the primary Green alternatives to ordinary Portland cement (OPC) concrete. The reason is that BCC exhibits enhanced environmental, economic and to an extent functional properties compared to the latter. However, this is dependent highly on the raw materials used in the BCC mix. In this chapter, a case study was conducted to optimize the mix design of BCC using the ECO_2 framework as a basis for the sustainability assessment. The case study is, according to the methodology of this PhD project, a validation of the applicability of the ECO_2 framework similar to case study 1 in Chapter 4 and case study 3 in Chapter 6. Moreover, the case study aims at presenting an opportunity for an empirical contribution to the research domain through the optimized BCC mixes.

The literature review in Chapter 2 suggested that the most promising supplementary cementitious materials (SCM) to replace ordinary Portland cement (OPC) in BCC are in Fly Ash (FA), Ground Granulated Blastfurnace Slag (GGBS), Silica Fume (SF), Powdered lime (LP) and Calcined Clay (CC). Hence, the first step in this case study, which is shown in section 5.2, was to do an extensive literature review on the functional properties of each of these types of BCC. Following the guidelines of the ECO_2 framework, the reviewed properties were: slump, compressive strength, chloride penetration and carbonation. The secondary data collected also builds on the environmental and economic impact database embedded in the ECO_2 framework in Chapter 3.

After describing the background of the prediction of the functional properties of concrete in section 5.2, the gap which is of concern for this case study is identified through the literature review in sections 5.3 and 5.5. The scope of this case study is then explained in section 5.4. Due to the numerous possibilities of mix designs for binary and ternary BCC mixes, in order to develop an optimization algorithm, it was required to develop a regression model for all four functional properties. In section 5.6, a regression model was prepared using artificial neural network to predict accurately any of the four functional properties required for any BCC mix within the scope of this case study. Finally, as seen in the flowchart below in Figure 5.1, section 5.7 will include the optimization model based on the functional properties regressed and the application of the ECO_2 framework responding to several sustainability assessment scenarios.

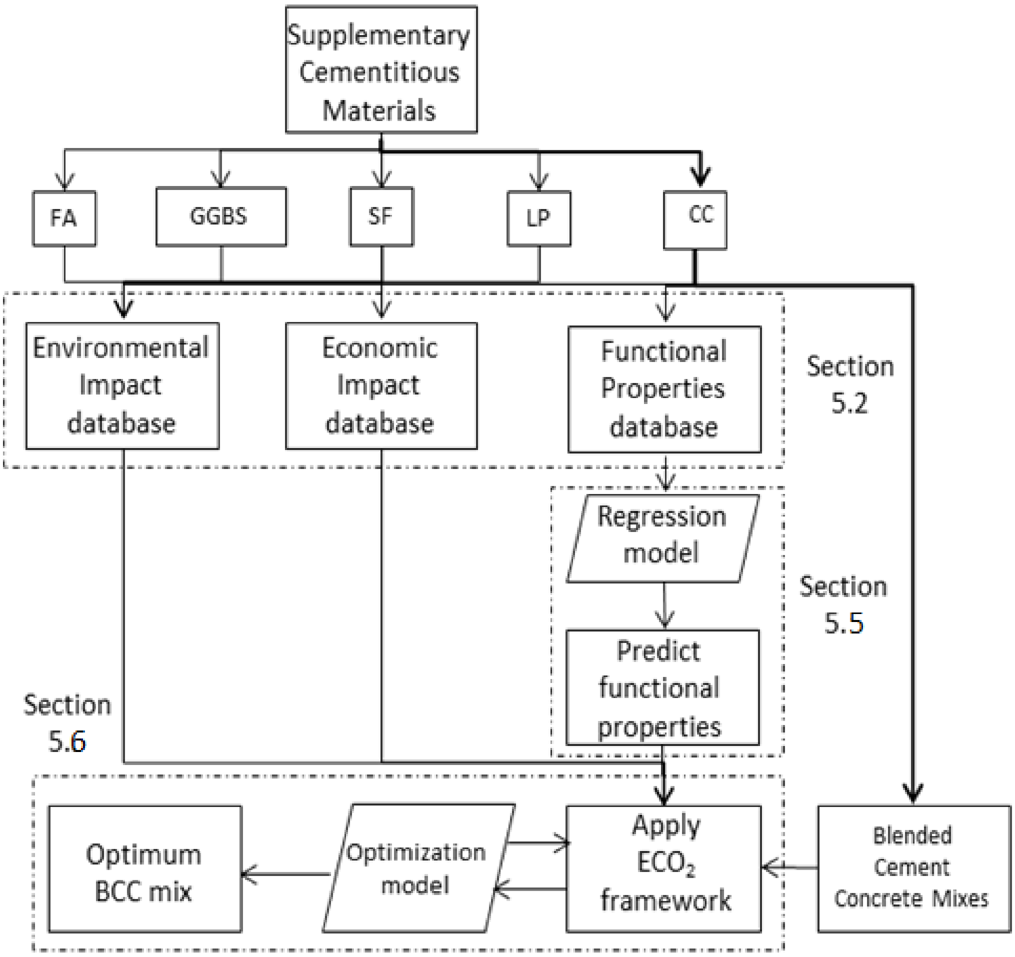


Figure 5.1: Description of the method followed throughout Chapter 5 for the BCC case study

5.2. Background

Recent reports by the World Bank show that the highest rate of growth in population is happening among the low-income countries, which constitute currently around 40% of the current global population (Scrivener et al., 2018). This increase in population size is equitable with a 65% increase in the urbanization within these countries, a social trend that is encouraged by the urban policies within most of these countries (Miller et al., 2017). Hence, consolidating its position as the most used building material worldwide; concrete use in low-income communities is expected to rise from a current yearly rate of a billion tonne to at least the double by 2050 (Yuli et al., 2018). Therefore, there is a real necessity for concrete to be cheaper to cater for the aforementioned need.

It is also established from the literature review, that cement production is a significant contributor to the rising climate change crisis. In order for the Paris conference target of a 2˚C decrease from pre-industrial levels change, there needs to be at least an 18% decrease in the carbon emissions from the cement industry (Scrivener et al., 2018). One tonne of ordinary Portland cement production produces approximately 900 kg of CO_2, half of which directly result from the calcination of the raw materials (Miller et al., 2018). This means that even if the sources of power are renewable and cleaner, there would still be a need to replace ordinary Portland cement by cementitious materials with a lower environmental impact.

Hence, in parallel with the incentives to subsidize the cost of cement, the need to decrease its environmental impact is a predominant driver for a more sustainable alternative. While the use of earth construction techniques which are both cheaper and environmentally friendly seem promising, the legal and technical restriction for integrating these solutions within an urban context are numerous (Maskell et al., 2016). The unavailability and unsuitability of timber for most of the geographic locations globally also hinders its use as a sustainable alternative (Bukauskas et al., 2018). This leaves sustainable concrete production as the primary way forward.

As per the findings from Chapter 2, the Green concrete production strategy, follows the following sustainable development objective; minimize the economic and environmental impact of concrete, while keeping adequate functional performance. The notion that is later developed through the ECO_2 framework to be, matching the functional parameters of the intended use of a concrete product while minimizing its Economic and Ecological impacts. Due to the technological hurdles preventing the integration of renewable sources of power, and the absence –to date- of enough support to commercialize alkali activated concrete, blended cement concrete remains the main candidate for replacing OPC as a sustainable concrete strategy.

5.3. Sustainability Potential of BCC

A blended cement concrete mix is one where cement is partially replaced with what is defined as a supplementary cementitious material (SCM). An SCM is either a hydraulic, pozzolanic or a filler material, which means that its contribution to the binding characteristics in a concrete mix is governed by a combination of its reaction with water similar to cement, its reaction with the chemical phases created through the cement hydration process or as a chemical catalyst respectively (Johari et al., 2011). Hence, the intrinsic factors that influence the performance and the degree of reactivity of a SCM are its chemical and physical composition.

In today's market, cements contain an average around 20% of SCMs (Scrivener et al., 2020). Apart from the under-research SCMs with minimal commercial presence such as municipal incinerated bottom ash (MIBA), bauxite residue and glass slag, the most pronounced SCMs are Fly Ash (FA), Ground Granulated Blastfurnace Slag (GGBS), Silica Fume (SF), and Calcined Clay (CC). This is established in Table 5.1 below, which is based on (Juenger et al., 2019) showing the availability of each of these SCMs versus the degree of integration of each in concrete products commercially.

Table 5.1: A comparison between the estimated global yearly production and use with concrete for several SCMs based on Juenger et al. (2019)

	Estimated Global Volume Production (Mt/year)	Estimated current use as a SCM (Mt/year)
FA	700-1000	350-400
GGBS	300-350	350-400
SF	1-3	1-2
CC	large accessible reserves	2-3
LP	large accessible reserves	250-300
MIBA	30-60	0
Bauxite residue	100-150	0
Waste glass	50-100	0

The basis upon which these five promising SCMs aforementioned are utilized by partially replacing OPC in BCC is their sustainability potential. Figure 5.2 shows the processing of FA, GGBS and SF and the production of LP and CC. When compared to the energy and emissions involved in producing OPC (especially the inevitable direct carbon emissions due to the calcination production process), the processing of these SCMs carries minimal energy use. This is an indicator for the minimal costs and environmental impact of these materials qualifying them to contributing at making the SCM based BCC more sustainable than OPC based concrete. Throughout the next subsections, the functional, environmental and economic properties of each of these BCC types are discussed in detail.

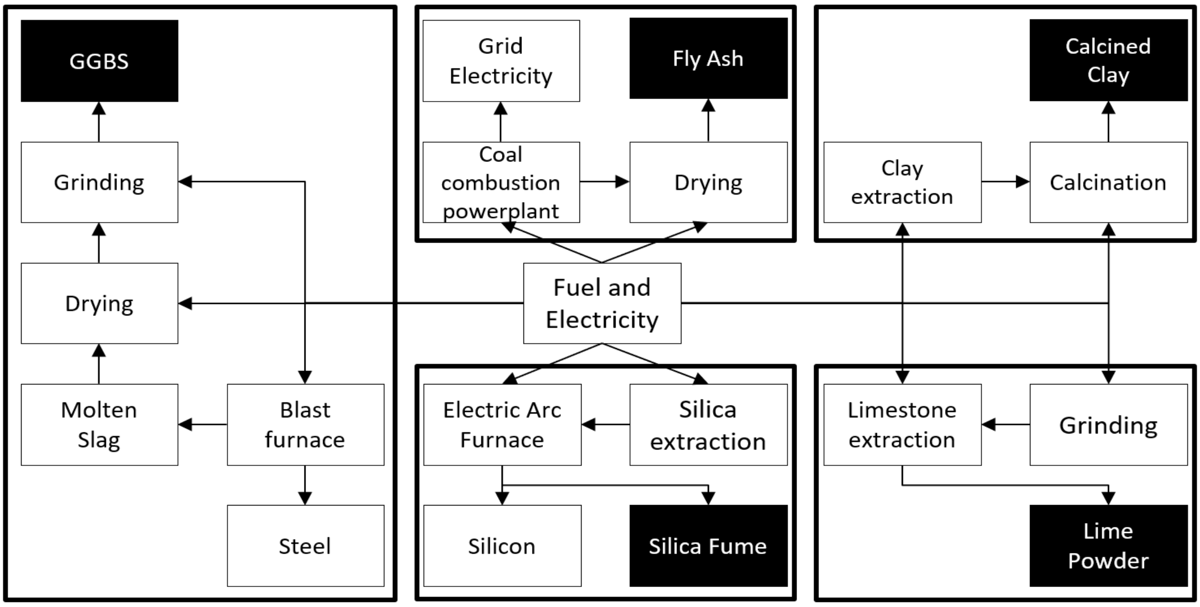


Figure 5.2: The production and recycling processes for FA, GGBS, SF, LP and CC

5.3.1. *Environmental Impact of BCC*

As established from the inventory database from Chapter 3, the higher the replacement ratio is of OPC with any of the 5 SCMs, the higher the savings are in terms of environmental impact. For example, using global warming potential (GWP) as an indicator, 0.89 kg eq CO_2 are attributed to the production of OPC. Meanwhile, the average for FA, GGBS, SF, LP and CC are 92,93,45,85 and 60% less based on the published values from secondary sources in Chapter 3 as seen in Figure 5.3.

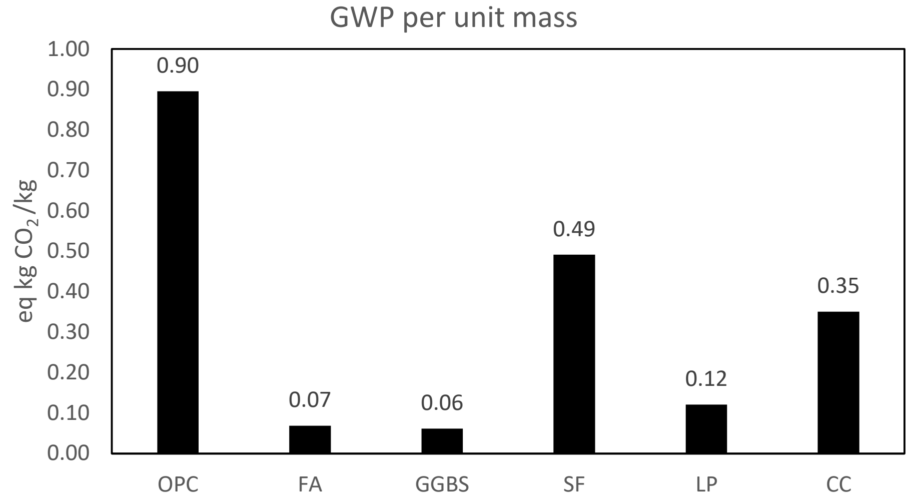


Figure 5.3: A comparison between the average values for the GWP per unit mass of OPC versus the SCMs under study

The low environmental impact could be understood examining the production/recycling processes of each SCM. As seen in Figure 5.1 Silica Fume is obtained as a by-product from silicon manufacturing and does not require further processing. At a temperature of approximately 2000°C, the reduction of high-purity quartz to silicon produces silicon dioxide vapor, which oxidizes and condenses at low temperatures to produce silica fume (Khan et al., 2018). Fly Ash and GGBS are both also industrial by-products from coal combustion and steel manufacturing in blastfurnaces respectively. FA is the reside, unburnt particles, of coal being burnt for electrical or hearing purposes which is captured by bag filters or through electrostatic precipitators (Giergiczny, 2019). Although it is ready to be bagged, capturing FA happens in humid conditions which requires a minor process of drying before its ready for use as an SCM. GGBS is obtained after molten slag, which is a superficial layer produced by iron oxides inside the blastfurnace at almost 1400°C, is dumped and quickly cooled by water jetting or quenching (Li et al., 2015). Similarly, GGBS is then in need for drying and mechanical grinding to be ready for use as SCM, but both processes also are minimal in terms of energy use.

Aside from the minimum processing energy in case of FA and GGBS (non-existent in SF's case), the fact that the 3 SCMs are by-products from industrial processes means that recycling them in concrete is also saving these inert materials from being landfilled, which is an environmental impact incentive (Yang et al., 2015). Limestone powder and calcined clay on the other hand are not by-products, rather fresh materials. Limestone powder is crushed and ground from natural limestone, which is mainly composed of skeletal fragment of organisms and can be formed from marine organisms, lacustrine and evaporite depositional environments (Wang et al., 2018). In comparison to Portland cement, LP only requires minimal energy for quarrying and grinding (Panesar et al., 2020). CC is manufactured by calcining naturally available Kaolinite clay in a temperature range of (700-800°C), which is also considerably less than the temperature required for the OPC production. Additionally, limestone and clay are abundant materials worldwide which reduces the potential for resources depletion (Sui et al., 2020).

On the other hand, it is important to note that the margin of the environmental impacts savings shown through the values in Figure 5.2 is not consistent across all SCMs. The following points provide the partial push back against the environmental gains from the use of SCMs:

- As explained earlier, the process of calcination of Kaolinite to produce calcined clay is still requiring of 700-800°C temperatures which is energy intensive, but still is far less than that of OPC and most importantly without emitting carbon dioxide as a result of the chemical reaction during the calcination process.
- According to the EU directive 2008, FA, GGBS and SF ought to be considered as by-products not as waste (Chen et al., 2010). This means that they are ought to be allocated a percentage of the environmental burden of their original production process, which are coal combustion, steel production and glass manufacturing respectively (Anastasiou et al., 2015). The average of the environmental impact for the original processes of each of the SCMs is presented in Table 5.2 from the database embedded in the ECO$_2$ tool. The value of the allocated environmental impact percentage varies depending on the selected methodology. If the allocation methodology is economic, then the value is determined based on the relative market value between the by-product, which is the SCM and the main product such as steel or electricity (Marinkovic et al., 2017). Otherwise, the allocation is determined as the relative mass of the SCM compared to the original product (Chen et al., 2010). A review of the values attributed to each SCM from the literature is summarized in Table 5.3.

Table 5.2: The average environmental impact for the original processes of FA, GGBS and SF from the ECO$_2$ tool database

	Electricity from coal	Steel	Silicon	
	/kWh	/kg	/kg	
GWP	3.19E-01	1.47E+00	2.69E+00	**kg eq CO$_2$**
ODP	7.70E-10	5.59E-08	2.10E-06	**kg eq cfc^{-11}**
AP	1.83E-03	5.09E-03	1.03E-02	**kg eq SO$_2$**
EP	2.96E-04	3.18E-03	3.02E-03	**kg eq PO$_4$**
ADPE	2.60E-03	1.26E-02	2.52E-02	**kg eq sb**
POCP	7.09E-05	8.12E-04	6.09E-04	**kg eq C$_2$H$_4$**
CED	9.10E-04	2.02E+01	5.02E+01	**MJ**
FW	3.75E+00	1.72E-02	1.17E-02	**m^3**

Table 5.3: A review of the impact allocation percentages for FA, GGBS and SF

Reference	Allocation %		
	FA	GGBS	SF
Timm et al., 2019	-	-	4.80%
Anastasiou et al., 2015	0.74%	0.07%	-
De Schepper et al., 2014	1.00%	-	-
Miller et al., 2018	0.06%	0.07%	-
Jiang et al., 2014	-	2.50%	-
Marinkovic et al., 2017	1.30%	-	-
Teixeira et al., 2016	0.03%	-	-
Van den Heede et al., 2017	1.00%	-	4.80%
Average	**0.53%**	**0.88%**	**4.80%**

- The third point is the availability issue. Although clay is an abundant material almost anywhere in the world, the research concerning CC was exclusive to high quality Kaolinite which is not as abundant (Scrivener et al., 2020). More importantly, the supply of GGBS and FA worldwide is threatened. Most of the steel production worldwide is shifting towards electric arc furnaces rather than blast furnace ones because it requires less energy and cost. For this fact, EAF production technique took over 55% of the market in the US in 2006 (Jiang et al., 2018). This is the basis of selecting the EAF slag as the scope of the first cases study in Chapter 4 sue to its sustainability potential. FA will also face a difficulty in sourcing due to the general trend of retiring coal-fired power plants worldwide. In the US, approximately 40% of coal-fired power plants have closed in the last five years and the Netherlands is expected to reach that target by 2030 (Juenger et al., 2019). The Canadian government will also eliminate the energy generated by coal by 2030 (Panesar et al., 2020). Chapter 6 discusses the issue of the UK concrete market alternatives to the expected halt of the UK's local FA sources by 2021.

5.3.2. Economic Impact of BCC

Due to the huge worldwide demand, cement factories are available in almost all countries around the world. Aside from the established reliability of concrete as a building material, the cost of producing cement is considered to be relatively low. The market price of a tonne of OPC ranges from £80 in the US and Europe to almost £40 in China (Scrivener et al., 2018). The fact that the technology is widespread and the business model of producing cement is profitable results in the widespread of cement production. However, pricing are rising and economically developing nations are in need of making cement even cheaper. A recent investigation identified the use of SCM as the most favourable cost reduction levers for the industry (Juenger et al., 2019). The literature review shows that, apart from SF and CC, replacing OPC with FA, GGBS or LP would yield more than 50% decrease in the cost of the resulting concrete as seen in Table 5.4.

Table 5.4: A review of the market prices for OPC, FA, GGBS, SF, LP and CC from the literature

		Market price per unit mass (£/tonne)					
Reference	**Country**	**OPC**	**FA**	**GGBS**	**SF**	**LP**	**CC**
Chen et al., 2019	France	125	35	23			
Crossin et al., 2012	Australia			100	890		
Habert et al., 2011	Switzerland		25	45			
Jiang et al., 2014	USA			74	500		
Joseph et al., 2017	India	43	15		400	3.1	22.1
Marinkovic et al., 2017	Serbia		3.5		1140		
McLellan et al., 2011	Australia		77				154
Mindess et al., 1996	Canada	77				40	
Navarro et al., 2018	Spain	88	38				
Park et al., 2012	South Korea	78	33	41	430		
Rahla et al., 2019	Portugal	65	28	37			
Wang et al., 2017	China	40	10				
Yang et al., 2017	China		12	7	385	17	
Zhang et al., 2014	China	58	9		275		
Mean		**72.11**	**24.35**	**42.56**	**574.29**	**20.03**	**88.05**
st dev		25.60	19.31	28.91	316.71	18.64	93.27

Nevertheless, the reduction in the expected cost for BCC compared to OPC based concrete would increase if carbon taxation rules apply. As established in Chapter 3, the ECO_2 framework is designed to accommodate for the carbon taxation costs expected to be applied in several countries worldwide. A summary of the relevant literature shows that -as seen in Table 5.5- the values set for the carbon tax, a fee imposed on the burning of carbon-based fuels, is considerable compared to that of OPC. Since a tonne of OPC is expected to cause an equivalent of 850 kg of CO_2 emissions, this would result in an average tax of around 14 £/tonne, which would cause the increase of the average market price of OPC by at least the same amount.

Table 5.5: A review of the values for carbon taxation worldwide from the literature

Reference	**Country**	**Policy Year**	**£/tonne eq. CO_2**
Di Filippo et al., 2019	USA	2019	30
Gharizadeh et al., 2020	Australia	2020	13
Imbabi et al., 2012	UK	2020	30
Shima et al., 2005	Japan	2020	11
Shi et al., 2019	Japan	2018	10
	Australia	2018	12
	China	2018	5
	Average		**16**

5.3.3. Functional properties of BCC

The performance of a BCC concrete mix to which any of the aforementioned SCMs takes part relies primarily, apart from the % replacement of OPC with one or more of the SCM, on the SCM's chemical and physical characteristics (Johari et al., 2011). As shown in the ternary graph in Figure 5.4, the chemical composition of any SCM is a mix of calcium, silicon and aluminium oxides. However, the chemical composition alone does not determine the chemical reactivity of an SCM.

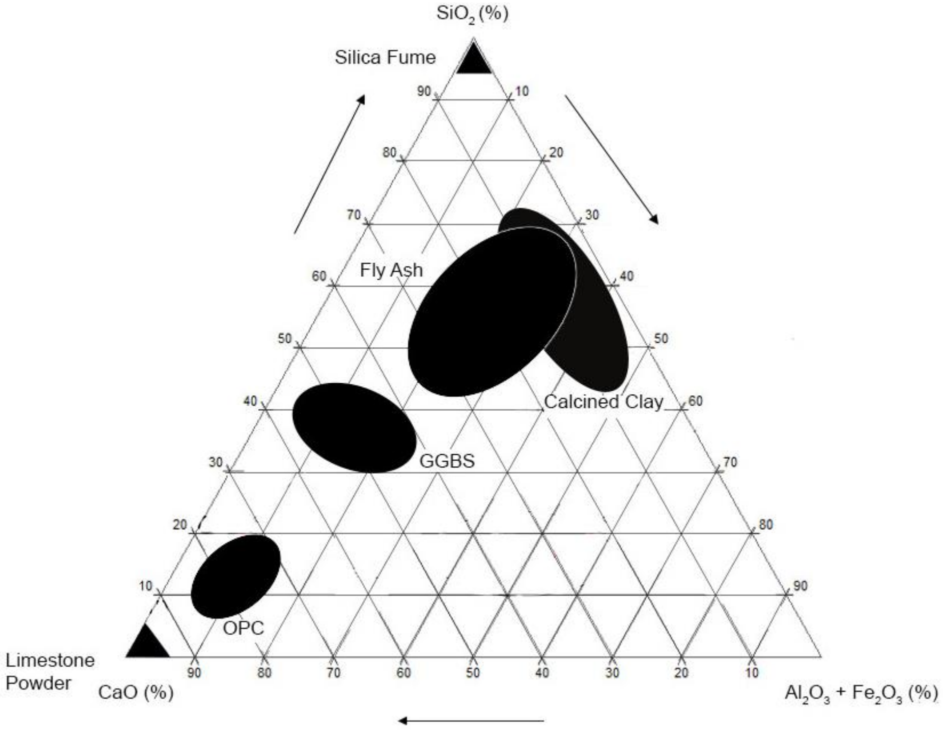


Figure 5.4: A ternary diagram showing the chemical composition of OPC versus the SCMs under study

A reliable indicator of the chemical reactivity would be either the total percentage of soluble siliceous, aluminosiliceous or calcium aluminosiliceous contents in an SCM or its portlandite consumption. The physical reactivity on the other hand, is directly correlated to the surface area of the SCM. A summary of the values of the average surface area of the five SCMs understudy is summarized in Table 5.6. The higher both values are, the more reactive an SCM is expected to be. The pozzolanic potential of an SCM could be tested using a Frattini test and the overall reactivity could be determined through the recently established R3 test (Li et al., 2018).

Table 5.6: A review from the literature of the physical characteristics of the SCMs under study

	Shape	**Reference**	**Surface area (m^2/kg)**	**Reference**
FA	Spherical	Wu et al., 2017	300-500	Jiao et al., 2017
GGBS	Angular	Divsholi et al., 2013	350-450	Zhang et al., 2013
SF	Spherical	Wongkeo et al., 2014	10,000-20,000	Meddah et al., 2014
LP	Angular	Wang et al., 2018	700-1300	Meddah et al., 2014
CC	Angular	Ramezanianpour et al., 2012	15,000-20,000	Poon et al., 2006

Hence, the functional properties of a BCC mix in which the SCM replaces OPC could be analysed in light of the reactivity of the SCM. The concrete functional properties that are considered within the scope of the ECO_2 framework are: Slump, Compressive strength, Chloride penetration and Carbonation. Accordingly, for each of the five SCMs under consideration in this case study, a review of the BCC mixes performances regarding these functional properties is given as follows:

- *Slump*

Due to the glassy structure of GGBS, the particles require less water to be coated, which causes a better slump (Teng et al., 2013). The spherical shape of the FA particles allow it to cause a ball bearing effect reducing the water demand of the concrete mix as well (Giergiczny, 2019). Moreover, the high surface area of LP while being chemically inert allows it to act as filler to reduce the water demand for concrete increasing its slump (Meddah et al., 2014). It is worth noting that while replacing OPC by FA with any % would increase slump, it is reported to only be the case for up to 50% GGBS and 15% LP replacement rates. On the other hand, the large surface area of both SF and CC, acts counter-effectively to increase the water demand for BCC concrete mixes and decrease their slump. The higher the replacement % of both SCMs for OPC, the higher the expected drop in slump (Johari et al., 2011).

- *Strength*

The governing chemical reaction between FA and GGBS when replacing OPC is a pozzolanic one. After the hydration of the calcium silicates from OPC, calcium silicate hydrates are formed among calcium hydroxide ions. The high pH level (>12) of the solution dissolves the inert anhydrous coating of FA and GGBS particle releasing their silicon, calcium and aluminium ions into the solution. The latter then reacts with the calcium hydroxide from the OPC hydration to form calcium silicate hydrates that occupy a larger volume and exhibit higher strength (Lothenbach et al., 2011). This latent hydraulic behaviour dictates that BCC containing FA and GGBS slow down the initial setting of OPC and hence decrease its early age strength. However, up until 30% and 70% replacement of OPC respectively, increases the strength of concrete marginally (<10%) at curing age of 28 days and more at 90 days (>30%) (Panesar et al., 2020). Although the chemical reaction by which SF and CC develop their strength carrying calcium silicate hydrate phases is also pozzolanic, the mechanism is different from that of FA and GGBS. Owing to their extremely fine particle size, both SCMs are reactive when replacing OPC enabling the densification and thickness reduction of the interfacial transitional zone of the binder matrix (Scrivener et al., 2018). This leads to early setting for the resulting BCC and higher early strength than that with FA and GGBS. This means that BCC with SF and CC is expected to exhibit up to 40% higher strength at both 28 and 90 days (Sui et al., 2019). The large surface area of LP, allows for more nucleation and hydration of OPC, hence increasing the strength of the resulting BCC. However, due to the limited pozzolanic activity of the LP as an SCM, its minor increase of strength (<15%) is only limited to when it replaces only 10-15% of OPC (Juenger et al., 2019).

- *Chloride penetration*

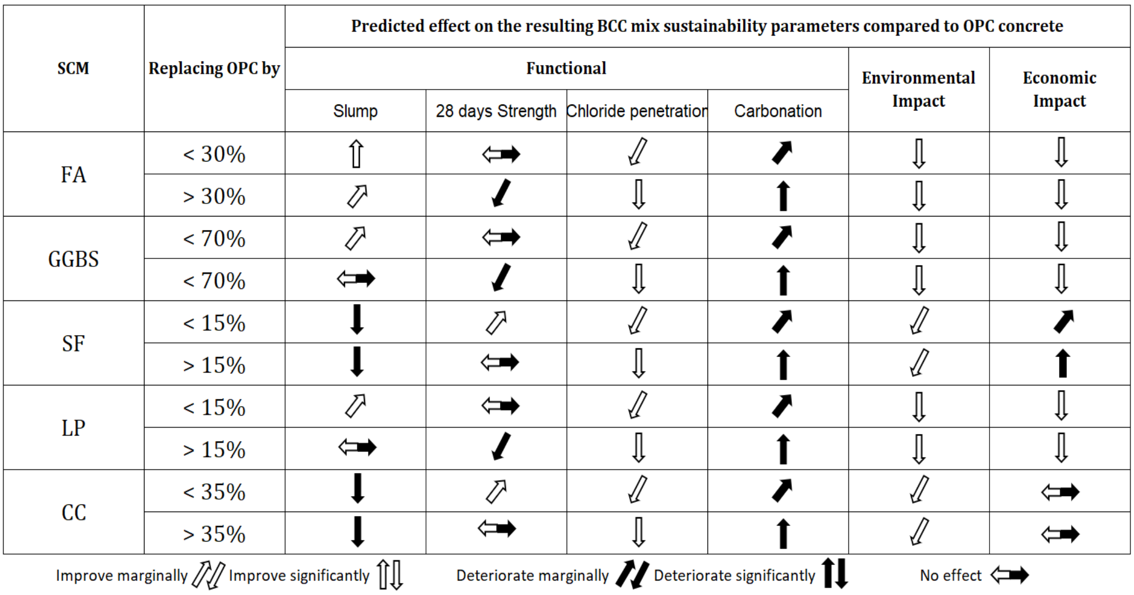
The addition of SCM as a partial replacement of OPC inevitably enhances the microstructure of the binder matrix when it comes to durability against chloride penetration. In the case of LP, the reason is the filler effect which causes an increase of the effective water to cement ratio and provides a larger space for the formation of hydration products (Sun et al., 2018). While for all other SCMs, the pozzolanic reaction replaces the portlandite with more calcium silicate hydrate phases leading to the formation of dense and less permeable microstructure with spasmodic pore framework. Both factors lead to less permeability, which enhances the durability of concrete to the penetration of chlorides (Kumar et al., 2020). It is reported that SF is the SCM with the lowest permeability as it replaces more OPC, followed by CC, then FA, then GGBS and finally LP (Pillai et al., 2019; Van den Heede et al., 2017). However, it is important to note that durability of reinforced concrete, as explained in Chapter 3, is not only dependant on the permeability of the matrix. It is rather the combined effect of the permeability and the chloride threshold, which is the percentage of chloride concentration at which the steel reinforcement would start to corrode (Panesar et al., 2018). Although replacing OPC with CC reduced the permeability of concrete significantly, the chloride threshold of BCC with CC is 0.2% by mass of binder, while OPC is 0.4% and FA based BCC is 0.6% (Pillai et al., 2019).

- *Carbonation*

Steel reinforcement embedded in reinforced concrete elements are protected by the passive cover layer of high pH (>11). The reaction between concrete and the CO_2 from the environment to which the concrete element is exposed causes portlandite and other calcium containing chemical phases within concrete to react and form calcium carbonates (Pillai et al., 2019). The durability of a concrete against carbonation induced corrosion of steel reinforcement is hence linked to the resistance of the concrete element to such carbonation process. Although SCM additions to concrete yield a denser microstructure, there is an evident unanimous agreement within the published articles that BCC has a lower resistance to carbonation compared to OPC concrete. The reason is that the pozzolanic reaction consumed the portlandite in the matrix, reducing the pH and increasing the probability of carbonation occurrence. Hence, regardless of the type, it is expected that FA, GGBS, SF, LP and CC would, if replaced OPC in a mix, render the resulting reinforced BCC less durable to carbonation (Meddah et al., 2018).

5.3.4. Summary of BCC sustainability potential

The summary of the previous sections is tabulated below in Figure 5.5. The optimization of a BCC mix based on any of the five SCMs is not a straight forward process. Although a consensus on the enhancement of the environmental impact is present for almost any OPC replacement with any SCM, the functional and economic impacts are not as clear.



SCM	Replacing OPC by	Predicted effect on the resulting BCC mix sustainability parameters compared to OPC concrete					
		Functional				Environmental Impact	Economic Impact
		Slump	28 days Strength	Chloride penetration	Carbonation		
FA	< 30%	⇧	⇦➡	⇙	⬈	⇩	⇩
	> 30%	⇗	⬋	⇩	⬆	⇩	⇩
GGBS	< 70%	⇗	⇦➡	⇙	⬈	⇩	⇩
	< 70%	⇦➡	⬋	⇩	⬆	⇩	⇩
SF	< 15%	⬇	⇗	⇙	⬈	⇙	⬈
	> 15%	⬇	⇦➡	⇩	⬆	⇙	⬆
LP	< 15%	⇗	⇦➡	⇙	⬈	⇩	⇩
	> 15%	⇦➡	⬋	⇩	⬆	⇩	⇩
CC	< 35%	⬇	⇗	⇙	⬈	⇙	⇦➡
	> 35%	⬇	⇦➡	⇩	⬆	⇙	⇦➡

Improve marginally ⇗⇙ Improve significantly ⇧⇩ Deteriorate marginally ⬈⬋ Deteriorate significantly ⬆⬇ No effect ⇦➡

Figure 5.5: A summary of the impact of different SCM replacement on functional, environmental and economic performance on the resulting BCC mixes

5.4. Description of the case study

The ECO$_2$ framework is developed to assess the sustainability of concrete based on performance specified criteria and replacing OPC with SCM appears to be the most established alternative to enhance concrete sustainability. Currently, the five most utilized SCMs are FA, GGBS, SF, LP and CC. The more OPC is replaced by any of these SCMs -with the exception of SF- there, the lower the environmental and economic impact of the resulting BCC would be. This is however dependent largely on the transportation distances and impact allocation for the SCMs compared to that of OPC. However, the ECO$_2$ framework logic values the functional performance of the concrete alternatives under comparison equally to the environmental and economic impact. The functional properties of BCC vary depending on the replacement ratio, the type of SCM and the functional property itself. Therefore, this case study, has the following objectives:

- Survey the literature to create a database of the experimental results done on BCC types reviewed for the functional properties included within the ECO$_2$ framework.
- Build a reliable and accurate non-linear regression model to predict the performance of a BCC mix based on a binary or ternary mix of OPC and any of: FA, GGBS, SF, LP and CC.
- Using the logic from the ECO$_2$ framework, run an optimization algorithm that deduces the most sustainable BCC mix based on several assumed scenarios including plain and reinforced concrete for several functional requirements.

In section 5.5, the data collection, database creation and regression model construction are explained. Section 5.6 then includes the process of developing the optimization algorithm along with the discussion of the obtained results of the optimum BCC mixes. In the final section of the chapter (5.7), a summary of the chapter findings is presented.

5.5. Prediction modelling

5.5.1. State-of-the-art

The business-as-usual method of implementing the ECO_2 framework as explained in Chapter 3 dictates a forward flow of the sustainability assessment process. This means that the user is responsible for entering the functional performance values for each concrete mix under study, which are that for slump, strength, chloride penetration and carbonation. For each alternative being considered, these values are compared against the project requirements of the assumed scenario: slump, strength and service life. Given the alternative passes the minimum performance requirement (higher than or equal to the required slump and strength values); the functional unit is then calculated accordingly. For this purpose, the user is directed to either test each alternative, in order to obtain the values for its functional performance or use a prediction model.

Whether it being a wide experimental campaign in a research centre or a pre-execution trial testing for a concrete construction project, it is wasteful to test all potential concrete mixes for slump, strength and especially durability testing. Concrete durability against steel corrosion due to either chloride penetration or carbonation, which is required within ECO_2, happens over decades (Sui et al., 2019). That is why accelerated tests were developed in standards to save time. However, testing the durability of concrete against chloride penetration -for example- through the ponding or immersion test such as ASTM C1556 and ASTM C1543 is expensive (Kumar et al., 2019). Similarly, testing the natural carbonation for concrete samples would take months or even years depending on the mix and exposure conditions (Bernal et al., 2014).

Hence, several researchers worked in recent years in developing prediction models for the slump, strength, chloride penetration and carbonation of concrete. A summary of the studied literature could be found in Tables 5.7 and 5.8 below. The models chosen within the search scope are those correlating between these four functional parameters and blended cement concrete mixes containing one or more of the five SCMs under study.

Table 5.7: A review of the number of independent and target variables from concrete prediction models found in the literature

Author	Year	Property	variables	CEM I	SCM			CA	FA	SP	Water	Strength	%CO_2	%RH	time
					FA	GGBS	SF								
Chandawani	2014	Slump	6	√	√			√	√	√	√				
Chen	2014		7	√	√	√		√	√	√	√				
Cihan	2019		5	√					√	√	√	√			
Hoang	2016		5	√				√	√	√	√				
Al-Shamiri	2019	Strength	6	√	√			√	√	√	√				
Golafshani	2020		7	√	√	√		√	√	√	√				
Naseri	2020		5	√				√	√	√	√				
Yu	2018		7	√	√	√		√	√	√	√				
Ghafoori	2013	Chloride Permeability	7	√	√		√	√	√	√	√				
Inthata	2013		6	√	√			√	√	√	√				
Mohamed	2018		8	√	√	√	√	√	√	√	√				
Najimi	2019		7	√	√		√	√	√	√	√				
Felix	2019	Carbonation Rate	8	√	√	√	√					√	√	√	√
Kellouche	2019		6	√	√						√		√	√	√
Luo	2014		4	√							√			√	√
Taffese	2015		10	√	√	√	√	√	√	√	√	√			√

Table 5.8: A review of the statistical significance of the concrete performance prediction models reviewed from the literature

Author	Property	Training points	Test points	R	RMSE	unit	MAPE (%)	Regression model
Chandawani	Slump	395	85	0.98	2.83	mm	1.38	hybrid GA-Artificial Neural Network (ANN)
Chen		70	24	-	90		-	parallel hyper-cubic gene expression programming (GEP)
Cihan		80	35	-	24.7		-	Decision Tree, Random Forrest, support vector machine (SVM), partial least squares, ANNs, and Fuzzy Logic
Hoang		76	19	0.97	5.4		3.68	SVM
Al-Shamiri	Strength	246	82	0.99	1.05	MPa	1.54	Extreme learning machine, ANN
Golafshani		772	258	0.97	4.96		-	ANN and Adaptive Neuro-Fuzzy Inference System (ANFIS)
Naseri		174	58	-	4.58		-	Soccer League Competition, Water Cycle Algorithm , Genetic Algorithm, SVM, ANN, and Linear Regression
Yu		1234	527	0.97	10.4		14	Cat swarm optimisation algorithm, SVM
Ghafoori	Chloride Permeability	60	12	-	-	Coulomb	5.35	Comparing linear, non-linear regression with BP-ANN
Inthata		216	54	0.96	479		12.72	BP-ANN
Mohamed		50	22	0.95	-		5.61	ANN
Najimi		50	22	-	176		-	ANN based on Forward feed artificial bee colony algorithm
Felix	Carbonation Depth	223	56	0.93	-	mm/day$^{0.5}$	-	BP-ANN
Kellouche		240	60	0.98	-		-	BP-ANN
Luo		30	5	-	-		5.04	Particle Swarm Optimization (PSO), BP ANN
Taffese		23	10	-	0.49		-	Neural Network, Decision Tree, Bagging and Boosting ML algorithms

5.5.2. *Identified gaps*

An apparent gap found in the surveyed literature is the absence of any model that predicts the performance of powdered lime or calcined clay among the rest of the SCMs. Besides, it is clear that the error is rather significant in the prediction models for chloride penetration and carbonation. Also, according to Kurda et al. (2019), the cement grade (42.5 or 52.5 MPa) makes the fundamental difference in the strength of the resulting concrete mix in which it is used. Hence, it is also required to consider the cement grade within the parameters under study in the regression models. Finally, the sample sizes of most of the proposed models in the literature are small (<30 data points per independent variable).

5.5.3. *Pre-bcc regression model*

Regression is a statistical method used to determine the strength and character of the relationship between one dependent variable and a series of other variables. In applications such as that of concrete properties where the relationship is not necessarily known, it is preferred to use machine learning methods to build the regression models. Machine learning is an application of artificial intelligence (AI) that provides systems the ability to automatically learn and improve from experience without being explicitly programmed. Machine learning focuses on the development of computer programs that can access data and use it to learn for themselves. Given a sample of observations $\mathrm{S} = \{(\underline{\mathrm{x}}, \mathrm{y}) | \underline{\mathrm{x}} \in \Re^{\mathrm{n}}, \mathrm{y} \in \Re\}$, where $\underline{\mathrm{x}}$ is the vector of independent variables and y the target variable, the regression problem is the search through the space of functions $(\mathrm{F}: \Re^{\mathrm{n}} \rightarrow \Re)$ for some function $\mathrm{f} \in \mathrm{F}$ that minimizes a defined loss function that describes the discrepancy between the prediction $\mathrm{f}(\underline{\mathrm{x}})$ and the observed value y. The loss function 5.1 below used throughout the regressors of the *Pre-bcc* model is the mean-squared prediction error (MSPE), where

$$\mathrm{MSPE} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{EXP}_{\mathrm{i}} - \mathrm{PRE}_{\mathrm{i}})^2}{\mathrm{n}} \qquad (5.1)$$

The search method through the function space is defined by two factors: the regression algorithm or technique and the set of parameters related to the search for the learned function f not part of its definition. The targeted variables for the regressors are the concrete properties tackled within the ECO_2 framework: Slump, 28 days compressive strength, durability to chloride induced corrosion through electric resistivity and natural carbonation rate. It is very important to note that, since it is acknowledged that the strength and durability of concrete is time dependent, the regression model was built on data specific to concrete mixes cured only for 28 days. The name of the regression model, which includes 10 input variables that constitute the concrete mix: water content, CEM1, FA, GGBS, SF, LP, CC, coarse aggregates, fine aggregates and superplasticizers, was selected as *Pre-bcc* because it was developed to predict the performance of BCC concrete.

5.5.3.1. Stack generation

In order to tackle the complexity of the problem, the regression was addressed using ensemble learning methods where multiple regression learners are grouped together to provide the final prediction (Mendes-Moreira et al., 2012). There are multiple ways of grouping learners to create an ensemble, the one used here is stacking or stacked generalization (Wolpert, 1992). The first level (L1) is made up of a set of m learners $h_i: \underline{\boldsymbol{x}} \in \boldsymbol{\mathfrak{R}}^n \to y \in \mathfrak{R}$, each of which is a result of searching a subset $S_i \subset S$ rather than the entire space. The output of these different learners is then "stacked" together along with the inputs as a vector that is fed into the second layer learner: $g: \underline{\boldsymbol{z}} \in \boldsymbol{\mathfrak{R}}^{n+m} \to y \in \mathfrak{R}$ so that the final output of the system is $y = g(h_1(\underline{\boldsymbol{x}}), \ldots, h_m(\underline{\boldsymbol{x}}); \underline{\boldsymbol{x}})$.

There is a wide range of machine learners that could be used in the boosting model, some of which were used in previous papers reviewed such as Support Victor Machine, Boot Strap Aggregations and Genetic Algorithms. The learners chosen for the *Pre-bcc* regression model were Random Forrest, Extreme Gradient (XG) Boost, Bayesian Ridge and Multi-layer Perceptron, which were implemented using off-the shelf python codes from the scikit library (https://scikit-learn.org/stable/index.html). After attempting several iterations, the XGBoost model was the model with the least error and hence was used for all L1 learners. This is consistent with the characteristics of XGBoost since it is designed to handle missing data with its in-build features and, is an optimum learner for small to medium datasets (Chen and Guestrin, 2016). After that, the final regressor is found by testing all four variants for whichever produces the lowers MSPE, which is the error calculated in equation 5.1 earlier.

As seen in Figure 5.6, the functional database was randomly divided into 80% training and 20% testing groups. The training data were used to develop the model parameters while the test data were used only to validate the model. Part of the challenge with this problem was how to define outliers when the underlying system being approximated is non-linear and multi-dimensional. The approach selected is to build a regression model and defining outliers as samples where the prediction error exceeds some criteria following that by Naseri et al. (2019). As the L1 regressors $\mathrm{h_i}$ are being built each covering a subset $\mathrm{S_i}$, the data $\cup_{\mathrm{i=0}}^{\mathrm{m}} \mathrm{S_i}$ are maintained and if the $|\cup_{\mathrm{i=0}}^{\mathrm{m}} \mathrm{S_i}| > 0.8|\mathrm{S}|$, then the model is considered a candidate and the data is saved. At the end of the pre-processing, the data associated with the candidate that has the lowest MSPE is then saved as the input data for the actual model generation ensuring that the output data is composed of disjoint subsets each of which can be adequately covered by a weak learner. This allows using the same control flow for model generation and pre-processing (outlier detection), the difference being that model generation does not actually throw away any data.

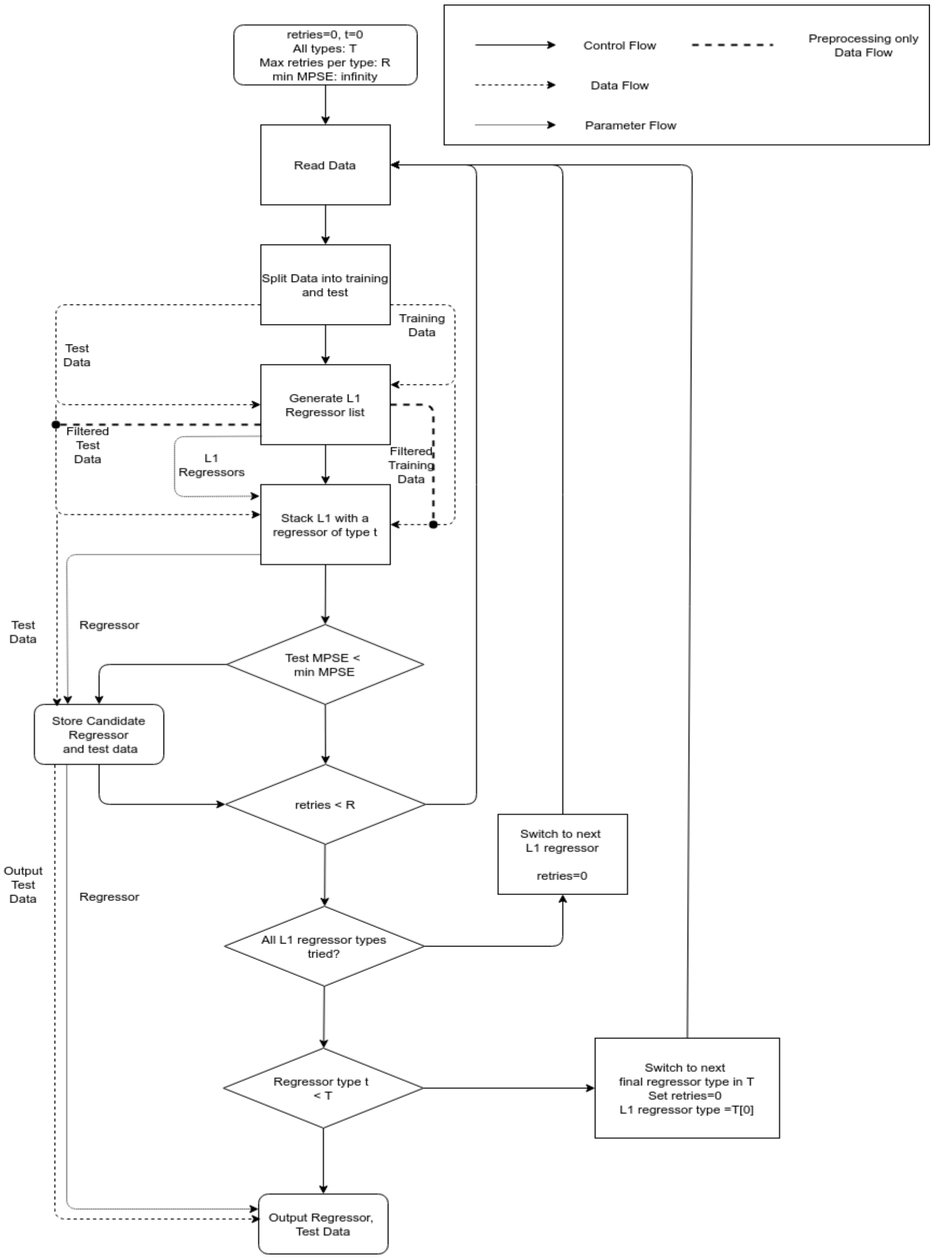


Figure 5.6: A flow diagram of the pre-processing algorithm for the multi-layer regression model prepared

5.5.3.2. Data collection

In order to build a statistically sound database for the four functional properties understudy, 1683 data points were collected from previously published papers as shown in the Appendix C. The data points represent a concrete mix each that include one or more of the SCMs and was tested against one or more of the functional properties. The mixes were extracted from 153 journal articles published between 1997-2020. The division of the datasets between the independent variables and targeted parameters is shown in Figure 5.7. Note that the total of the values represented in the pie charts differ from the total points surveyed because a paper could include more than one SCM and could have been tested against more than one property. The inclusion criterion is that the tests done on the concrete mixes are standard and that the paper is published in either a conference, journal or, a thesis.

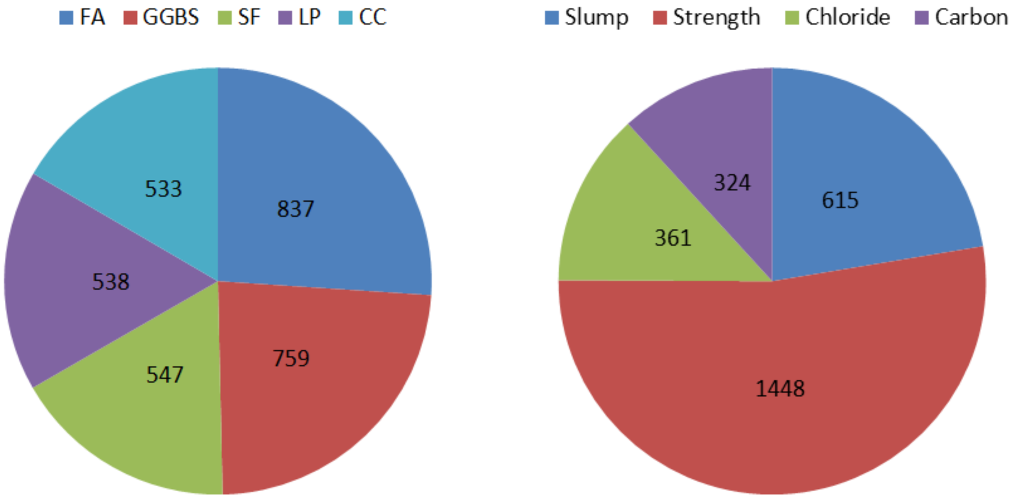


Figure 5.7: The number of times each mix constituent (left) and target variable (right) was mentioned in the database developed for the *Pre-bcc* regression model generation

The online databases used were: EThOS, Google scholar, SCOPUS, Science Direct and Research Gate. The search words were different combinations of the names of the SCMs and the functional properties under investigation. The inclusion criteria were that: 1) The tests done on the concrete mixes were following the ACI, EN or RILEM standards, 2) The study is either a dissertation or a peer-reviewed article as a conference proceeding or a journal article, 3) The strength, chloride resistivity and carbonation testing was done on 28 days cured concrete samples and 4) The concrete mixes reported in the study include one or more of the SCMs and was tested against one or more of the functional properties.

5.5.3.3. Model generation

The approach to the process of generating learners h_i at L1 as well as selecting the subset of samples S_i was not an off-the-shelf implementation. The intuition behind the approach is that the data used for the *Pre-bcc* model comes from different sources with potentially different conditions that may be difficult to fit together (especially in the presence of outliers when the model generation is used in pre-processing). Moreover, since multiple learners exist, each set of learners might be focusing on the data from a subset of sources $B_k \subset S$. However, if sources were grouped at random, it is likely some of the data subsets might be over or under fit. In line with the concept of boosting where multiple weak learners are created in stages similar to the concept of gradient descent steps (Friedman, 2000), a smaller task was created to develop subsequent learners by removing the sources that fit first. So, when a learner $h_i$is found by using cross-validation grid search and fit on a subset S_i, only sources that have any elements above a certain error are used for the subsequent learner. If the coverage of the current h_i is below a certain amount, the model is not admitted, and the algorithm terminates when the number of elements out of coverage is less than 10% of the data. The algorithm terminates without convergence if multiple iterations yield inadequate coverage, in which case the data is reshuffled and will need to search for a new set of L1 models. The flow chart in Figure 5.8 shows this process.

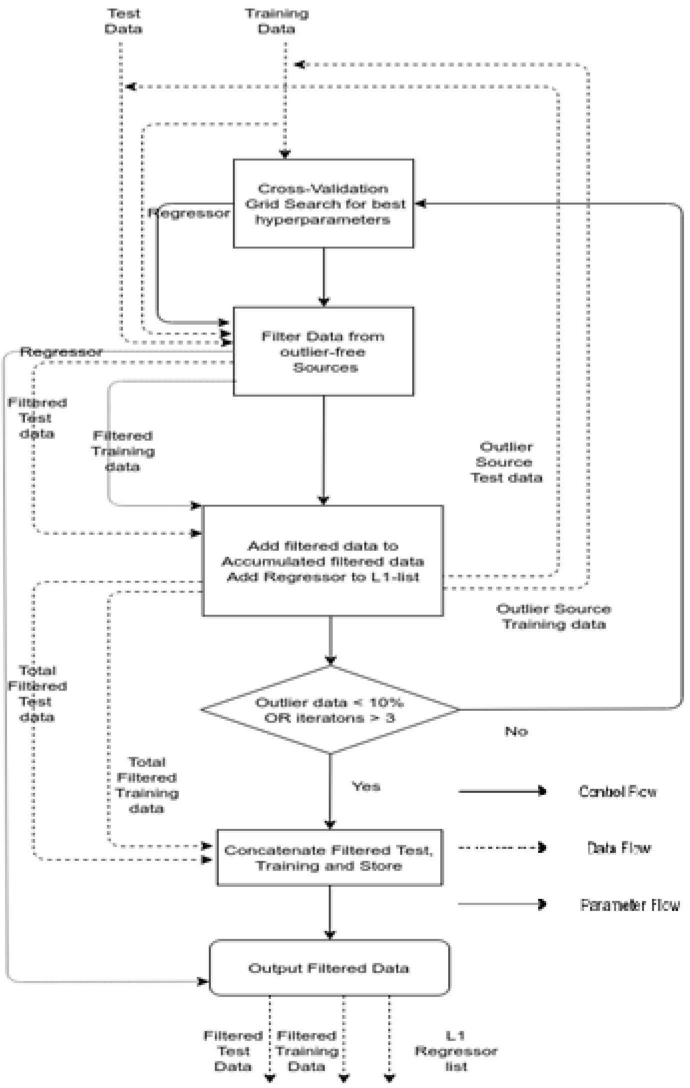


Figure 5.8: A flow diagram showing the Pre-bcc regression model generation algorithm

5.5.3.4. Analysis of regression

Using the database explained in 5.6.2, the regression models were built and the output was validated against the true values of the testing dataset. Table 5.9 shows the architecture that resulted from the model selection process described above as well as the training/test data sizes and the performance of the models. The prediction accuracy was measured using 3 different statistical metrics; the aforementioned MSPE, the mean absolute percentage error (MAPE) and the correlation coefficient R. The formula for MAPE is as follows, where n is the number of times the summation iteration happens, A_t is the true value and F_t is the predicted one:

$$\mathrm{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right|$$

Table 5.9: The optimized learner type for level 2 of each regression model and its statistical significance

Variable	L2 learner type	Training Size	Test Size	Statistical Significance		
				MSPE	MAPE	R
Slump	Random Forest	474	74	20.5%	12.5%	0.95
Strength	Bayesian Ridge	1090	212	12.0%	9.0%	0.96
Chloride resistivity	Random Forest	241	33	18.0%	14.5%	0.93
Carbonation	XGB	278	34	18.7%	15.2%	0.94

Comparing the statistical significance of the *Pre-bcc* regression models developed in this chapter with the average in the regression models found in the literature shows that although the *Pre-bcc* model was developed using more data points compared to the others, the statistical correlation is slightly worse as shown in Table 5.10.

Table 5.10: A comparison between the statistical significance *Pre-bcc* and the average of the literature regression models

Author	Property	Statistical Significance	
		R	MAPE (%)
Literature average	Slump	0.98	2.53
Pre-bcc		0.95	12.5
Literature average	Strength	0.98	7.77
Pre-bcc		0.96	9.01
Literature average	Chloride resistivity	0.96	7.89
Pre-bcc		0.93	14.5
Literature average	Carbonation	0.96	5.04
Pre-bcc		0.94	15.2

For each of the four target variables, the evaluation of the performance and behaviour of the regression models could be summarized as follows:

- Figure 5.9 shows the plot of the predictions vs actual values over the test data is to visualize goodness of fit. As can be seen, the models provide a usable fit. As expected, areas with more data present (since both test and training data come from the same distribution), result in better performing models.

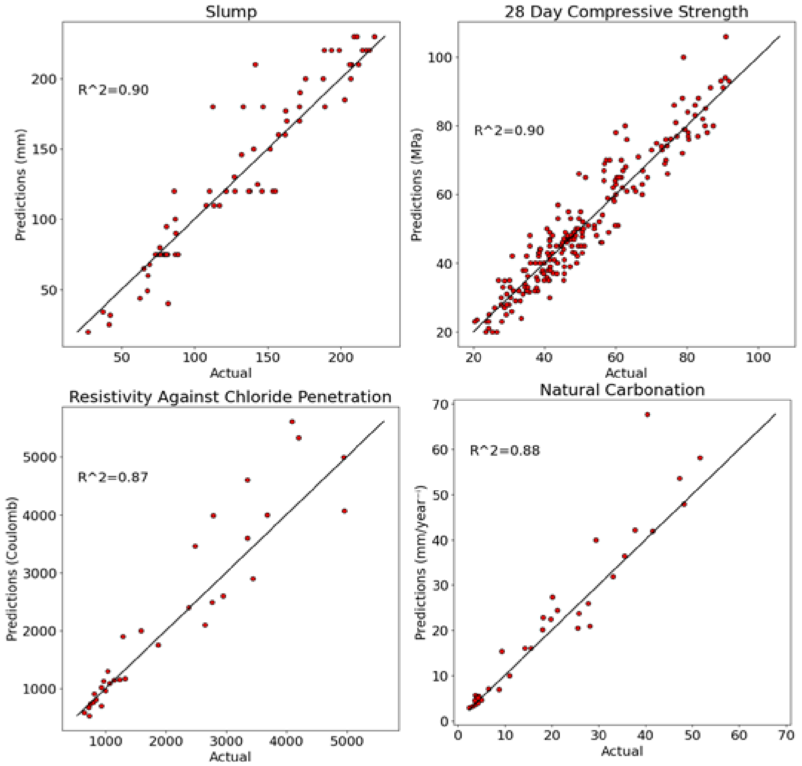


Figure 5.9: Predicted vs actual values for the concrete functional parameters of the *Pre-bcc* prediction model

- As seen in Figure 5.10, the plots of the residuals vs predictions over the entire set provide a measure of bias. With the exception of slump, the models show no noticeable bias based on the fact that the residuals appear as a normal distribution with zero mean throughout the different regions of the data set. The slump variable does show bias since the residuals are mostly positive in the lower values of the prediction and mostly negative in the upper values.

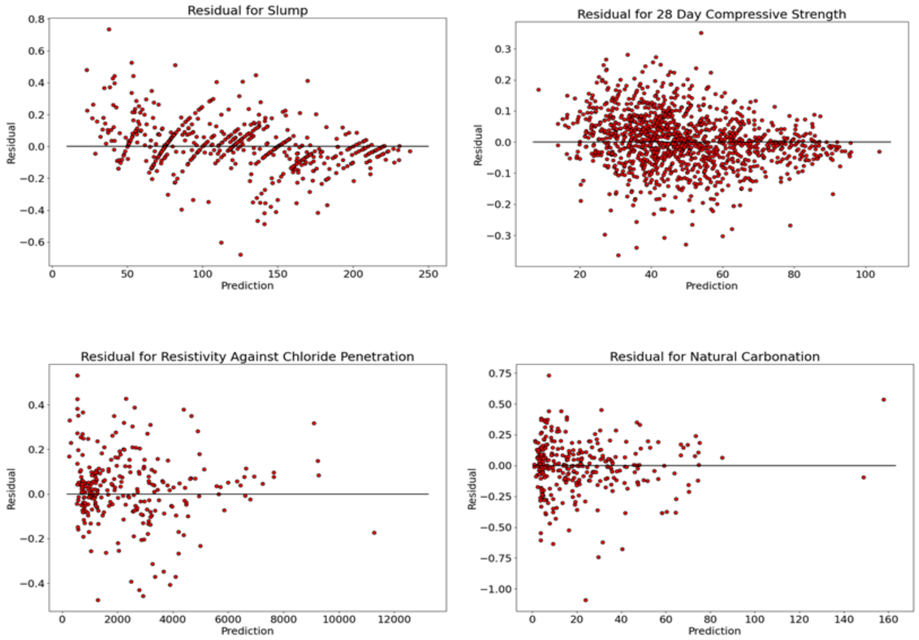


Figure 5.10: The residual error across the four functional parameters of the *Pre-bcc* prediction models

5.6. Optimization of the BCC mixes

The main objective of this chapter is to optimize the mixing proportions of binary and ternary blended cement concrete mixes incorporating FA, GGBS, SF, LP and CC as SCMs concerning the ECO_2 sustainability index score. Any optimization process is an attempt to find the optimum solution for an objective function within a set of constraints. The objective function of this case study is the ECO_2 index calculation. As explained in Chapter 4, the process of assessing the sustainability of a concrete mix using ECO_2 requires primarily the user to input, besides the scenario assumptions and inventory data, the functional properties of the mix. Hence, the regression model in section 5.6 was developed to establish, through the use of multiple machine learning techniques, an accurate non-linear regression model. This model, based on an extensive database, is now established as a reliable predictor for the slump, strength, chloride penetration resistance and natural carbonation for BCC.

5.6.1. Objective function

The first step in optimizing the mixing proportions of BCC, which is the objective of the chapter under study, is to select the relevant scenario for the ECO_2 calculation. As explained in Chapter 3, a scenario defines the boundaries that dictate the LCA calculations. Prior to defining the two selected scenarios for this case study, it is significant to recall the ECO_2 index calculation process as follows. The ECO_2 index is calculated by averaging the normalized economic score (Z') and the normalized ecological score (Y) as in equation 5.2, Z' and Z, which is the absolute economic score of each mix, are calculated as per equations 5.3 and 5.4.

$$ECO_{2_i} = Y'_i * 0.5 + Z'_i * 0.5 \qquad (5.2)$$

$$Z'_{\mathrm{i}} = \frac{\max(\mathrm{Z_i}) - \mathrm{Z_i}}{\max(\mathrm{Z_i}) - \min(\mathrm{Z_i})} \qquad (5.3)$$

$$\mathrm{Z_i}\ (\$/\mathrm{m}^3) = \sum_{j=1}^{n} \left(\frac{\text{Market price}}{kg} * \mathrm{Wi}\right) * \mathrm{N_i} \qquad (5.4)$$

The market price of each constituent j (cement, FA and so on) is a variable for which the values were obtained from the literature in Chapter 3 and are shown in Table 5.11 below and W_i is the mass per unit volume of that constituent (j) in this mix (i). N is the service life repeatability variable explained in Chapter 4 that is assumed as 1 if the scenario is of plain concrete or is calculated as equation 5.5 if reinforced.

$$N_i = \frac{SL_{Ri}}{SL_{Pi}} \qquad (5.5)$$

Where SL_R is a constant representing the required service life for this reinforced concrete scenario (most probably the value is either 50 years or 100 years) and SL_P is a variable representing the predicted service life of mix i, which is calculated as in equation 5.6 below where X is a constant representing the concrete cover (usually between 30 and 70 mm) and Kn_i is the natural carbonation rate of mix (i) (mm/sqrt(year)) predicted by the *Pre-bcc* regression model developed in section 5.5.

$$SL_{Pi} = \left(\frac{X}{K_{ni}}\right)^2 \qquad (5.6)$$

The normalized ecological score Y_i is the average of the normalized score of 7 environmental impact indicators. The absolute value of each of the environmental impact indicators (GWP, AP, EP, ODP, etc) is calculated in a similar fashion to the economic impact.

$$Y'_i = Avg\ (Y'_{GWPi}\ ,Y'_{ODPi}\ ,Y'_{EPi}\ ,Y'_{APi}\ ,Y'_{POCPi}\ ,Y'_{ADPEi}\ ,Y'_{CEDi}) \qquad (5.7)$$

$$Y'_{GWPi} = \frac{\max(\ Y_{GWPi}) - Y_{GWP_{\mathrm{i}}}}{\max\ (Y_{GWP_{\mathrm{i}}}) - \min\ (Y_{GWP_{\mathrm{i}}})} \qquad (5.8)$$

$$\frac{Y_{GWPi}}{m^3} = \mathrm{N} * \sum_{j=1}^{n} \left(\frac{GWP_j}{kg} * \mathrm{Wi}\right) \qquad (5.9)$$

Where GWPj/kg is the value per kg for constituent (j) of mix (i) which is found in Table 5.11 below and W_i is the mass per unit volume of this constituent (j) in this mix (i) the mass of the binder multiplied by the ratio between the binder the constituent (j) and N was defined earlier.

Table 5.11: Average values for the inventory data of all BCC components from the ECO_2 tool database (Appendix B)

	Water	Cement	FA	GGBS	SF	CC	LP	CA	FA	SP
Price	2.77E-03	8.72E-02	3.62E-02	3.70E-02	5.74E-01	8.80E-02	2.00E-02	1.18E-02	1.20E-02	1.43E+0
GWP	2.50E-04	8.96E-01	6.21E-03	3.99E-02	7.73E-05	3.51E-01	1.21E-01	1.03E-02	6.72E-03	9.08E-01
ODP	5.57E-12	2.08E-08	4.47E-09	4.46E-09	6.04E-11	1.52E-09	6.54E-12	8.15E-08	8.15E-08	3.84E-05
AP	0.00E+0	2.90E-03	4.14E-05	1.37E-04	2.96E-07	3.24E-04	4.58E-06	1.53E-05	8.10E-06	5.44E-02
EP	1.26E-07	4.16E-04	4.75E-06	6.67E-06	8.70E-08	4.89E-05	3.23E-05	5.39E-06	2.82E-06	9.24E-04
ADPE	6.83E-07	1.35E-03	1.80E-04	2.88E-04	7.26E-07	1.68E-04	1.66E-04	1.49E-05	5.07E-05	4.94E-03
POCP	6.32E-08	1.14E-04	1.90E-06	1.59E-05	1.75E-08	1.09E-05	5.32E-06	4.53E-06	9.83E-07	1.88E-04
CED	2.95E-04	4.19E+0	4.38E-01	2.14E-01	1.44E-03	2.60E+0	7.64E-01	7.19E-02	5.78E-02	1.98E+1

Two scenarios were defined for the optimization problem. The first is assuming a plain concrete application. This means that N is equals to 1 and the only governing functional parameters are the slump (which is required to be at least 100 mm in order to achieve a minimum class of S3) and the compressive strength. As established through the literature, there is a clear significance in specifying the minimum required compressive strength for the concrete alternative under study. Hence, in the first and second scenarios, 8 sub-scenarios were defined for the following minimum 28-days compressive strength classes (20MPa, 30, 40, 50, 60, 70, 80 and 90 MPa). In the second scenario, the concrete was assumed to be used for reinforced applications. Hence, the chloride penetration resistance was defined as a minimum of 2000 coulombs and the minimum concrete cover and required service life (SL_R) of 50mm and 50 years, respectively.

5.6.2. Constraints

The objective optimization problem is hence achieving the mix with the highest ECO_2 score while satisfying certain constraints as follows. First, A mix is a varying percentage of the following components: Cement (Grade 42.5 or 52.5), FA, GGBS, SF, LP, CC, Coarse aggregates, Fine aggregates and Superplasticizer. Logically, the first constraint is that the summation of the volume of all mix constituents in a unit volume of concrete must also equals 1000, where **ρ**, which is the specific gravity of all components and W_i is its mass per unit volume is summarized in Table 5.12.

$$\frac{W_{cement}}{\rho_{cement}} + \frac{W_{FA}}{\rho_{FA}} + \frac{W_{GGBS}}{\rho_{GGBS}} + \frac{W_{SF}}{\rho_{SF}} + \frac{W_{CC}}{\rho_{CC}} + \frac{W_{LP}}{\rho_{LP}} + \frac{W_{Coarse}}{\rho_{Coarse}} + \frac{W_{Fine}}{\rho_{Fine}} + \frac{W_{SP}}{\rho_{SP}} = 1000$$

Table 5.12: The specific gravity of BCC mix constituents according to Yang et al, (2016)

Water	Cement	FA	GGBS	SF	CC	LP	Coarse	Fine	SP
1	3.15	2.25	2.91	2.25	2.41	2.65	2.61	2.71	1.22

The second constraint is concerning the practicality of the mixes. As explained in the *Pre-bcc* regressor in section 5.6, the difference in the cement grade affects the strength of the resulting mix. Hence, either the 42.5 cement grade is used or the 52.5 one and not a combination of both. Also, the mix is only allowed a maximum of 3 binder types to be used, one cement type and a combination of 2 more of any of the five SCMs (FA, GGBS, SF, LP and CC). The third constraint is about the best practice when it comes to concrete mixes. The literature review from section 5.6 showed that preferably the ratio between the fine aggregates to the total weight of the aggregates should be kept between 0.4-0.52. Also, the total of both ratios of the coarse aggregates to the binder total and the fine aggregates to the binder total should be kept in the range 2.5-6.5 (Wang et al., 2018).

5.6.3. Optimization approach

The previous information proves that there are several challenges that are specific to the optimization process understudy. First, the optimized mix is selected out of what is called the search space and in order to define this search space there needs to be certain limits that govern the selection of each of the mixing proportions. The range in which the each of the constituents fall was obtained from the literature review of the regression models discussed in section 5.6 and is shown in Table 5.13. The first challenge then is that the step size by which the search space is formed is too small causing a 3.15×10^{21} wide space within the 10 dimensions ruling out the possibility of using a simple approach such as grid search. The second challenge is concerning the nature of the constraints, which require the use of the regression learners developed in section 5.6 for strength, slump, carbonation and resistivity. The use of those functions which are non-linear, non-convex, and not differentiable rules out any attempt at turning the constrained optimization into non-constrained optimization using differentiable techniques. The third and final challenge is concerning the analysis of results. Although the ECO_2 score is a single objective function, it is in fact a weighted linear formulation of multiple objective functions. This means that an analysis of the results requires considering multi-decision metrics.

Table 5.13: Recommended range for the ration of each BCC mix constituent relative to binder content (Wang et al., 2018)

	Binder	Water	CEM I	FA	GGBS	SF	LP	CC	Coarse	Fine	SP
	kg/m^3	Ratio of constituent to Binder									
Min	200	0.25	0.1	0	0	0	0	0	0.5	0.5	0
Max	600	1	1	0.5	0.9	0.15	0.2	0.5	5.5	5.5	0.022
step	25	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.005

In order to address these, the general approach was the use of Evolutionary methods as opposed to gradient-based methods, specifically Genetic Algorithms. It was also decided to first use the optimization algorithm subject to the same constraints in order to find the extrema (normalization constants), then use those as the normalization constants. At the same time, during ECO_2 optimization, the new mixes are checked for providing new maxima or minima for any of the 8 indicators, and the normalization constants are updated accordingly. This approach is shown in Figure 5.11 below.

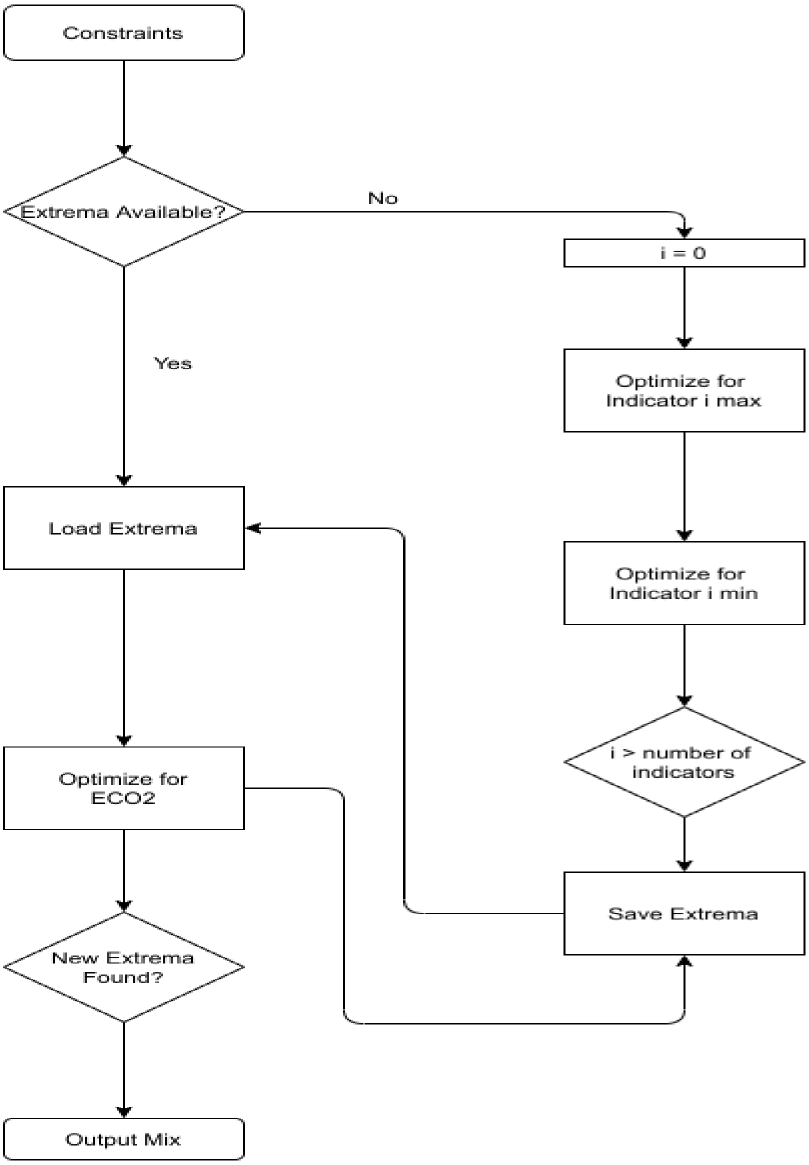


Figure 5.11: A flow chart showing the ECO_2 population generation algorithm

5.6.4. Optimization Implementation

5.6.4.1. Background

Several researchers tackled the same optimization problem attempting to reach the most sustainable blended cement concrete mix that achieves a combination of the functional compliance while minimizing the cost and environmental impact. Almost all models employed Evolutionary Algorithms (EA) which are a class of optimization algorithms inspired by the concepts of evolutionary theory (survival of the fittest and the processes of selection, mutation ...etc). An EA builds an initial population of individuals $\mathrm{P_o}$, and until reaching either convergence or a maximum number of iterations, the algorithm evaluates the population using some mapping $\mathrm{F}: \mathrm{P} \rightarrow \Re$, and applies a set of operators $\mathrm{H} = \{\mathrm{H}_1, \ldots, \mathrm{H}_r\}$, resulting in a new population for the next iteration $\mathrm{S}_{i+1} = \mathrm{H}_r\left(\ldots \mathrm{H}_2\left(\mathrm{H}_1(\mathrm{P}_i)\right)\right)$ (Deb, 2011).

Naseri et al. (2020) proposed a model that optimizes the mixing proportions of OPC based concrete on the basis of minimizing one economic indicator (cost) and one environmental impact indicator (GWP) while satisfying one functional indicator (28 days compressive strength). Wang (2019) on the other hand, optimized the proportions of FA and GGBS based ternary BCC on the basis of the same single economic and environmental indicators. The added value in the latter was the inclusion of a slump and carbonation as well as strength as functional indicators. However, in both models, the shortcomings are apparent. Firstly, the models were exclusive to only two types out of the five well-known SCMs. Secondly, the economic and environmental impact was only assessed using single indicators. Finally, the functional parameters prediction models assumed linear performance in Wang (2019) and only included strength in Naseri et al. (2020).

Genetic algorithm (GA) is a classic meta-heuristic algorithm based on genetics and natural selection that examines the feasible region to find better solutions through iterations that satisfy the objective function within the boundary constraints and is hence commonly deployed as optimization and search technique (Branke et al., 2008). In a GA, at each iteration g (referred to as a generation), the population of individuals (referred to as chromosomes) goes through a specific set of operators inspired by genetics with some variations within implementation. Each chromosome includes given genes and each gene implies a characteristic of data. In a GA, a population, which is a set that contains all chromosomes, is initially generated randomly and is updated with each iteration (Naseri et al., 2020). The $\mathrm{ECO_2}$ GA algorithm was implemented using the DEAP framework [https://github.com/deap/deap] and the operators were defined as follows.

5.6.4.2. Optimization operators

A typical GA would include a mechanism for the generation of the population that complies with a set of constraints and 3 main operators namely: selection, crossover and mutation. For the $\mathrm{ECO_2}$ optimization GA, the following operators were designed as shown in the flowchart in Figure 5.12:

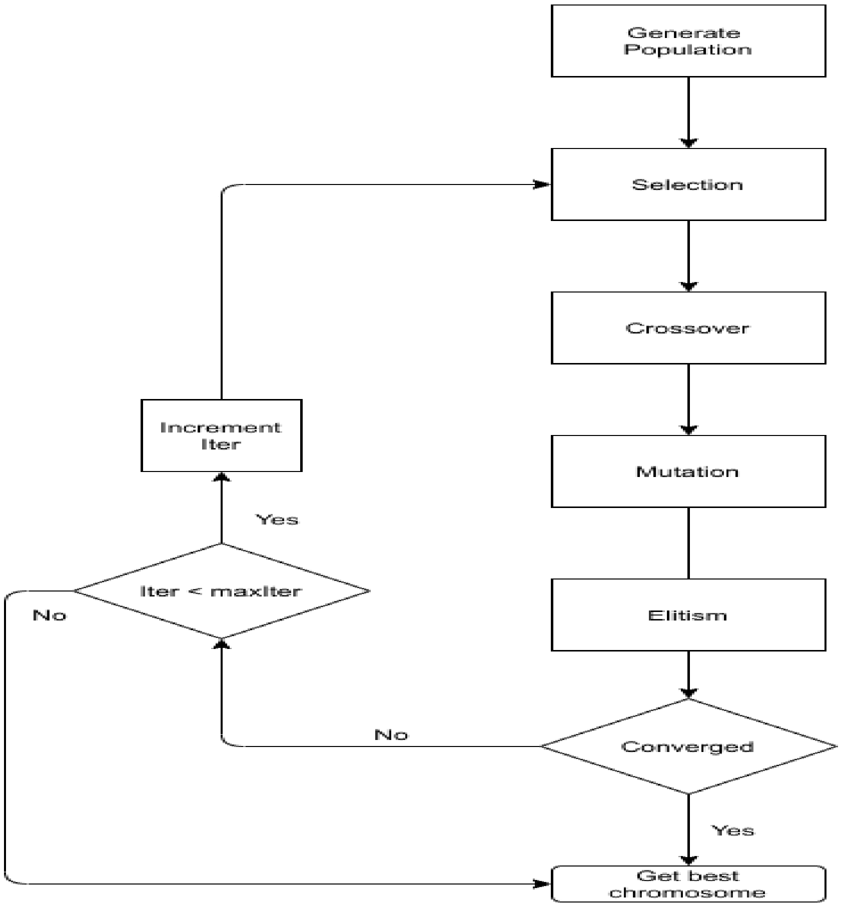


Figure 5.12: A flowchart showing the ECO_2 GA operators

- Generation: One advantage of EA is that the individual generation can be used to only consider mixes that comply with the constraints. In order to do this, ECO_2 generates an individual (chromosome) $p = (p_1 - p_{10})$ where the attributes p_i are as in Table 5.14:

Table 5.14: The element notation for the generated chromosomes of the ECO_2 GA

Element	Domain	Meaning
p_1	{0,1}	whether cement45 or cement52
p_2	{0,1,2,3,4}	the index of the first additive from the index set A= {FA, GGBS, SF, LP,CC}
p_3	{0,1,2,3}	the index of the second additive from the set $A - A[p_2]$
p_4	[0.25,1]	the water to binder ratio
p_5	[0.1,1]	Hint for cement to binder ratio
p_6	[0,1]	Hint for the factor of [min,max] to use for the first additive defined by p_2
p_7	[0,1]	Hint for the factor of [min,max] to use for the first additive defined by p_3
p_8	[0.4,0.52]	the ratio Fine / (Coarse + Fine)
p_9	[2.5,6.5]	the term (Coarse/Binder + Fine/Binder)
p_{10}	[0,0.07]	SP to binder ratio

- Evaluation: Since this research uses the same algorithm for both generating the extrema (normalization factors), and for the optimization, the evaluation function is slightly different between the two cases;
    - ECO_2 optimization: this is the ECO_2 score for the mix generated by the individual.
    - Search for Extrema: d is +1 for maxima and -1 for minima.
- Selection: The selection operator is used to enhance the overall population score by only selecting half of the population and cloning them. The method used here is tournament selection with a tournament size of 3. So, elements of 3 are randomly selected and the highest score of each is chosen. This strategy allows the algorithm to widen the search space rather than a greedy best individual selection strategy.
- Crossover: The crossover operator takes pairs of individuals $u, v \in P_g$within the population at generation g with a probability of c_x , and a randomly chosen string of attributes are swapped for the two individuals. The value for $c_x$used for ECO_2 was 0.7 for optimization and 0.6 for extrema generation.
- Mutation: The mutation operator randomly chooses individuals at a probability of c_m, and within that, the attributes are randomly changed at a rate c_r according to Gaussian distribution. The value for $c_x$used for ECO_2 was 0.1 for optimization and 0.03 for extrema generation. The value for c_r was constant at 0.05.
- Elitism: This operator combines the best of the parent population (from the previous generation), and the offspring (resulting from the operators above) to ensure that the performance is monotonically increasing. Note that elitism was not used for scenario 1 but scenario 2 would not converge otherwise.

5.6.4.3. Constraints handling

The constraints that are based on the regression output were implemented using the DEAP Delta-Penalty function, evaluating a point where the constraint was not met as 0, i.e. $\mathrm{J_i(G(p))} \notin [\mathrm{l_i}, \mathrm{u_i}] \Rightarrow \mathrm{F(p)} = 0$. Given the evaluation function $\mathrm{F(p)}$ defined above, this is equivalent to a hard barrier at those points within the search space.

5.6.4.4. Termination Criteria

Finally, The ECO_2 GA terminates when the evaluation of the best element of the population is not changing for 7 iterations.

5.6.5. Results and Discussions

5.6.4.1. Scenario 1

The first scenario was for plain concrete, where the durability functional parameters are of no impact on the ECO_2 score calculation. For each strength class (20, 30, 40, 50, 60, 70, 80, and 90 MPa), a sub-scenario was prepared. As defined in the constraints, all these mixes are fulfilling the minimum slump requirement (100mm). The optimum mixes for each sub-scenario are shown in Table 5.15 and the results showed the following trends in the data.

Table 5.15: The optimized mix designs from the ECO_2 GA model for the plain concrete scenario

Min Strength	Binder	Water	CEMI-42.5	CEMI-52.5	FA	GGBS	SF	LP	CC	Coarse Aggregates	Fine Aggregates	SP
MPa	Kg/m^3											
20	300	285	0	105	0	0	0	45	150	905	672	2.02
	265	255	0	80	65	120	0	0	0	1023	694	0.04
	280	280	0	85	55	0	0	0	140	980	655	0.04
30	325	210	115	0	80	130	0	0	0	1061	726	1.80
	330	205	0	115	0	215	0	0	0	1077	737	2.74
	300	215	0	90	90	0	0	0	120	1085	742	0.79
40	325	125	130	0	0	0	0	35	160	1108	880	5.21
	380	145	135	0	0	225	0	20	0	1124	781	4.62
	305	155	0	90	75	0	0	0	140	1161	775	1.87
50	335	110	0	100	150	85	0	0	0	1137	867	0.77
	340	115	100	0	85	0	0	0	155	1193	822	0.96
	335	115	0	100	150	0	0	0	85	1199	805	0.77
60	350	120	170	0	90	90	0	0	0	1037	963	7.85
	340	95	0	100	0	220	0	0	20	1255	867	1.76
	325	125	0	100	0	75	0	0	150	1188	821	1.69
70	340	90	135	0	0	170	0	35	0	1237	851	3.14
	340	100	150	0	0	50	0	0	140	1237	851	3.14
	325	95	115	0	80	0	0	0	130	1234	849	2.79
80	330	90	180	0	35	0	0	0	115	1164	956	6.34
	345	95	0	120	0	175	0	0	50	1215	886	1.91
	345	95	120	0	0	120	0	0	105	1215	886	1.91
90	360	90	250	0	35	75	0	0	0	1152	926	8.01
	360	90	250	0	35	0	0	0	75	1152	926	8.01
	360	90	235	0	20	0	0	0	105	1152	926	8.01

- A important insight from the data is that regardless of the % of SCM replacement and the type of SCM used to replace the OPC, the optimal sustainable BCC mixes depend highly on decreasing the total binder content. It is noticeable that the higher the strength, the higher the required binder content, but it is all in the range of 300-360 kg/m^3.
- Silica fume is not utilized in any of the BCC mixes regardless of the strength. It is established in the literature that the main contribution of SF to the mix is to enhance the strength, but it is apparent that the higher environmental and economic impact of SF as an SCM overcomes its functional merit.
- As shown in Figure 5.13, it is noticeable in all optimum mixes that SCMs can replace up to 70% of CEM without compromising the strength required to fulfill the scenario assumptions except in the 90 MPa case. Also, the most predominant SCM in use was found to be CC, then GGBS, then FA and finally LP. This follows through from the observation from the database that was used to develop the regression model in Section 3.6 that CC has a high potential given its reduced environmental and economic impact while enhancing the functionality of BCC. This insight affirms the potential of the lime-calcined-clay-cement LC_3 to be integrated more in the future as a sustainable BCC.

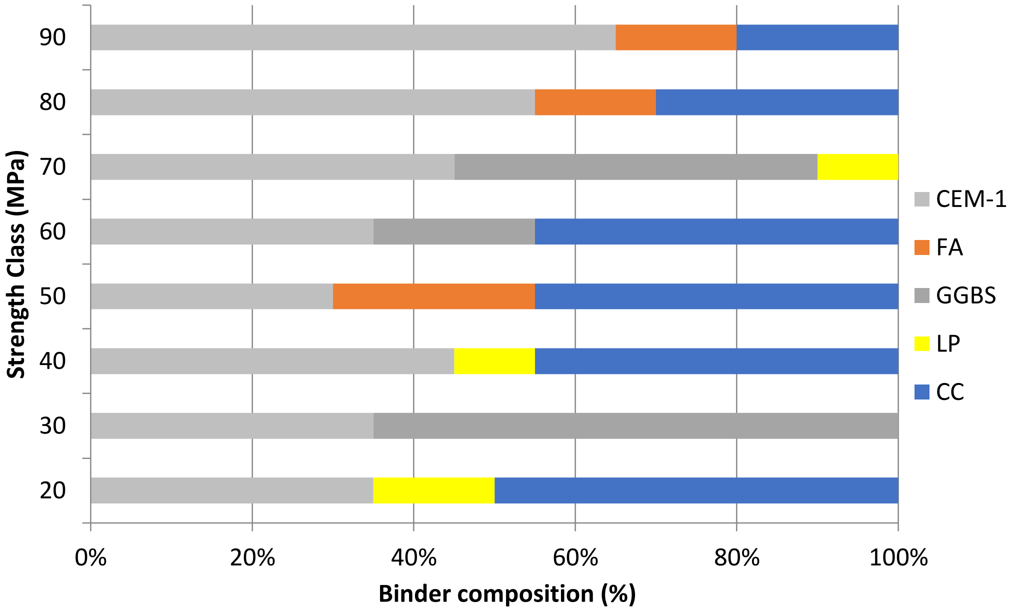


Figure 5.13: The optimum replacement ratios for the different SCMs for each strength class in scenario 1

- The higher the strength, the lower the water to binder ratio, which is consistent with the hypothesis assumed as assumed in the literature. This is however reflected by an equivalent increase in the dosage of the superplasticizer in the mix in order to achieve the minimum slump requirement assumed in the scenario (>100mm).
- There is no clear trend on a difference between the use of CEM I of grade 42.5 and CEM 1 of grade 52.5 although the latter is proven, through the regression model developed within section 3.6 to enhance slightly the strength due to its also slightly higher environmental impact.

5.6.4.2. Scenario 2

The second scenario on the other hand is assuming a 50-year old building service life for reinforced concrete with a 30mm concrete cover. Hence, it was decided that the optimal BCC mixes should satisfy the boundary conditions of resisting the deterioration of the concrete elements against carbonation and chloride penetration. The assumed atmospheric carbon dioxide concentration was 0.05% and the minimum required resistivity against chloride penetration is 1200 coulombs. Similar to scenario 1, for each strength class, a sub-scenario was prepared and a minimum requirement of a 100mm slump was set. The optimum mixes for each sub-scenario are shown in Table 5.16 and the results are shown as follows.

Table 5.16: The optimized mix designs from the ECO_2 GA model for the reinforced concrete scenario

Min Strength	Binder	Water	CEM I	FA	GGBS	LP	CC	Coarse Aggregates	Fine Aggregates	SP
MPa	Kg/m^3									
20	470	305	210	235	0	25	0	752	606	4.31
	470	380	195	80	195	0	0	576	623	0.60
30	410	140	205	185	0	20	0	1021	863	4.38
	490	300	170	125	0	0	195	783	592	2.59
40	510	240	280	0	25	0	205	915	622	5.03
	470	280	210	120	140	0	0	839	627	3.61
50	550	180	275	0	0	30	245	946	716	3.49
	520	165	260	0	260	0	0	1029	725	0.96
60	410	125	330	0	75	5	0	1141	810	8.30
	410	105	245	0	0	60	105	1102	885	0.61
70	505	150	250	175	0	0	80	996	719	10.42
	390	100	275	100	15	0	0	1155	836	4.74
80	460	145	415	0	0	20	25	1113	749	6.92
	575	150	315	175	85	0	0	861	838	3.03
90	430	135	410	0	0	0	20	954	959	6.30
	570	150	400	0	145	25	0	1036	714	3.88

- The binder content total is higher than that of scenario 1. As seen in Table 5.16, the range is between 470-570 kg/m^3. Although the higher binder content is associated with higher environmental and economic impact, meeting the durability requirements of the scenario defined minimizes N yielding an overall higher sustainability index score.
- As shown in Figure 5.14 below, the added durability requirements decreased the ability to replace the OPC with SCM from an average of 60-70% in scenario 1 to only 30-40%. Also, the prevailing SCM shifted from CC to FA and GGBS. The water to binder ratio also decreases with almost the same ratio as in scenario 1 with the increasing strength requirements.

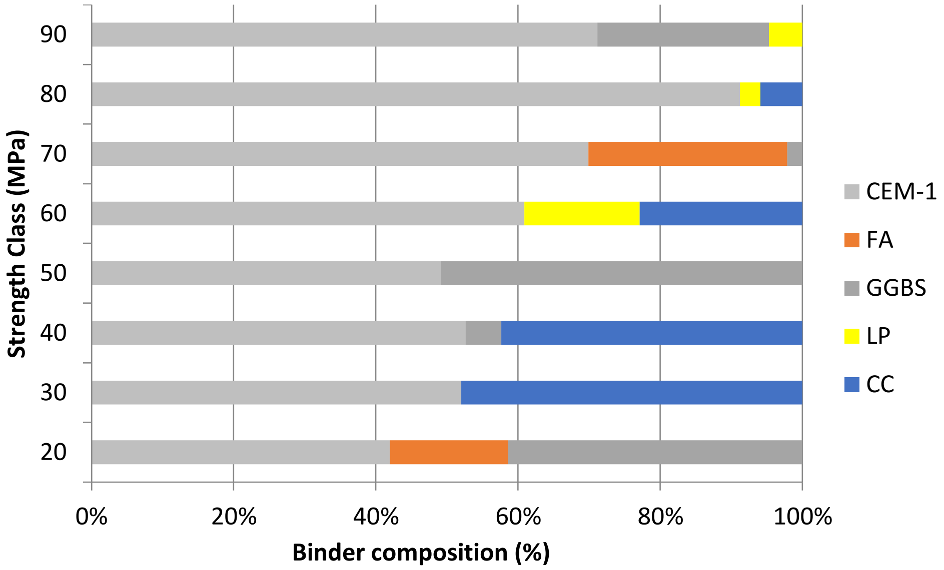


Figure 5.14: The optimum replacement ratios for the different SCMs for each strength class in scenario 2

5.6.6. *Comparison against other models*

In order to validate the significance of the novel optimization model, the results were compared against that presented by both models reviewed in the literature. Since both models from the literature assume a plain concrete scenario, the selected optimized concrete mixes were those from scenario 1 by ECO$_2$. Since cost, GWP and CED are the only three common indicators between the three models, they were used to selected assess the economic and environmental impact of each alternative. As seen in Table 5.17 below, for each strength class (sub-scenario), the mix design proposed by the ECO$_2$ optimization model proves to be cheaper and of less environmental impact than the ones proposed by Naseri et al., (2020) and Wang (2019) by at least 70 and 30% respectively. The results are considered to be valid because the same inventory data, assumptions and calculation process was used to calculate the values of the price, GWP and CED for the three models.

The reason behind the enhanced performance of the ECO$_2$ optimization model could be the fact that the *Pre-bcc* regression model yielded a more accurate prediction of the mixes within the boundary conditions allowing for the lowest possible binder content and highest possible SCM replacement ratio. Also, the fact that the ECO$_2$ optimization model, unlike the one by Naseri et al. (2020) or Wang et al. (2018) allows for including calcined clay as an SCM, which is proven to enhance the performance of the mixes while minimizing the environmental and economic impact. However, the limitation of this hypothesis is that, for all three models, the performance of the assumed mixes is actually similar to the predicted as well as the accuracy of the underlying inventory data used for the environmental and economic impact calculations.

Table 5.17 A comparison between the optimized ratio of the different constituents of the BCC using the ECO$_2$ model and Naseri et al., (2020) and Wang (2019) referred to as E, N and W respectively

MPa	20		30			40			50			60		70	
Source	E	N	E	N	W	E	N	W	E	N	W	E	W	E	W
B	280	250	300	330	380	305	360	455	335	417	515	325	466	325	527
W	280	184	215	188	167	155	170	167	115	160	167	125	151	95	149
CEM1	85	250	90	330	140	90	360	140	100	417	155	100	466	115	527
FA	55	0	90	0	200	75	0	200	150	0	200	0	0	80	0
GGBS	0	0	0	0	40	0	0	115	0	0	160	75	0	0	0
CC	140	0	120	0	0	140	0	0	85	0	0	150	0	130	0
Coarse	980	1125	1085	895	1024	1161	1125	983	1199	1125	939	1188	1125	1234	1055
Fine	655	799	742	945	683	775	742	655	805	701	640	821	701	849	719
SP	0.04	0.47	0.79	0.52	4.95	1.87	1.85	5.90	0.77	1.61	6.74	1.69	2.09	2.79	5.24
Price	33	46	37	52	49	40	57	52	41	61	56	42	65	44	75
GWP	109	242	116	312	148	122	341	151	123	392	167	134	436	136	493
CED	601	1185	656	1513	894	706	1670	925	713	1902	1010	735	2117	790	2431

5.7. Summary

In this chapter, another case study was carried out in validation of the ECO_2 framework in and an attempt to present novel empirical findings around sustainable blended cement concrete (BCC) mixes. The main objective of the case study was to optimize, using the ECO_2 index from the framework developed and explained in Chapter 3, the sustainability of BCC mixes utilizing one or two supplementary cementitious materials (SCMs) from the following (FA, GGBS, SF, LP and CC). The assumed scenarios were of plain and reinforced concrete and the constraints for the objective function were stated in line with other models found in the literature on the rules that govern the concrete mixing proportions. In order to calculate the objective function for the optimization, the ECO_2 sustainability index, the first step done in section 5.2 was to do an extensive literature search on the environmental and economic impact inventory data on each of the SCMs studied. This is the first contribution of this study.

In order to then predict the functional properties of the potential BCC mixes, the third and final pillar of the ECO_2 sustainability index calculation, a regression model was built in section 5.6 using a non-linear multi-layer artificial neural network. The *Pre-bcc* regression model required the formulation of an extensive database from more than 150 published articles yielding more than 1600 data points for tests that measure either slump, strength, chloride resistivity or carbonation of BCC mixes including one or a few of the aforementioned SCMs. The regression models, which is the first of its kind to cover all these functional properties for all these SCMs, were proven to be statistically accurate (R= 0.94-0.97) compared to others from the literature and this is sought to be the second contribution of this study.

After that in section 5.7 the ECO_2 optimization model was ran using an off-the shelf genetic algorithm (GA) to which the previous data from sections 5.2 and 5.6 were input. The optimized mixes using the ECO_2 GA model for each class were compared against the mix design proposed by papers from the literature and were found to be at least 70% cheaper and of 30% less environmental impact. The main reason in this enhancement, which is considered to be the third and most significant contribution of this case study, is that although the same objective function was used for all optimization models, the depth provided by the *Pre-bcc* model allowed a wider range of selection.

Chapter 6

Case Study #3: Assessing the sustainability potential of fly ash use in concrete after 2021 within the UK using the ECO_2 tool

6.1. Introduction

This chapter aims at presenting the results of the third case study conducted within the scope of this PhD project. The literature review in chapter 2 concluded that there is evidence to support the sustainability potential of using fly ash (FA) in concrete due to the fact that it is a low-cost industrial by-product. Moreover, the case study conducted using the ECO_2 tool in Chapter 5 established that including fly ash as a partial cement replacement in blended cement concrete enhances the sustainability compared to OPC concrete. Due to its abundance from coal powered factories within the UK market, locally sourced FA has been used widely in recent years as a main component of sustainable concrete products. However, recent reports highlight that starting 2021, FA will not be produced locally in the UK due to the governmental plan to shut down all coal powered power plants. A survey of the literature concerning the potential issue presented through concrete manufacturers and researchers to date shows two potential solutions: to import FA from abroad and to process locally landfilled FA. Although both alternatives are seen as adequate, there is a concern that the added costs and environmental impact to make them available in the UK market could overcome their positive impact as a sustainable addition to concrete. Hence, this case study is dedicated towards analysing the sustainability potential of these 2 proposed solutions to make FA available in the UK beyond 2021 using the ECO_2 tool. Primary data concerning the environmental and economic profile of the proposed FA alternatives were collected from governmental reports and concrete manufacturers' reports. Finally, the data were analysed under several scenarios and the results were discussed as follows.

The contents of this chapter were published in the 244th volume of the "Cleaner Production" journal on 20th January 2020 under the title "Comparative life cycle assessment between imported and recovered fly ash for blended cement concrete in the UK". The paper included the following authorship responsibilities, conceptualization (Wai Ming Cheung, Brabha Nagaratnam, and Rawaz

Kurda), preliminary analysis, data collection, data analysis, data interpretation, and writing the paper (Hisham Hafez), and revision (Wai Ming Cheung, Brabha Nagaratnam, and Rawaz Kurda).

6.2. Background

6.2.1. Sustainability potential of FA concrete

6.2.1.1. Functional properties

As established in chapter 5, partially replacing OPC with FA is believed to enhance the long term strength and durability properties of concrete. This is primarily why it is considered as the main mineral addition used in blended cement concrete (Assi et al., 2018). When designed for the same water to binder ratio, FA based concrete shows better strength as plain cement concrete (Hossain et al., 2017). Goleski et al. confirms that after 180 days of curing, concrete with up to 30% FA replacing OPC exhibits superior fracture toughness and strength (2018). Van den Heeded et al. (2017) reported that even high volume fly ash (HVFA) concretes mixes have comparable mechanical and durability performance to concrete without fly ash. Dhir et al. (2016), found that the chloride binding ability increased up to replacement levels of 50% by mass and then declined at 64% compared to OPC concrete mixes. It has been shown in laboratory studies that fly ash reacts pozzolanically with calcium hydroxide to produce calcium-silicate hydrates (C-S-H), which produces a more refined pore structure, reduces permeability, and increases the capacity to bind chlorides compared to ordinary Portland cement (OPC) concrete. On the other hand, the lack of calcium hydroxide in FA concrete mixes means a higher penetration of hydrocarbon ions and hence less resistance to carbonation when compared to that of OPC concrete. (Hossain et al., 2017).

6.2.1.2. Environmental impact

Besides increasing the durability and mechanical properties, the use of waste material instead of cement is intended primarily to decrease the latter's environmental impacts and avoid the burden from landfilling such waste (Muller et al., 2014). A well-recognized comprehensive method of analysing such environmental impact is Life cycle assessment (LCA) (Knoeri et al., 2013). Using LCA, it was argued that replacing 35% of the OPC in a concrete mix with FA could reduce the global warming potential (GWP) up to 30% (Tait and Cheung, 2016). The same conclusion was found when recycled aggregates were used along with 30% OPC replacement with FA (Turk et al., 2015). The use of higher volume of FA (60% and 65% respectively) yielded even more reduction in GWP equivalent to almost 50% (Marinković et al., 2017). According to environmental protection agency (EPA, 2008) the use of 4.2 million tons FA in concrete annually reduces GWP emissions equivalent to that from 2.5 million cars. This is given the assumption that the average car travels for about 10.000 km a year (Hemalatha and Ramaswamy, 2017). Although the environmental impact of producing FA is almost negligible, it could be higher dependant on the proximity of the concrete production facility from the FA source. Based on the findings by Panesar et al. (2020), the environmental impact resulting from the transportation means and distances of FA could overcome its savings against cement especially in terms of ‘‘ecotoxicity”, ‘‘human toxicity” and ‘‘resources and fossil fuels”. Another factor that could prove detrimental to the sustainability potential of FA is its impact allocation, which is basically portioning the environmental burden of the original production process (Marinkovic et al., 2017). In line with the EU directive 2008, FA is considered a by-product not a waste and thus ought to be allocated a percentage of the environmental burden of its original production process, which is coal combustion (Anastasiou et al., 2015). The first scenario is “Mass allocation” where the percentage allocation is based on the relative mass between the waste material as a by-product and the mass of the total (the effective mass of electricity + the mass of FA). The second scenario is “Economic allocation” in which the percentage allocated is based on the relative market value between the final product, which is FA and electricity (Chen et al., 2010). LCA studies on Green concrete tend to use economic allocation for FA since it is usually a lower number, which allows positive results relative to OPC, but the fluctuation of market prices brings uncertainties to the calculations (Marinkovic et al., 2017).

6.2.1.3. Economic impact

As depicted in the literature review in chapter 2 and shown below in Table 6.1, the average price of FA is less than half that of OPC. This means a potential of decreasing the price of a unit volume of the concrete where FA replaces up to 30% of OPC up to 20%.

Table 6.1: Cost of FA, OPC, transportation and coal as per the literature review from chapter 2

			Cement	**FA**
1st Author's Name	**Year**	**Country**	**£/tonne**	**£/tonne**
Chen	2019	France	125	35
Chen	2010	France		20
Habert	2011	Switzerland		25
Navarro	2018	Spain	88	38
Panesar	2019	Canada	180	135
Park	2012	South Korea	78	33
Rahla	2019	Portugal	65	28
Seto	2017	Canada		107
Wang	2017	China	40	10
Yuan	2017	China	100	
Zhang	2014	China	58	9
Joseph	2017	India	43	15
Mindess	1996	Canada	77	
Yang	2017	China		12
McLellan	2011	Australia		77
mean	**8.72E+01**	**3.62E+01**		
st dev	**3.71E+01**	**3.77E+01**		

However, similar to the previous concerns raised in the potential environmental impact improvement of using FA instead of OPC, the transportation costs should be included.

6.2.2. FA based blended cement concrete market

6.2.2.1. Global use of FA

The main areas of development of FA are: construction, mining and terrain management which makes it a very versatile material in the construction sector. Hence, FA has been widely used in many research purposes all over the world. Since thermal and electrical energy in Poland in more than 90% is produced in coal combustion processes, approximately 20 million tons of siliceous FA is produced each year (Kurdowski, 2014). China alone produced 700 million tonnes in 2014, making FA the fifth largest raw material available on Earth (Wang et al., 2017). In the USA, more than 24 out of the total produced 40 million tonnes of FA were used as a partial replacement to OPC in concrete (Moffat et al., 2017)

6.2.2.2. Use of FA in the UK

In the UK, the use of FA is established in many sectors of the construction market. According to a report by the UK Quality Ash Association (UKQAA), FA is added directly to clinker in cement factories, added partially to OPC in precast concrete and concrete blocks as well as being used in soil stabilization (UKQAA, 2015). In 2014, out of 4 million tonnes of FA produced, more than 2 million tonnes were utilized in the concrete industry in the aforementioned applications (UKQAA, 2014). Several cement manufacturers such as Hanson Heidelberg Cement Group produce ready blended cement packages with 35% FA replacement to OPC (Tait and Cheung, 2016). Contractors have been encouraged to utilize FA in construction due to the presence of different standards as EN 450 and BS 8500. Even though the demand for FA appears to be increasing, the future concerning the availability of local supply is not promising.

6.3. Description of the case study

6.3.1. Problem statement

According to a governmental report published in 2017, the UK government is opting to close down all coal operated power plants after 2021 (BEIS, 2017). Starting 2013, the production of coal has already been decreasing in the UK and will continue to decline till it nullifies by 2021 (BEIS, 2013). Hence, the BEIS report proposes two solutions to make FA available beyond the seizure of coal production namely, importing FA from abroad and restoring landfilled FA.

6.3.2. Proposed alternatives

6.3.2.1. Recycling landfilled FA

The first alternative is to recover landfilled FA from the UK. An extensive study from Dundee university established that, due to variations in the coal quality, only 40-50% of the current FA residue in the UK are currently used and the rest is simply landfilled (McCarthy et al., 2013). A report by the department for Business, Energy and Industrial Strategy (BEIS, 2017) argue that given suitable recovery technologies are utilized, the current reserve of almost 50 million tonnes of stockpiled FA could be enough to meet decades of demand for use in concrete in the UK. Several technologies were found in the literature attempting the recovery of FA using lab based processes such as the “mechanical processing” technique developed in the centre for Applied Energy Research at the University of Kentucky (Robl et al., 2006). The process involves characterization of the landfilled FA followed by hydraulic classification (Robl et al., 2006). Another technique is the “Triboelectrostatic beneficiation” in which FA particles are pumped into a copper tube that causes an active charge that separates the FA particles and recovers the fine particles suitable for use (Bultras et al., 2015). In addition, the “Dry-processing” technique developed in the University of Dundee, which was reported to successfully recover 90% of random samples of FA, was found to include some energy consumption data (McCarthy et al., 2018). Although it is intuitive to regard the recycling of landfilled waste as an improvement, further investigation of the associated environmental impacts of the recovery techniques is needed. The energy needed and the resulting emissions from the recovery process of the FA could end up causing negative environmental impacts that surpass that of OPC as well as increasing its costs dramatically. This would render the idea of replacing OPC with FA useless in terms of sustainability.

6.3.2.2. Importing FA to the UK

Although for many years there has been a discussion on diversification of energy production, perspectives and strategies of the governments in many countries around the world for the coming years, and even decades, it is predicted that coal will remain a major source of energy. On the basis of Hemalatha and Ramaswamy (2017), global coal usage is expected to increase 3.4% over the next 2 decades despite the retirement of many coal plants in countries such as the UK. Up to date almost 750 million tonnes of FA is generated each year in the World (Blissett and Rowson, 2012) and in the future one should expect to increase this quantity to 2100 million tonnes in 2031 (Hemalatha and Ramaswamy, 2017).

Looking into the potential for importing FA from other countries where FA would continue to be available, two private companies: Power Minerals Co. (Paoli, 2016) and Ecocem Co. (Lambe, 2018) have already started importing from Europe (Germany, Italy, Spain, and Portugal) and China respectively. However, this raises concerns on the environmental impact associated with long transportation distances that might end up cancelling the benefits of the imported FA (IFA) replacing OPC. Since FA carries negligible emissions as a product, most of the weight of importing FA could be attributed to its transportation process (O’Brien et al., 2009). An LCA study is needed then to calculate the critical transportation distance of FA beyond which substituting OPC with FA would result in higher environmental impact (O’Brien et al., 2009). A similar study concluded that transportation could attribute up to 30% of the environmental impact of the concrete produced depending on the distances travelled by the different concrete constituents (Lopez Gayyare et al., 2015). Nevertheless, increasing transportation distances beyond 20% reduces the environmental benefits of replacing fresh aggregates with recycled ones (Uzzal Husain et al., 2016). A similar research by Gursel et al. (2016) concluded that importing cement from further away China rather than Malaysia, the GWP of concrete in Singapore increases by 11%.

6.3.3. Summary

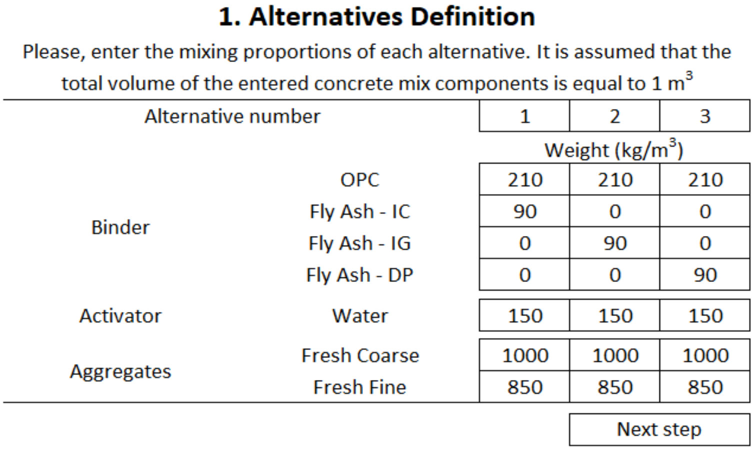
It is now clear that starting 2022, concrete producers and users in the UK will be facing a challenge of sourcing FA. The proposed alternatives from the literature, which constitute the scope of this study and chapter, are to either import FA or recover landfilled FA in the UK. In order to research a decision on the sustainability of both of these alternatives, including sub-scenarios such as the country of origin of the FA being Germany or China, a LCA will be prepared. By using the ECO_2 framework, the environmental and economic impact of each of the proposed alternatives will be assessed and quantified. The case study serves as a validation for the ECO_2 framework. This is the first study of its kind to evaluate the environmental impact of a FA recovery process and hence the outcome could be a valuable contribution to the concrete industry.

6.4. Applying the ECO_2 tool

As discussed in Chapter 3, to implement the ECO_2 there are five stages to be followed. First, the alternatives are defined, and then the scenarios. After that, the functional unit for each alternative is calculated, the inventory data input and finally calculating the impact and the ECO_2 index. In the next subsections, these steps will be shown and data from the case study will be utilized to validate the tool development and conclude the optimum solution for sourcing FA to the UK starting 2022 in terms of economic and environmental sustainability.

6.4.1. Define alternatives

This study is comparing the sustainability score of three alternatives to sourcing FA in the UK. The first two alternatives; IC and IG, present the opportunity of importing FA from China and Germany, respectively. The reason behind selecting these two countries from all the ones from which companies were already found importing FA is that they represent the shortest and longest transportation route to the UK. Also, as exhibited in the literature, both countries do not show signs of stopping the production of electricity from coal in the near future. The third alternative represents the option of recovering the currently landfilled FA through the Dry-processing method. The third alternative is denoted as DP. The predecessor for including any alternative in this scope is the fact that it would perform in an identical manner to locally sourced FA in the UK. This means that the three alternatives are assumed to have the same chemical and physical composition to each other and to the FA being traded commercially currently in the UK. Hence, the three alternatives defined IC, IG and DP are, as seen in Figure 6.1, concrete alternatives that include a 30% replacement of OPC with imported FA from China, Germany and Dry-processing recycled FA, respectively.



1. Alternatives Definition

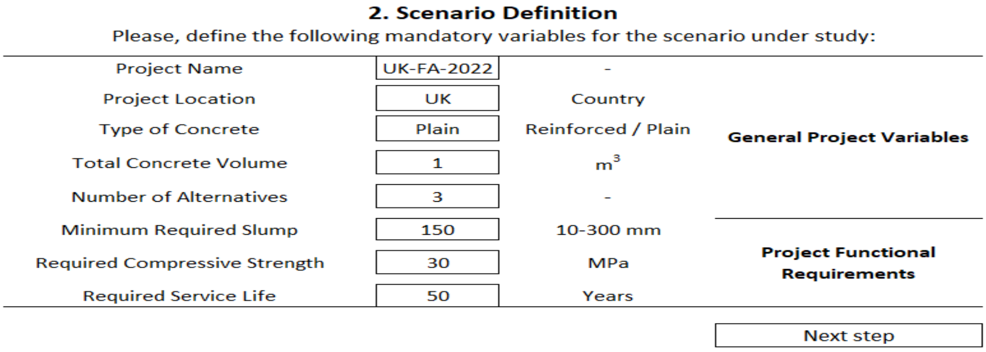
Please, enter the mixing proportions of each alternative. It is assumed that the total volume of the entered concrete mix components is equal to 1 m^3

Alternative number		1	2	3
		Weight (kg/m^3)		
Binder	OPC	210	210	210
	Fly Ash - IC	90	0	0
	Fly Ash - IG	0	90	0
	Fly Ash - DP	0	0	90
Activator	Water	150	150	150
Aggregates	Fresh Coarse	1000	1000	1000
	Fresh Fine	850	850	850

Figure 6.1: A screenshot of the 2nd step of the ECO_2 tool: Defining all alternatives

6.4.2. *Define scenario*

The ECO_2 framework allows for several scenarios to allow users to change the scale of the comparison, the type of concrete and the proposed location for the project. However, in this study, there is no need to be defined except one scenario, which could be seen in Figure 6.2. The reason is that the location is known to be the United Kingdom and since all alternatives are believed to exhibit the same functional performance.



2. Scenario Definition

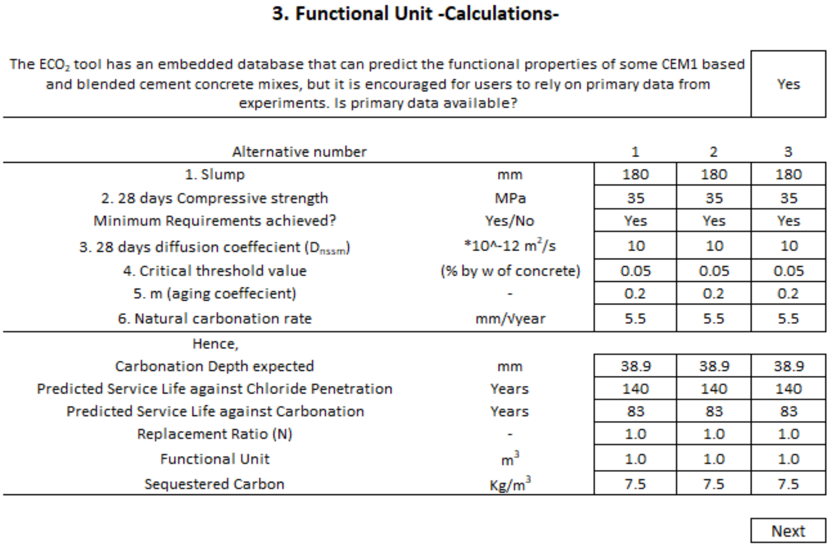
Please, define the following mandatory variables for the scenario under study:

Project Name	UK-FA-2022	-	**General Project Variables**
Project Location	UK	Country	
Type of Concrete	Plain	Reinforced / Plain	
Total Concrete Volume	1	m^3	
Number of Alternatives	3	-	
Minimum Required Slump	150	10-300 mm	**Project Functional Requirements**
Required Compressive Strength	30	MPa	
Required Service Life	50	Years	

Figure 6.2: A screenshot of the 2^{nd} step of the ECO_2 tool: Scenario Definition

6.4.3. *Calculate functional unit*

As demonstrated earlier, the underlying assumption in this study is that the 3 alternatives would behave in an identical manner to the commercially traded FA in the UK market. This assumption is valid given the first two are imported to replace the local FA so the same specifications would apply and the third is recycled from the same source as established earlier in the literature. This means that the functional performance of the three alternatives would be equal and hence the following data in Figure 6.3 were input for the FU calculation step in the ECO_2 tool.



3. Functional Unit -Calculations-

The ECO$_2$ tool has an embedded database that can predict the functional properties of some CEM1 based and blended cement concrete mixes, but it is encouraged for users to rely on primary data from experiments. Is primary data available?	Yes

Alternative number		1	2	3
1. Slump	mm	180	180	180
2. 28 days Compressive strength	MPa	35	35	35
Minimum Requirements achieved?	Yes/No	Yes	Yes	Yes
3. 28 days diffusion coeffecient (D_{nssm})	$*10^{-12}$ m^2/s	10	10	10
4. Critical threshold value	(% by w of concrete)	0.05	0.05	0.05
5. m (aging coeffecient)	-	0.2	0.2	0.2
6. Natural carbonation rate	mm/√year	5.5	5.5	5.5
Hence,				
Carbonation Depth expected	mm	38.9	38.9	38.9
Predicted Service Life against Chloride Penetration	Years	140	140	140
Predicted Service Life against Carbonation	Years	83	83	83
Replacement Ratio (N)	-	1.0	1.0	1.0
Functional Unit	m^3	1.0	1.0	1.0
Sequestered Carbon	Kg/m^3	7.5	7.5	7.5

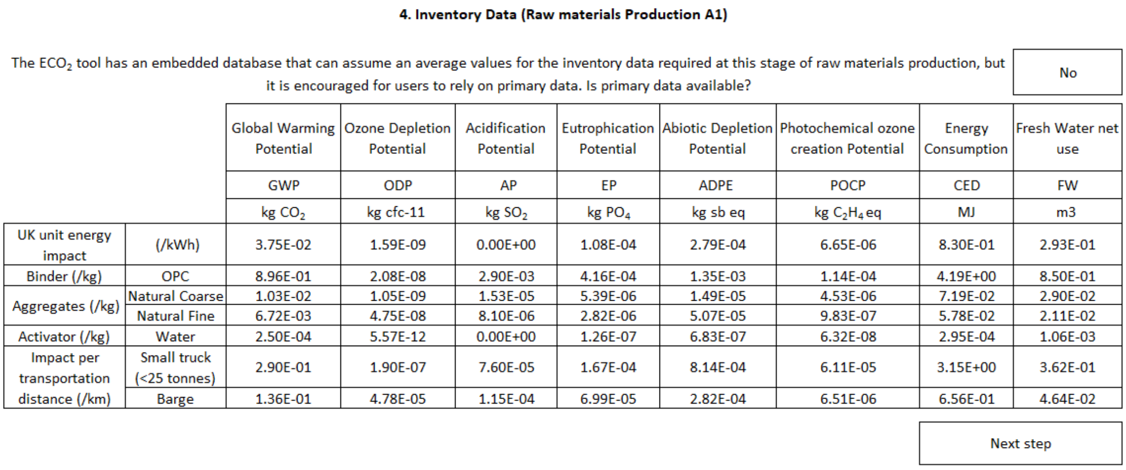
Figure 6.3: A screenshot of the identical FU calculations for the three alternatives understudy

6.4.4. Environmental inventory data

The fourth step in the ECO$_2$ tool is to decide on the inventory data values. The inventory data is divided into two groups; the environmental impact calculations group and another one for the economic impact calculations. Concerning the environmental impact inventory data, the data is divided into the following processes: raw materials production, raw materials transportation then the concrete construction and demolition.

6.4.4.1. Raw materials production

The inventory data concerning the raw materials production is given in two groups: the first is the data concerning the production of all the concrete mix components except for the fly ash. The values for these variables, which could be seen in Figure 6.4, are extracted from the secondary inventory database from the ECO$_2$ tool which, as explained in Chapter 3, is a combination of peer-reviewed articles and the Ecoinvent database.



4. Inventory Data (Raw materials Production A1)

The ECO$_2$ tool has an embedded database that can assume an average values for the inventory data required at this stage of raw materials production, but it is encouraged for users to rely on primary data. Is primary data available?	No

		Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication Potential	Abiotic Depletion Potential	Photochemical ozone creation Potential	Energy Consumption	Fresh Water net use
		GWP	ODP	AP	EP	ADPE	POCP	CED	FW
		kg CO_2	kg cfc-11	kg SO_2	kg PO_4	kg sb eq	kg C_2H_4 eq	MJ	m3
UK unit energy impact	(/kWh)	3.75E-02	1.59E-09	0.00E+00	1.08E-04	2.79E-04	6.65E-06	8.30E-01	2.93E-01
Binder (/kg)	OPC	8.96E-01	2.08E-08	2.90E-03	4.16E-04	1.35E-03	1.14E-04	4.19E+00	8.50E-01
Aggregates (/kg)	Natural Coarse	1.03E-02	1.05E-09	1.53E-05	5.39E-06	1.49E-05	4.53E-06	7.19E-02	2.90E-02
	Natural Fine	6.72E-03	4.75E-08	8.10E-06	2.82E-06	5.07E-05	9.83E-07	5.78E-02	2.11E-02
Activator (/kg)	Water	2.50E-04	5.57E-12	0.00E+00	1.26E-07	6.83E-07	6.32E-08	2.95E-04	1.06E-03
Impact per transportation distance (/km)	Small truck (<25 tonnes)	2.90E-01	1.90E-07	7.60E-05	1.67E-04	8.14E-04	6.11E-05	3.15E+00	3.62E-01
	Barge	1.36E-01	4.78E-05	1.15E-04	6.99E-05	2.82E-04	6.51E-06	6.56E-01	4.64E-02

Figure 6.4: A screenshot of the values for the environmental inventory data from the ECO$_2$ database

The second group of inventory data is that concerning the production of FA. The imported FA, whether from China or Germany, are simply produced as a by-product of the coal powered electricity power plants. Hence, the only environmental impact attributed to the process is that allocated from its original process. As established in Chapter 3, based to the EU directive 2008, FA is considered a by-product not a waste and thus ought to be allocated a percentage of the environmental burden of its original production process i.e., coal combustion (Anastasiou et al., 2015). In order to calculate the allocation scenario for FA; the difference in prices of FA relative to electricity in both countries were surveyed. In China, the cost of electricity and FA was found to be 0.11 ₤/kWh (CEIC, 2018) and 10 ₤/tonne (Alibaba, 2019; Wang et al., 2016) respectively, while the electricity price in Germany was 0.29 ₤/kWh (Statista, 2018). Due to the absence of any commercially available data around the price of FA in Germany, it was assumed to be the average from the ECO$_2$ database in Table 6.1, which is 36 ₤/tonne (Alberici et al., 2017). Assuming both countries use the same coal combustion techniques, 2689 kWh of electricity and 80 kg of FA can be produced from burning one tonne of coal (Seto et al., 2017). Hence the economic allocation for the IFA from China and Germany is calculated to be 0.25% and 0.50%, respectively. The mass allocation was calculated as 9.3% for both. A summary of the allocation percentages for all alternatives could be found in Table 6.2. It should be noted that the economic allocation percentages calculated are fairly lower than the ones in the literature (4% in Seto et al., 2017 and 1% in Chen et al., 2010). This could be attributed to discrepancies in the primary data used.

Table 6.2 A summary of the allocation scenarios for all materials included in the study

Symbol	Local Electricity Price (₤/kWh)	Local FA Price (₤/tonne)	FA generated/ Coal (Kg/t)	Electricity Generated/ Coal (kWh/t)	Mass Allocation (%)	Economic Allocation (%)
FA-DP			No Allocation			
FA-IC	0.11	9	80	2689	9.3	0.25
FA-IG	0.29	36	80	2689	9.3	0.50

The recycled FA through the Dry-processing method is not allocated any impact from the original process, but rather awarded the avoidance of the landfill. However, the process of recycling is the significant source of its energy consumption and thus its environmental impact. The process, as described by McCarthy et al (2018) entails drying, sieving and finally mechanical grinding as shown in Figure 6.5 below. According to McCarthy et al. (2018), the process successfully recycles 90% of the landfilled FA into a FA conforming to the BS EN 450-1 which is the same standard to which the local and imported FA would comply. According to Baker et al. (2015), the landfilled FA has an average water content of 15-20% and the energy required to remove it by oven drying at 105°C is around 200 kWh/tonne. Sieving is assumed to be done using an industrial 250W vibrating machine, which can sieve 50 kilos each round (10 minutes per round according to the BS EN 196-1:2005 standard). Hence, the energy required for the sieving process is around 1 kWh/tonne, so it is negligible. McCarthy et al. (2018) states that the mechanical grinding is carried out using a “Fritsch Pulverisette” machine in 500 g batches with 20 minutes of operation each. The machine operates at 110V and 0.5A as per its technical catalogue so the energy demand for the grinding process is estimated at around 330 kWh/tonne. Summing up the aforementioned as in equation 6.1 below yields a total of 590 kWh/tonne as the energy demand for recycling FA using the Dry-processing method.

$$\text{Energy demand for FA-DP} = \frac{200 + \frac{110\,volts * 0.5\,amp * 60\frac{minutes}{hour}}{0.5\,tonnes * 20 minutes}}{90\%\ effeciency} = 589\ \text{kWh/tonne} \quad (6.1)$$

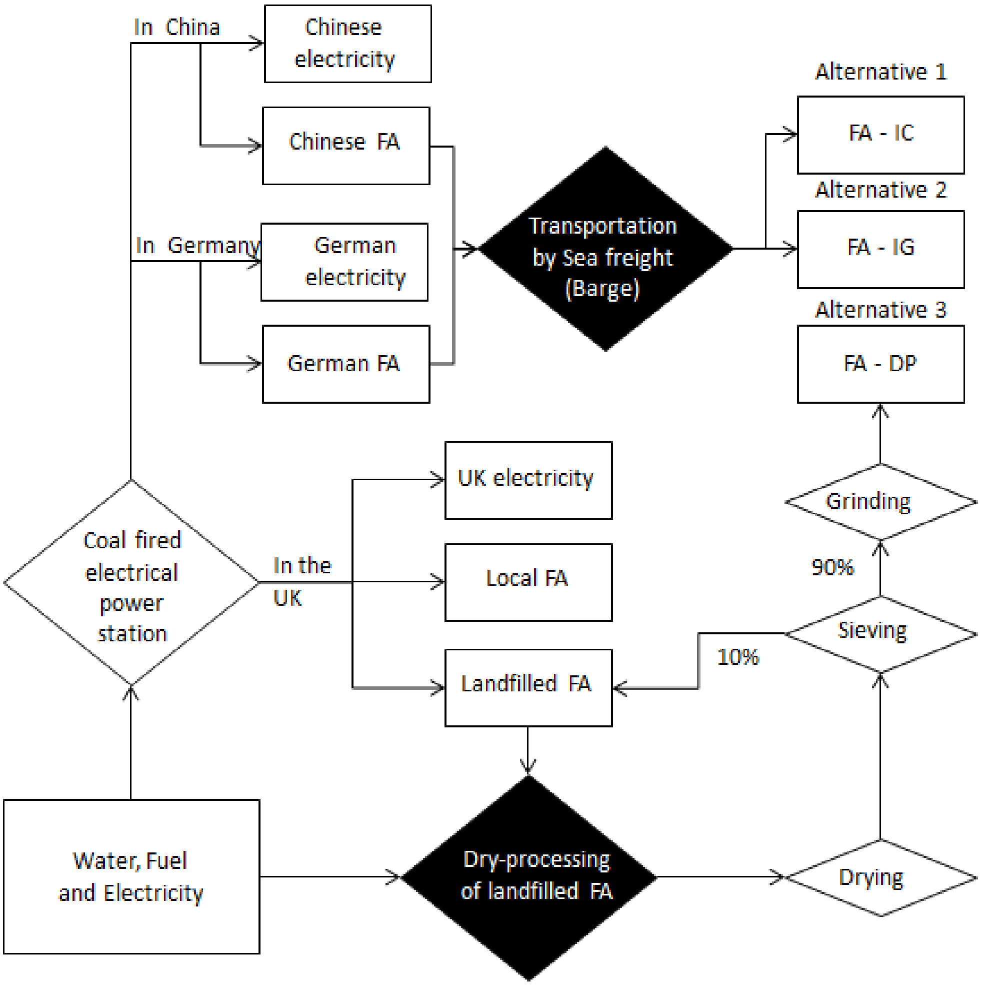


Figure 6.5: A flowchart showing the production and transportation process for the studies alternatives

6.4.4.2. Production of the FA alternatives

Based on the assumptions stated in section 6.4.4.1, the environmental inventory data for the 3 FA alternatives under study could be calculated as follows. After calculating the mass and economic impact allocation values for the imported FA, the economic allocation percentage is selected. The reason is that although economic allocation is dependent on the time-dependant market prices of the raw materials, it is the most preferred in the literature (Seto et al., 2017). According to Marinkovic et al. (2017), in case the difference between the price of main and secondary process generating the SCM product is more than 25%, economic allocation should be chosen over mass allocation. Hence, the environmental impact for the production of FA-IC and FA-IG are calculated by multiplying the economic impact allocated value for each by the environmental impact of electricity production from coal in China and Germany respectively. On the other hand, the environmental impact for the recovered FA alternative is calculated by multiplying the total energy used by the environmental impact of the average energy unit in the UK. These calculations are summarized in Table 6.3 below.

Table 6.3: Inventory data for the production processes of the three FA alternatives understudy

		GWP	ODP	AP	EP	ADPE	POCP	CED	FW
		kg eq CO_2	kg cfc-11	kg SO_2	kg PO_4	kg sb eq	kg C_2H_4 eq	MJ	m^3
Chinese unit energy from coal	/kWh	8.76E-02	5.00E-10	1.08E-03	7.22E-05	5.26E-04	3.34E-05	8.55E-01	1.06E-01
FA-IC production	allocation %	0.25%							
FA-IC production	/tonne	2.19E-01	1.25E-09	2.70E-03	1.80E-04	1.32E-03	8.34E-05	2.14E+00	2.66E-01
Germany unit energy from coal	/kWh	3.19E-01	7.70E-10	1.83E-03	2.96E-04	2.60E-03	7.09E-05	9.10E-04	3.75E+00
FA-IG production	allocation %	0.50%							
FA-IG production	/tonne	1.59E+00	3.85E-09	9.13E-03	1.48E-03	1.30E-02	3.54E-04	4.55E-03	1.88E+01
UK unit energy impact	/kWh	3.75E-02	1.59E-09	0.00E+00	1.08E-04	2.79E-04	6.65E-06	8.30E-01	2.93E-01
Recovered FA production	kWh	590							
Recovered FA production	/tonne	2.21E+01	9.40E-07	0.00E+00	6.39E-02	1.65E-01	3.92E-03	4.90E+02	1.73E+02

6.4.4.3. Raw materials transportation

Since the location of the case study is assumed to be the UK, the selected transportation means for the imported FA was selected as sea freight by a barge. The selected ports from UK, China and Germany were Newcastle, Hong Kong and Bremen. The freight distances were calculated using an online tool http://ports.com/sea-route/. The calculated freight distances are assumed to be only for a single trip considering that other products are transported back on the same carrier. The average transportation distances for all remaining concrete constituents between the source and the concrete batch plant were extracted from the ECO_2 tool database as seen in Table 6.4. The imported FA as well as the recycled FA are assumed to be transported from the ports/landfill a distance equivalent to that of the average values of FA transportation from the ECO_2 tool database. All the transportation distances by a small truck with the UK are considered as a 1.7 multiplier of the actual geographic distances according to the LCA methodology of the ECO_2 framework.

Table 6.4: The inventory values for the transportation distances of the concrete constituents

Materials	Transportation Means	Aggregates	Water	OPC	FA-DP	FA-IC	FA-IC
Transportation Distance (km)	Small truck (<25 tonnes)	82	0	52	67	67	67
	Sea freight (barge)	-	-	-	-	9000	1400

6.4.4.4. Summary of raw materials environmental impact data

As agreed in Chapter 3, the environmental impact of each concrete constituent is the addition of the production impact, the transportation impact and that of the original allocation scenario in case of FA, GGBS or SF as seen in equation 6.2 below. The values for the summarized impact of each concrete constituent per unit mass is shown in Table 6.5.

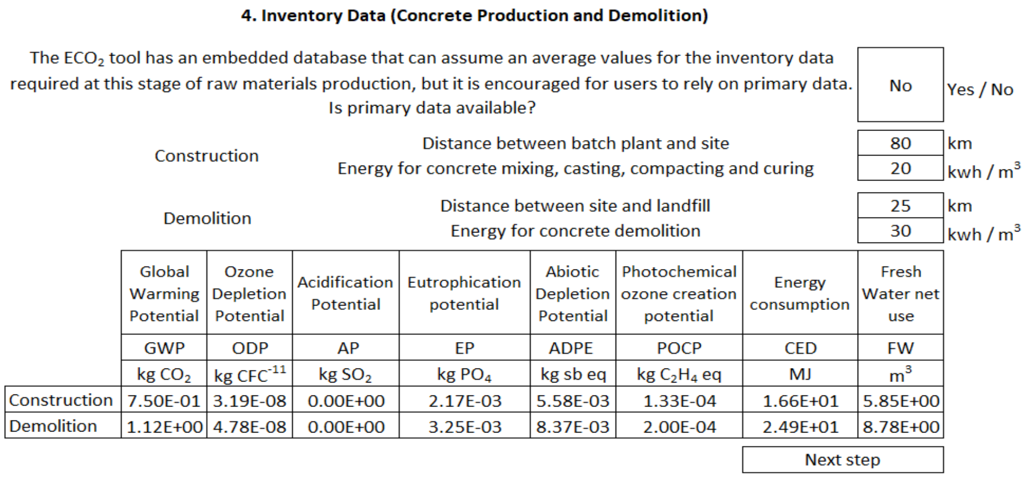
$$\frac{GWP_{j\,upstream}}{kg} = \frac{GWP_{j}production}{kg} + \frac{GWP\ transportation}{kg.km} * 1.7 * D_j\ (km) +\ GWP_j allocated(if\ any) \qquad (6.2)$$

Table 6.5: Summary of the total environmental inventory data of the concrete constituents per unit mass

		Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication potential	Abiotic Depletion Potential	Photochemical ozone creation potential	Energy consumption-on	Fresh Water net use
		GWP	ODP	AP	EP	ADPE	POCP	CED	FW
		kg CO_2	kg CFC^{-11}	kg SO_2	kg PO_4	kg sb eq	kg C_2H_4 eq	MJ	m^3
Binder (/kg)	OPC	9.19E-01	3.72E-08	2.91E-03	4.29E-04	1.42E-03	1.19E-04	4.44E+00	8.78E-01
	FA-IC	1.86E+00	6.45E-04	1.56E-03	9.60E-04	3.90E-03	9.41E-05	9.17E+00	6.64E-01
	FA-IG	3.16E-01	1.00E-04	2.58E-04	1.65E-04	6.88E-04	2.02E-05	1.69E+00	1.53E-01
	FA-DP	5.12E-02	2.01E-08	7.64E-06	8.05E-05	2.46E-04	1.01E-05	8.06E-01	2.09E-01
Aggregates (/kg)	Natural Coarse	4.60E-02	2.45E-08	2.46E-05	2.59E-05	1.15E-04	1.20E-05	4.59E-01	7.35E-02
	Natural Fine	4.23E-02	7.09E-08	1.75E-05	2.33E-05	1.51E-04	8.49E-06	4.45E-01	6.56E-02
Activator (/kg)	Water	2.50E-04	5.57E-12	0.00E+00	1.26E-07	6.83E-07	6.32E-08	2.95E-04	1.06E-03

6.4.4.5. Concrete construction and demolition

There is nothing specific to the current case study concerning these processes, so the values were taken as the average from the ECO_2 tool as seen in Figure 6.6 below.



4. Inventory Data (Concrete Production and Demolition)

The ECO_2 tool has an embedded database that can assume an average values for the inventory data required at this stage of raw materials production, but it is encouraged for users to rely on primary data. Is primary data available? No Yes / No

Construction
Distance between batch plant and site 80 km
Energy for concrete mixing, casting, compacting and curing 20 kwh / m^3

Demolition
Distance between site and landfill 25 km
Energy for concrete demolition 30 kwh / m^3

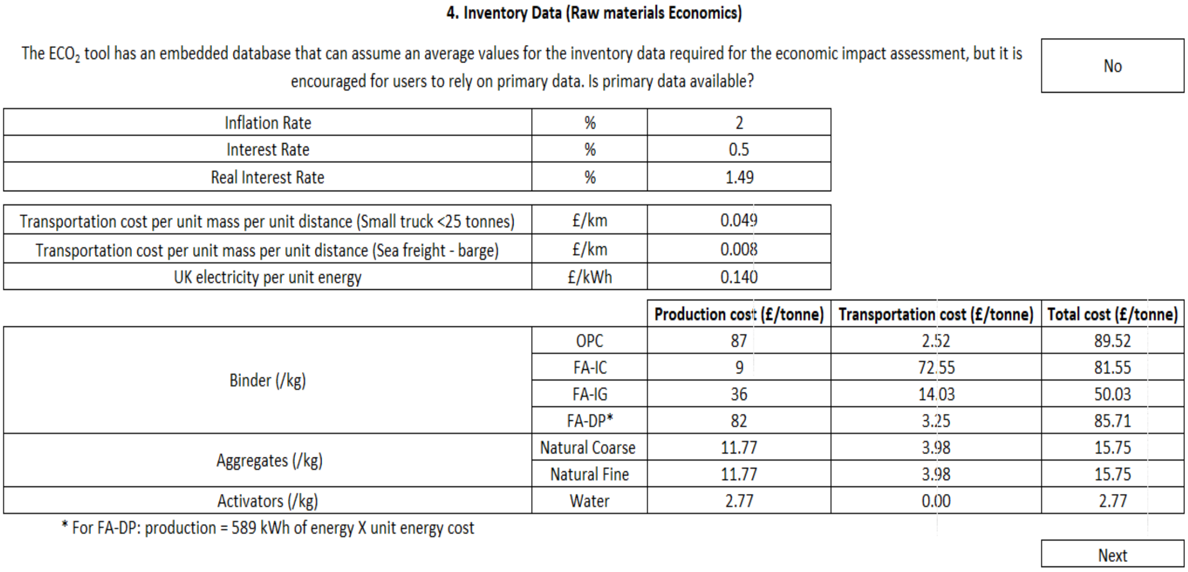
	Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication potential	Abiotic Depletion Potential	Photochemical ozone creation potential	Energy consumption	Fresh Water net use
	GWP	ODP	AP	EP	ADPE	POCP	CED	FW
	kg CO_2	kg CFC^{-11}	kg SO_2	kg PO_4	kg sb eq	kg C_2H_4 eq	MJ	m^3
Construction	7.50E-01	3.19E-08	0.00E+00	2.17E-03	5.58E-03	1.33E-04	1.66E+01	5.85E+00
Demolition	1.12E+00	4.78E-08	0.00E+00	3.25E-03	8.37E-03	2.00E-04	2.49E+01	8.78E+00

Figure 6.6: A screenshot of the average inventory data for concrete production and demolition from the ECO_2 database

6.4.5. *Economic Inventory Data*

The primary data for the economic impact of the different concrete constituents include that the price of FA imported from China is 9 £/tonne (Alibaba, 2019). Also, to calculate the production cost for the recovered FA alternative, the price of the electricity in the UK was found to be 0.14 £/kWh (UKPower, 2019). Other than that, the rest of the economic inventory data were surveyed from the literature. First, the cost of transporting the raw materials per km via sea freight was found to be

0.008 ₤/km (Jamora et al., 2020), while the rest of the inventory data found below in Figure 6.7 were extracted from the ECO_2 database.



4. Inventory Data (Raw materials Economics)

The ECO_2 tool has an embedded database that can assume an average values for the inventory data required for the economic impact assessment, but it is encouraged for users to rely on primary data. Is primary data available?

No

Inflation Rate	%	2
Interest Rate	%	0.5
Real Interest Rate	%	1.49

Transportation cost per unit mass per unit distance (Small truck <25 tonnes)	£/km	0.049
Transportation cost per unit mass per unit distance (Sea freight - barge)	£/km	0.008
UK electricity per unit energy	£/kWh	0.140

		Production cost (£/tonne)	Transportation cost (£/tonne)	Total cost (£/tonne)
Binder (/kg)	OPC	87	2.52	89.52
	FA-IC	9	72.55	81.55
	FA-IG	36	14.03	50.03
	FA-DP*	82	3.25	85.71
Aggregates (/kg)	Natural Coarse	11.77	3.98	15.75
	Natural Fine	11.77	3.98	15.75
Activators (/kg)	Water	2.77	0.00	2.77

* For FA-DP: production = 589 kWh of energy X unit energy cost

Figure 6.7: A screenshot of the economic inventory data of this case study from the ECO_2 tool

The method, by which the cost of each concrete constituent showed in Figure 6.7 was calculated, is using the following equation 6.3. C_p and C_t are the market price per unit mass and the transportation cost per unit mass and unit distance of each raw material, respectively. D_j is the transportation distance, which equals the geographic distance between the source of the raw material and the concrete batch plant. Unlike the transportation distance input in the environmental impact assessment, this distance is not doubled under the assumption that the return trip is accounted for as a part of the charged cost of transportation.

$$C_b = C_p + C_t * D_j \tag{6.3}$$

6.4.6. *Calculate the ecological impact*

The tool calculates the impact for concrete production for each alternative and then adds to it the construction and demolition impact as per equation 6.4 below.

$$\frac{GWP_i}{m^3} = \sum_{j=1}^{n}\left(\frac{GWP_{j\,upstream}}{kg} * \frac{kg_j}{m^3}\right) + \frac{GWP_i construction}{m^3} - \frac{GWP_i sequestered}{m^3} + \frac{GWP_i\, demolition}{m^3} \tag{6.4}$$

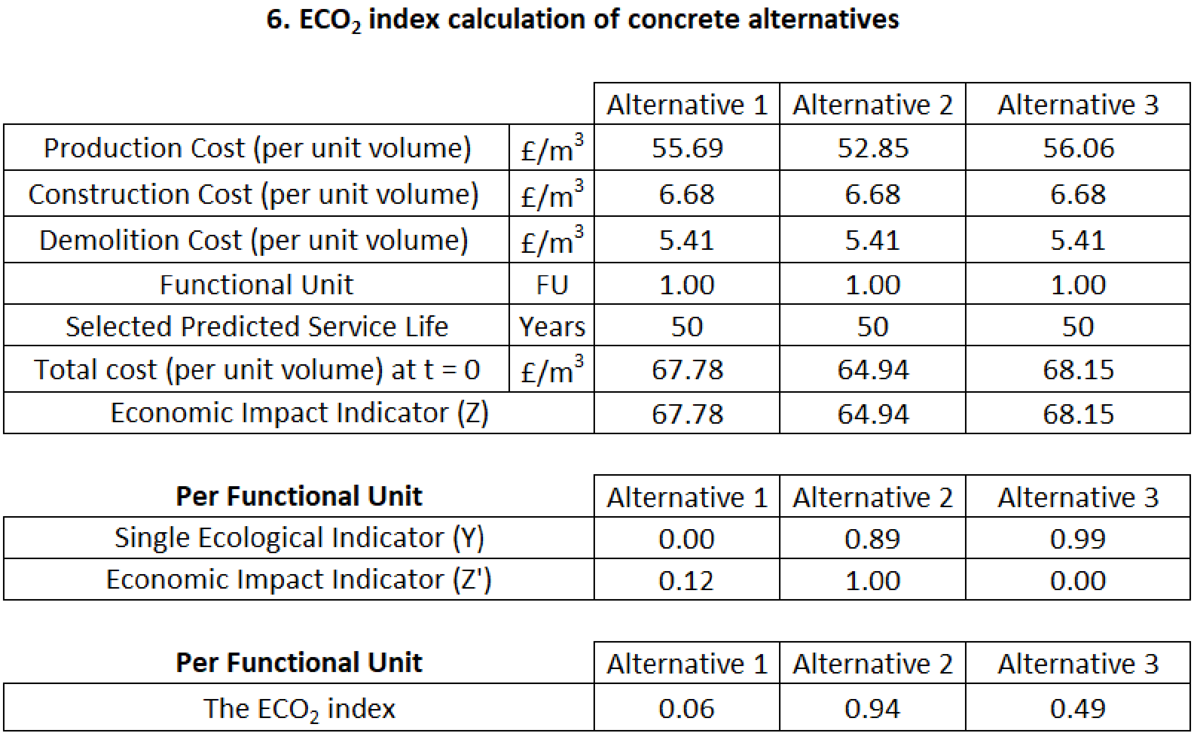
After that, the comparative scores for each environmental impact indicator (GWP, ODP ... etc.) are normalized using equation 6.5, where V_f is the normalized value for an indicator i. For each alternative, the average of the normalized score for all 8 indicators is then averaged into a single ecological indicator.

$$V_i' = \frac{max\,(V_i) - V_i}{max\,(V_i) - min\,(V_i)} \tag{6.5}$$

6.4.7. Calculate the ECO$_2$ index

As seen in Figure 6.8, the final step in the ECO$_2$ calculation is to calculate the average between the normalized score for the economic and economic impact indicators per alternative. In this case study, due to the absence of variability among the studied alternative's service lives, the economic impact indicator Z is equals to the total cost calculated by using equation 6.6. C_i is the total cost per unit volume of alternative i, C_b is the baseline cost per unit volume while C_c and C_d are the costs per unit volume of the construction and demolition from the ECO$_2$ database.

$$C_i = C_b + C_c + C_d \tag{6.6}$$



6. ECO$_2$ index calculation of concrete alternatives

		Alternative 1	Alternative 2	Alternative 3
Production Cost (per unit volume)	£/m^3	55.69	52.85	56.06
Construction Cost (per unit volume)	£/m^3	6.68	6.68	6.68
Demolition Cost (per unit volume)	£/m^3	5.41	5.41	5.41
Functional Unit	FU	1.00	1.00	1.00
Selected Predicted Service Life	Years	50	50	50
Total cost (per unit volume) at t = 0	£/m^3	67.78	64.94	68.15
Economic Impact Indicator (Z)		67.78	64.94	68.15

Per Functional Unit	Alternative 1	Alternative 2	Alternative 3
Single Ecological Indicator (Y)	0.00	0.89	0.99
Economic Impact Indicator (Z')	0.12	1.00	0.00

Per Functional Unit	Alternative 1	Alternative 2	Alternative 3
The ECO$_2$ index	0.06	0.94	0.49

Figure 6.8: A screenshot of the final step of the case study: calculating the ECO$_2$ index

6.5. Discussion of results

6.5.1. Case study results

After conducting the LCA for the three concrete alternatives using the ECO$_2$ framework, this leads to the following conclusions:

- As seen in Figure 6.9a, the difference in absolute values across the eight environmental impact indicators between the three alternatives was minimal (except for ODP). Nevertheless, in terms of normalized scores as seen in Figure 6.9b, alternative 1 (importing from China) seemed to always have the highest impact (this rewarded with 0) followed by alternative 2 (importing from Germany) with a marginal difference than alternative 3 (recovering landfilled FA), which is rewarded with a 1.

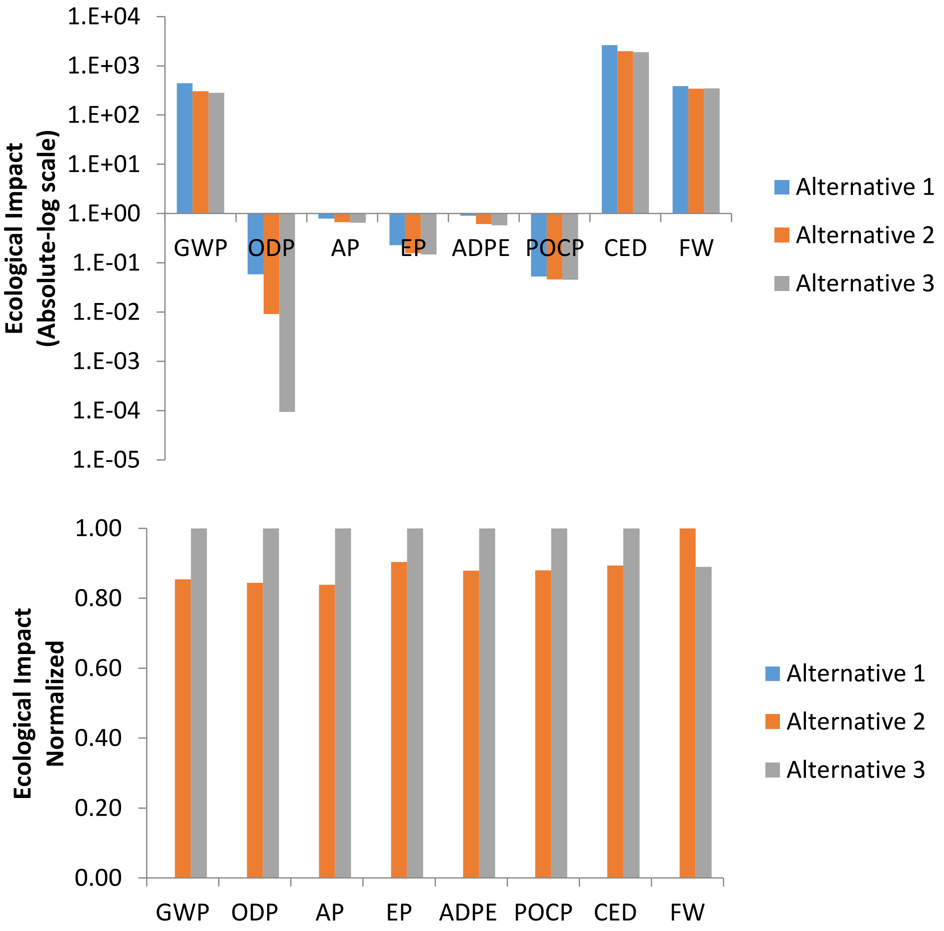


Figure 6.9: A comparison between the absolute (a) and normalized (b) environmental impact indicators for the three alternatives under study

- A similar conclusion was deduced concerning the comparative absolute values of the economic impact indicator across the three alternatives as seen in Figure 6.10. Alternative 3 (FA-DP) > alternative 1 (FA-IC) > alternative 2 (FA-IG) with the minimal difference of 1 % and 5% respectively.

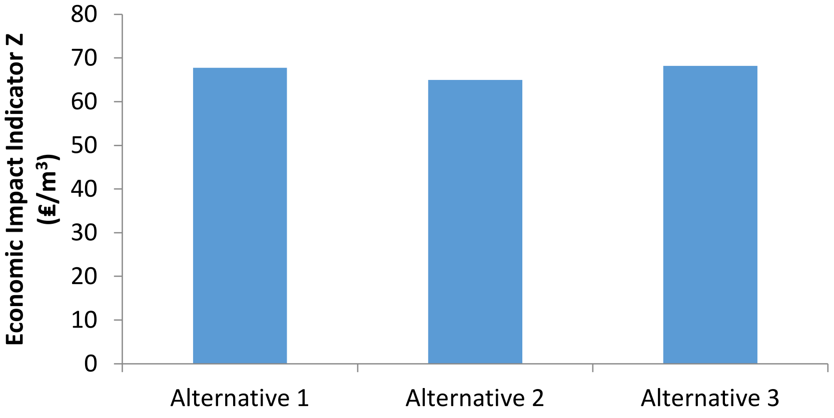


Figure 6.10: Comparison between the absolute values of the economic impact indicator of the three alternatives

- By aggregating the normalized single ecological and economic scores by a 50-50 weighting, it was deduced that the ECO_2 score of the best alternative which is importing FA from Germany is higher than that of recovering landfilled FA by 50%. The latter, as seen in Figure 6.11, is in its turn higher than the least favourable alternative, importing FA from China also by 50%.

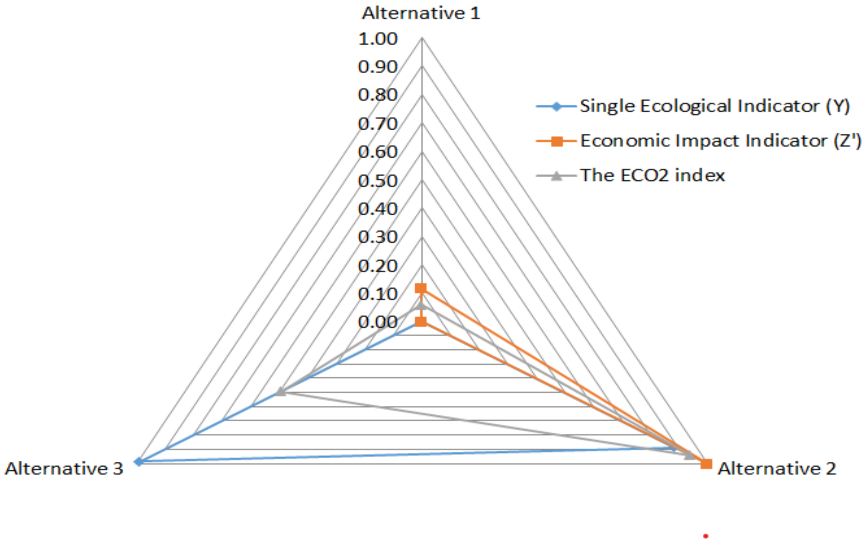


Figure 6.11: The single normalized ecological, economic and ECO_2 score of the three alternatives

- As seen in the past findings, the fact that the FA constitutes only 30% of the binder, which is less than 10% by weight of the whole concrete mix, makes the contribution of FA to the final score less renounced. Hence, in order to demonstrate the comparison clearly, the analysis was repeated based on 1 kg of each of the three FA alternatives. The values for the 8 environmental impact indicators in Table 6.4 show that recovering FA is 10-100 times less than importing FA from China mainly due to the impact from transportation associated with the latter. Also, the total cost per unit mass of the three alternatives, importing FA from China, importing it from Germany and recovering landfilled FA are 82, 50 and 86 £/tonne, respectively. Hence, the economic impact varies widely if compared per unit mass making the FA-IG alternative (2) almost 100% less than recovered FA (alternative 3).

6.5.2. Sensitivity analyses

The fact that the study contains primary data such as the price of energy, environmental impact from recovering the FA or that of the anticipated transportation distance between the exporting country and the UK makes the results sensitive to the accuracy of the data source. Therefore, two sensitivity analyses were conducted to assess the effect of changing these primary data on the resultant ecological and economic scores across the three alternatives. In order to clarify the discrepancies, building upon the findings from the previous section, the comparison is done based on a unit mass of each FA alternative not on concrete.

6.5.2.1. Change environmental inventory data for energy use

The first sensitivity analysis is concerned with the environmental impact. The energy required for the Dry-processing method was assumed as a total of 590 kWh/tonne based on the data extracted from McCarthy et al. (2018). However, assuming the operation would be scaled up, it is reasonable to assume the energy required might decrease, or increase depending on the sophistication of the technology. Hence, the first sensitivity scenario is the change in the third alternative's energy ± 50%. First, the decrease of the energy to 295 kWh/tonne decreases the price per tonne to £44.5, while increasing it to 885 kWh/tonne increases the price to 123.7 £/tonne. If the price of the recovered FA alternative decreased to £44.5/tonne, the concrete alternative with recovered FA would have been favoured over importing FA from Germany in the baseline scenario. In addition, as seen in Figure 6.12, the change of the environmental impact (in absolute values) of a unit mass of is negligible in response to the ± 50% change in the energy requirement. The justification behind this is that the impact from the recycling process of the recovered FA is small compared to that from the transportation process.

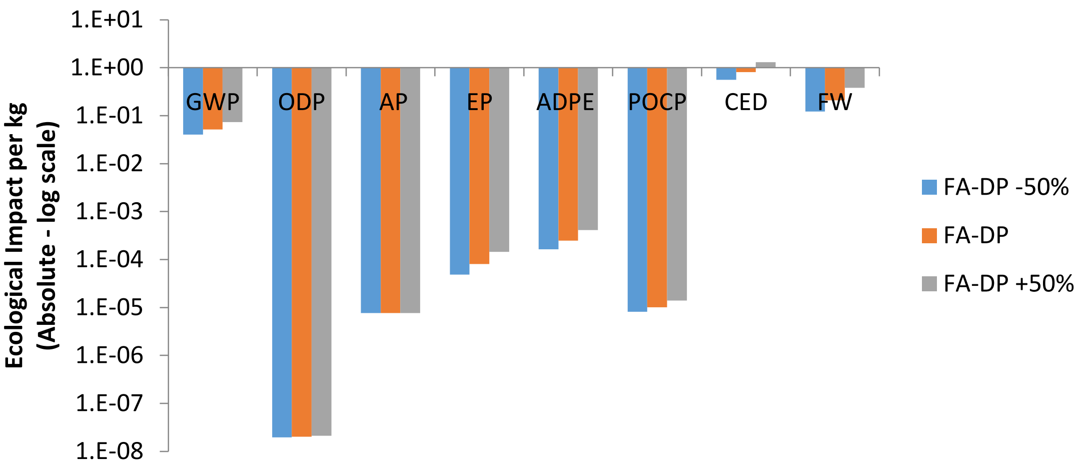


Figure 6.12: The sensitivity of the GWP of the recovered FA to change in the energy demand for the recovery process

6.5.2.2. Change environmental inventory data for barge transportation

The baseline scenario highlighted that the main source of the environmental impact for the first two alternatives of importing FA stems from the transportation process. This means that there is a significant weight of the analysis on the inventory environmental data attributed to the sea freight means of transportation. Although the numbers used were obtained from the ECO_2 database which was originally built using the Ecoinvent database, it is still liable to change. Hence, the second sensitivity analysis done was to assess the effect of changing the environmental impact attributed to the Barge transportation means by ±50%. The results show that, increasing the environmental impact of transporting FA by a barge by 50% would increase the impact of importing FA from China and Germany by almost the same percentage. However, this minimally affects the normalized impact compared to the recovered FA as shown in Figure 6.13.

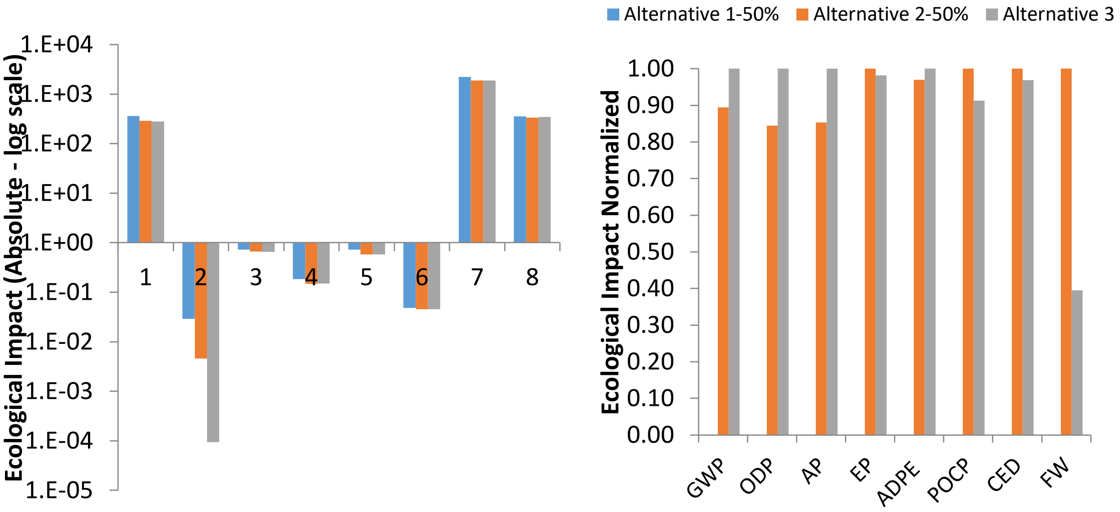


Figure 6.13: The absolute (left) and normalized (right) environmental impact of the three FA alternatives based on a 50% decrease scenario in the impact of Barge transportation

On the contrary, although increasing the impact of barge transportation by 50% also only increases the per unit mass impact of the imported FA by the same percentage, a difference is noticed in the normalized score. As opposed to the baseline scenario where recovering FA had the lower single ecological score, increasing the impact as aforementioned by 50% makes the imported FA from Germany the alternative with the higher score as seen in Figure 6.14.

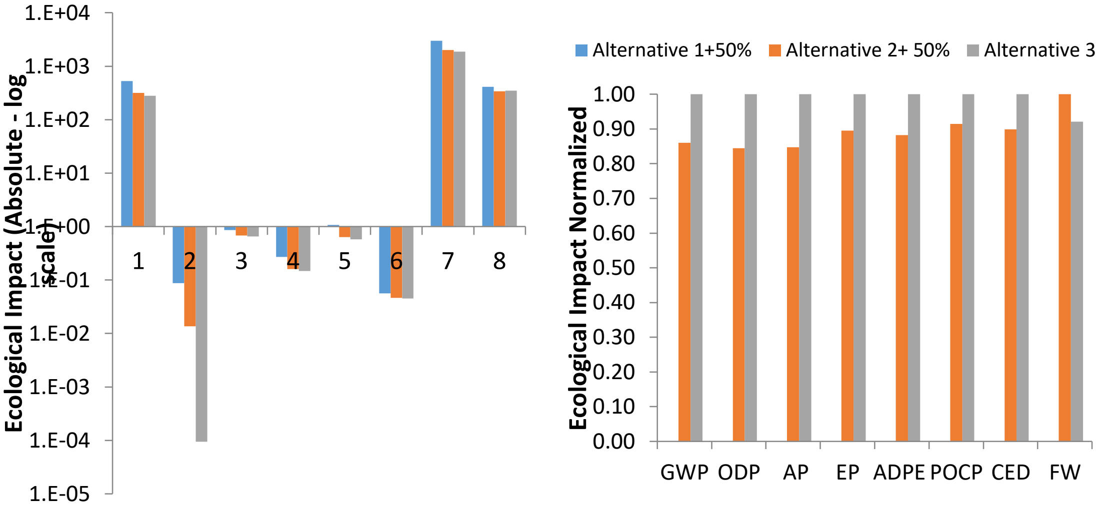


Figure 6.14: The absolute (left) and normalized (right) environmental impact of the three FA alternatives based on a 50% increase scenario in the impact of Barge transportation

6.5.2.3. Change energy prices

The baseline scenario also included an assumption that the price of a unit of energy in China, Germany and the UK is £ 0.11, £0.29 and £0.14 respectively. This affects the allocated impact for the imported FA alternatives as well as the economic impact of the recovered one. Hence, it was decided to study the change in the single ECO_2 score across the three alternatives based on a ±50% change in these values. Decreasing the energy prices 50% yielded halving the value of the allocated environmental impact for both imported FA alternatives, while also halving the cost per unit mass of the recovered FA alternative. The decrease in environmental impact of the imported FA alternatives did not have an effect on the single ecological score since transportation is the more dominant source of impact. This meant that the ecological single score remained in the favour of recovered FA over both imported FA alternatives. Nevertheless, the decrease in the unit cost of the recovered FA made it the cheapest alternative among the three making it the most sustainable alternative not importing FA from Germany followed by the latter then importing FA from China. Increasing the energy prices by 50% similarly increased the value of the allocated impact by 50% but this did not affect the order of preference in terms of the ecological score since both alternatives were originally the highest among the three. Similarly, although increasing the price of the energy cost increased the unit price of the recovered FA alternative by the same amount, it did not affect the single economic score or the ECO_2 score. The reason is that the FA-DP was the alternative with the highest cost to start with.

6.6. Summary

In this chapter, the final case study of the PhD project was prepared based on the ECO_2 framework. The case study investigated a current issue facing the UK concrete market with a forecasted seizure on all coal powered electrical power plants starting 2021. This would result in the absence of locally produced FA, which is a main product in the concrete market. The potential solutions proposed for sourcing FA are importing it from China and Germany being the furthest and nearest countries commercially trading FA with the UK respectively or recovering landfilled FA. For the past 100 years of producing FA as a by-product to burning coal and before FA was used predominantly in concrete manufacturing, it was mainly landfilled. The most energy efficient lab based technique found in the literature for recovering FA from this process is the Dry-processing method. Hence, the case study considered these 3 alternatives for sourcing FA: importing it from China (FA-IC), importing it from Germany (FA-IG) and recovering landfilled FA through the Dry-processing method (FA-DP). The study relied on a mix of primary data and secondary ones. Examples of the primary data used are the energy demand for the Dry-processing method of recovering FA, the distance covered by sea freight means for transporting FA from Germany or China to the UK and the prices of FA in each of the aforementioned countries. The three alternatives were assumed to be replacing OPC by 30% in a typical blended cement concrete mix with just sand, gravel and water. The rest of the economic and environmental inventory data were, similar to previous case studies, extracted from the ECO_2 tool such as the impact per unit energy, per unit distance of the barge and the cost of the remaining concrete constituents.

The findings from the baseline scenario are that, mainly owing to the significant transportation impact, the ecological score for importing FA from China is the worst among the three followed by importing it from Germany which is less than that of recovered FA. The latter's biggest contribution is the energy required to recycle the FA through the Dry-processing method. When it comes to cost, due to the increased cost of the unit energy, the recovered FA scored the worst single economic impact followed by importing it from Germany and finally China. The combined score then means that importing FA from Germany has the most optimum alternative when it comes to sustainability followed by recovering it from landfills and finally importing it from China. The most significant conclusion when it comes to the real life application is that although it is cheap to acquire, importing FA from China has almost as high of an environmental impact as OPC which overcomes the original incentive to use FA in concrete in terms of sustainability.

Following the baseline scenario, three sensitivity analyses were prepared to investigate the potential impact of changing the following parameters on the final outcome of the case study: changing the assumption on energy use, changing the environmental inventory data for transportation via barge and finally changing the market price of energy. The first analysis, changing the energy use by 50%, caused an equivalent significant change on the recovered FA alternative. This means that, decreasing the impact by 50% would mean 50% less environmental impact and 50% cheaper FA deeming the alternative the most optimum to use over the imported ones and vice versa. The second analysis scenario, changing the impact associated with transportation, has less significant impact on the environmental impact of the imported alternatives. The reason is that both alternatives were already higher than the recovered FA alternative in the baseline scenario so increasing the transportation impact by 50% just increased this gap maintaining the same order. On the contrary, decreasing the impact by 50% meant that importing FA from Germany has less ecological score than that of the recovered FA one enhancing its superiority as the most optimum alternative. Finally, decreasing the energy prices 50% yielded halving the value of the allocated environmental impact for both imported FA alternatives, while also halving the cost per unit mass of the recovered FA alternative. The decrease in environmental impact of the imported FA alternatives did not have an effect on the single ecological score since transportation is the more dominant source of impact. This means that the ecological single score remained in the favour of recovered FA over both imported FA alternatives. Nevertheless, the decrease in the unit cost of the recovered FA made it the cheapest alternative among the three making it the most sustainable alternative not importing FA from Germany followed by the latter then importing FA from China. Increasing the energy prices by 50% similarly increased the value of the allocated impact by 50% but this does not affect the order of preference in terms of the ecological score since both alternatives were originally the highest among the three.

Finally, it is thought that the chapter presented another opportunity for the validation of the applicability of the ECO_2 tool while tackling a real contemporary issue. The case study projected some solutions for the FA availability issue in the UK beyond 2021 and compared between them using primary data published for the first time. Although the findings are contextual and speculative, the comparison provides basis to address the issue for when more accurate data is available.

Chapter 7: Conclusions, recommendations and future work

7.1. Introduction

The growing concerns over the sustainability of the Earth's resources have been the driving source of change in the construction sector. Throughout the chapters of this dissertation, the work presented was attempting to portray the effectiveness of the recent efforts within the concrete industry to remediate its established significant environmental impact. Concrete is a generic material that ranges widely in its components, characteristics and consequently environmental impact. The basic and most conventional concrete type is that prepared with OPC and virgin aggregates. Conventional concrete has a carbon footprint of 300 kg eq CO_2/m^3 on average of which 90% is attributable to OPC (Habert et al., 2011). The main contributors to the significant negative environmental impact of conventional concrete are OPC and natural aggregates. The current production rate of more than 4 billion tonnes of OPC annually is responsible for 7% of the global CO_2 emissions (Colangelo et al., 2018). Every tonne of OPC production is responsible for almost 800 kg of CO_2 emissions on average (Kurda et al., 2017). Half of the emissions could be attributed to the chemical process of calcining the OPC clinker and the rest to the CO_2 emissions resulting from the energy required to extract the raw materials, transport them and heat up the kilns to 1450 degrees (Wang et al., 2019). Therefore, in accordance with the sustainable built environment aspirations, several policies and industrial changes are occurring in the concrete industry to decrease its environmental impact. However, sustainability is not exclusively assessed on the basis of the environmental impact. Sustainability is a multi-faceted objective that encompasses the environmental, economic and functional performance of a product or process. In order to judge the effectiveness of any of the aforementioned strategies in making concrete more sustainable, it is necessary to come up with a sustainability assessment framework. This would work as a bridge between the industrial efforts and the policies attempted at the concrete sustainability objective. The aim of this research work was to develop a framework that combines the environmental, economic and functional parameters specifically to concrete.

7.2. Contributions

In order to pursue the aspired aim of this research, the first step, which also constitutes the first contribution of this dissertation, was to do an extensive search of the literature. The objective of the literature review was to validate the research gap and explore the answers provided by previous publications to the research questions presented by this study, or similar ones.

7.2.1. Literature review

The first group of literature showed that several frameworks were found that use the multi-criteria decision analysis (MCDA) methodology for concrete sustainability assessment based on two or more pillars of sustainability. However, only MARS-SC (Rahla et al., 2018) and CONCRE*Top* (Kurda et al., 2019) were selected as the base case frameworks to build on due to their relevance and novelty. The gaps found in the both frameworks indicated the need to develop a novel framework for concrete sustainability that allows for different scenarios for comparison between alternatives. More importantly the new framework should integrate the functional indicators of a concrete alternative in the environmental and economic assessment method rather than separating it as a separate pillar. In order to tackle the latter, the second group of reviewed literature was a systematic review of the methodology and results of life cycle assessment (LCA) of concrete. LCA is the most widely accepted tool to assess and compare these acclaimed environmental and economic indicators (Anastasiou et al. 2015). The review revealed that the new framework should include, for a reliable concrete LCA study, a Cradle-to-Grave scope, a priority for the use of primary data and should include Impact allocation for SCM based concrete. As a validation for the framework to be developed, three case studies were decided and hence the last group of reviewed literature was around the potential of producing a sustainable concrete mix by alkali activating a waste slag, the functional performance of blended cement concrete utilizing a combination of SCMs and finally the proposed solutions to the anticipated halt in fly ash production locally in the UK resulting from the potential closure of all coal fired power plants starting 2022.

7.2.2. ECO2 framework

Using a deductive logic in the research methodology, the novel framework, which is the second and most significant methodological contribution of this research, was developed under the name “ECO_2”. The new framework is distinguished from the previously reviewed frameworks by the following features in the perspective to functional performance. In both frameworks, functional indicators are quantified through a process similar to the environmental and economic indicators. This would dictate that 2 concrete mixes, where the first has higher environmental impact and higher functional performance, would have the same sustainability score as that of a lower functional performance and lower environmental impact when in reality the one with the lower functional performance might be suitable for the intended application. Hence, the ECO_2 framework was developed to create a paradigm shift when it comes to the assessment of the functionality of a concrete mix. Rather than quantifying the functional performance in absolute manner, the concrete mix is matched against project specific requirements in a performance based approach, where a concrete mix is first checked against the project's minimum requirements in terms of workability and strength. After that, the functional unit is calculated as $\mathrm{FU_i = N_i * 1m^3}$ where N is the replacement ratio of the concrete alternative, reflecting the number of times it would need to be replaced to fulfil the required service life. With regards to the remaining LCA stages, the systematic review showed that the inclusion of the "use" phase is necessary to account for the carbon sequestration and the "end-of-life". Hence, the novel ECO_2 framework is built using a Cradle-to-Grave boundary condition for any LCA study included. In addition, impact allocation is the process of portioning the environmental burden of the original process to the waste material being recycled in the product under study. This is primarily significant in Green concrete LCA studies where materials such as FA, GGBS and SF are used and hence they ought to be considered as by-products not as waste. Unlike the methodology found in both frameworks under review, the ECO_2 framework was designed to always allocate a percentage of the original impact in case any of the three materials were used. The ECO_2 framework was also designed with a logical gate that only allow the user to enter inventory data from a secondary source when a primary one is absent.

7.2.3. Framework validation

After developing the ECO_2 framework, an excel based tool was developed as a first step to validate the framework's applicability. The tool calculates the weighted average of the economic and environmental impact indicators in order to compare, based on the ECO_2 sustainability index, between a limited numbers of concrete mixes against specific project requirements. After that, three case studies were conducted to validate the reliability of the framework and usability of the tool.

7.2.3.1. Case study #1

The first case study was attempting, besides the validation of the reliability for the ECO_2 framework to assess the sustainability potential of concrete and the usability of its tool, to present an empirical contribution in the domain of Green concrete materials. The first case study was aimed at assessing the sustainability potential of alkali-activated concrete from electric arc furnace slag using the ECO_2 tool. An experimental program was put in place at the University of Lisbon in Portugal and all the necessary material was procured locally to test the functional performance of EAFS based AAC. The tests performed were slump, strength, chloride penetration and carbonation. After that, data from the test results as well as the site-specific environmental and economic properties were collected to assess whether the ECO_2 tool can generate a converging judgement on the sustainability index that is comparable to the hypothesis from the literature. Several AAC mixes were designed to test the effect of changing the precursor from FA to EAFS and changing the water: precursor ratio on the three sustainability pillars: performance, environmental and economic impact.

The preliminary conclusion was that due to the deteriorated functional properties of the EAFS based AAC mixes, the optimum mixes using the ECO_2 sustainability index were that of only FA. However, this was only valid in terms of reinforced concrete, because when a scenario with plain concrete was assumed, the EAFS based mixes exhibited a significantly improved sustainability potential using the ECO_2 index. Due to the complexity of the sustainability assessment calculations, it would not have been easy for users to analyse the optimum mix based on the combined functional, environmental, and economic impacts. Hence, besides validating the applicability of the tool, the use of the ECO_2 tool was critical to make this assessment easier and allow for the optimization of the mixing proportions of AAC mixes with a target of the highest achievable single sustainability score.

7.2.3.2. Case study #2

The second attempt at validating the use of the ECO_2 and the reliability of the novel framework was through conducting another case study concerning the sustainability assessment of blended cement concrete (BCC). BCC is a concrete type that utilizes one or two of pozzolanic materials with lower environmental impact than OPC to replace the latter with varying percentages. The fact that these supplementary cementitious materials (SCMs) are either processed ones such as FA, GGBS or SF or low energy ones such as calcined clay (CC) and powdered lime (LP), allows for a hypothesis that the resulting BCC would have a lower environmental impact than conventional OPC concrete. However, as agreed, the sustainability assessment process through ECO_2 combine, not only the environmental impact, but the economic impact while gauging the concrete performance against project specifications. Hence, the main objective of the case study was to optimize, using the ECO_2 index, the sustainability of BCC mixes utilizing one or two SCMs from the aforementioned. In order to calculate the objective function for the optimization, the first step was to do an extensive literature search on the environmental and economic impact inventory data on each of the SCMs studied. The *Pre-bcc* regression model, which was built using a non-linear multi-layer artificial neural network, required the formulation of an extensive database from more than 150 published articles yielding more than 1600 data points for tests that measure either slump, strength, chloride resistivity or carbonation of BCC mixes including one or a few of the aforementioned SCMs. The *Pre-bcc* regression model, which is the first of its kind to cover all of these functional properties for all SCMs, was proven to be statistically accurate (R= 0.94-0.97) compared to others from the literature. After that, the ECO_2 optimization model was ran using an off-the shelf genetic algorithm (GA) to which the previous data from the regression model and the inventory ecological and economic database were input. The optimized mixes using the ECO_2 GA model for each class were compared against the mix design proposed by papers from the literature and were found to be at least 70% cheaper and of 30% less environmental impact. The main reason in this enhancement, which is considered to be another empirical contribution of this case study, is that although the same objective function was used for all optimization models, the depth provided by the ECO_2 regression model allowed for a wider range of selection.

7.2.3.3. Case study# 3

Studying the sustainability potential of utilizing fly ash, among other SCMs in concrete showed a promising impact and an established record of successful integration in the industry, especially in the UK. However, forecasted closure on all coal powered electrical power plants starting 2021 is threatening the presence of locally produced FA. The potential solutions proposed in the literature for sourcing FA to the UK are importing it from China and Germany being the furthest and nearest country with the lowest and highest selling price of FA respectively or recovering landfilled FA through the Dry-processing method. Hence, the third case study presented in this dissertation considered these three alternatives for sourcing FA: importing it from China (FA-IC), importing it from Germany (FA-IG) and recovering landfilled FA through the Dry-processing method (FA-DP). Besides serving as a validation of the usability of the ECO_2 tool, the case study aimed to present an empirical contribution regarding the most sustainable solution to this problem of FA availability in the UK market beyond 2021. The study relied on a mix of primary data and secondary ones. Examples of the primary data used are the energy demand for the Dry-processing method of recovering FA, the distance covered by sea freight means for transporting FA from Germany or China to the UK and the prices of FA in each of the aforementioned countries. The rest of the economic and environmental inventory data were, similar to previous case studies, extracted from the ECO_2 tool such as the impact per unit energy, per unit distance of the barge and the cost of the remaining concrete constituents.

The findings from the baseline scenario were that, mainly owing to the significant transportation impact, the ecological score for importing FA from China was the worst among the three followed by importing it from Germany which was a bit less than that of recovered FA. The latter’s biggest contribution was the energy required to recycle the FA through the Dry-processing method. When it comes to cost, due to the increased cost of the unit energy, the recovered FA scored the worst single economic impact followed by importing it from Germany and finally China. The combined score then meant that importing FA from Germany is the optimum alternative when it comes to sustainability followed by recovering it from landfills and finally importing it from China. The most significant conclusion when it comes to the real life application is that although it is cheap to acquire, importing FA from China has almost as high of an environmental impact as OPC which overcomes the original incentive to use FA in concrete in terms of sustainability. Following the baseline scenario, three sensitivity analyses were prepared to investigate the potential impact of changing the following parameters on the outcome of the case study: changing the assumption on energy use, changing the environmental inventory data for transportation via barge and finally changing the market price of energy. The decrease in environmental impact of the imported FA alternatives did not have an effect on the single ecological score since transportation is the more dominant source of impact.

7.3. Recommendations

. The literature clarified that a radical change is required in the concrete industry to reduce its environmental impact. Although an ideal situation lies in controlling the consumption of building materials principally, it is known that a hindering factor lies in the economic and social incentives behind the drive for the increasing rate of urbanization globally. Hence, in order to achieve the more feasible objective of creating more sustainable concrete mixes, there needs to be a reliable measure of concrete sustainability as a reference point that encompasses the functional, environmental and economic aspects. The novel ECO_2 framework proposed in this dissertation was validated as a reliable starting point. The other contributions presented in this study varied, as shown in the previous subsection, between methodical and empirical ones allowing for an over-arching environmental, economic and social judgement to stem beyond the academic level to impact the industrial and political domains. Suggestions that align with the findings from this research that are believed to be aligned with the aspired change include:

- All concrete related raw materials should be carbon taxed. This would ensure that, although transferrable to the end-user as an increase in the concrete price, the choice to rely on OPC and other environmentally highly impactful raw materials would be penalized by an equivalent increase in taxes.
- ASTM, ACI and RILEM and the rest of the concrete testing and regulating entities would be encouraged to produce performance-based specifications for concrete that limits the concrete products specifications to project specific requirements. This would require prediction models for each functional property coupled with the resulting service life predictions to ensure reliable functional unit calculations of LCA studies.
- Government-lead initiatives to assess and document the environmental impact of all processes included in the concrete supply chain would ensure the presence of certified EPDs (environmental product declarations) to be used as inventory data sources in concrete LCA studies.
- Governments and environmental regulatory boards could introduce incentives for concrete production companies complying with objectives that are measured using the ECO_2 sustainability assessment indices.
- International transportation of concrete raw materials should be monitored against specific environmental impact thresholds related to phenomena such as depletion of sandy beaches linked with over-extracting river sand as well as carbon emissions associated with international trade of cement, lime, FA and other raw materials.

7.4. Future work

The contributions presented in this dissertation were continuity on with previously published research in the realm of sustainable concrete technology. Even the acclaimed paradigm shift to the functional unit calculation that is presented within the novel ECO_2 framework and constitutes a major share in the added value of the presented research, largely stems from the performance based specifications concept. Hence, it is believed that it is necessary to present routes by which future research could build on the contributions presented in this dissertation such as:

- The excel based tool for executing the ECO_2 framework could be up-scaled using a more advanced programming language with a more user-friendly graphical interface such as Lab view or python. The new software could accommodate features such as allowing users to update the built-in beta version of the ECO_2 database through connecting the software to an online server with primary environmental inventory data on concrete mixes they produce pending the approval of the original author. Another feature in the upgraded version of the software would be for users to save “projects” or analyses that they run using the software on their storage devices.
- The limitations of the ECO_2 framework are mainly the absence of the quantification of the uncertainty embedded within the sustainability index calculation process. Whether it is from the service life predictions of each concrete mix or the inventory data for the environmental and economic impact of each of the constituents, there is an uncertainty in calculating any ECO_2 index. Hence, there is a plan to target this and include the uncertainties in the next version of the framework.
- The findings from the case study involving the optimization of blended cement concrete based on the ECO_2 sustainability index were limited to the boundaries in the regression model, which in return was limited to the nature and number of points available in the input functional properties database. Hence, it would be better to make the database available online and allow users to add to it their experimental findings from new types of SCM or more data on the same types surveyed. This would build a wider boundary that would then allow for a wider range of the optimization model.
- The experimental results from the case study exploring the performance of alkali activated electric arc furnace slag were not comparable to that of the base case which included the use of fly ash as a precursor. Hence, it is worth exploring to do more tests utilizing water glass and changing the sodium ration in the alkaline solution to enhance the mechanical and durability properties and re-run the sustainability assessment scenario to determine the optimum mixes.

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Appendix A

The sources for the systematic literature review of concrete related LCA for chapter 2

#	Title	1st Author's Name	Year	Country	Economics	GT/GV	Mix Design	Inventory data
1	The influence of supplementary cementitious materials on climate impact of concrete bridges exposed to chlorides	Al-Ayish	2018	Sweden	No	Grave	Yes	Yes
2	Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials	Anastasiou	2015	Greece	Yes	Grave	Yes	Yes
3	Life cycle assessment for environmental product declaration of concrete in the Gulf States	Biwas W. K.	2017	Qatar	No	Gate	Yes	No
4	Life cycle energy and environmental analysis of partition wall systems in the UK	Broun	2011	UK	No	Grave	Yes	No
6	Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended Portland cements containing fly ash and limestone powder	Celik K.	2015	USA	No	Gate	Yes	No
8	Durability and environment evaluation of an eco-friendly cement based material incorporating recycled chromium containing slag	Cheng	2018	China	No	Gate	Yes	No
9	Eco-mechanical index for structural concrete	Chiaia	2014	NA	No	Gate	No	Yes
10	Life Cycle Assessment of concrete manufacturing in small isolated states: the case of Cyprus	Chrysostom C.	2015	Cyprus	No	Gate	Yes	No
11	Life cycle assessment of recycled concretes: A case study in southern Italy	Colangelo	2017	Italy	No	Grave	Yes	Yes
12	Life Cycle Assessment (LCA) of Different Kinds of Concrete Containing Waste for Sustainable Construction	Colangelo	2018	Italy	No	Gate	Yes	No
13	Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint	Collins	2010	NA	No	Cradle	No	Yes
15	Measuring the eco-efficiency of cement use	Damineli B.	2010	Brazil	No	Gate	No	No
16	Life Cycle Assessment of Completely Recyclable Concre	De Schepper M.	2014	Belgium	No	Cradle	Yes	No
18	Developing an LCA methodology to account for the environmental benefits of design for deconstruction	Densley Tingley	2012	UK	No	Cradle	No	No
19	Life cycle assessment to evaluate the environmental performance of new construction material from stainless steel slag	Di Maria	2018	NA	No	Gate	Yes	No
20	A closed-loop life cycle assessment of recycled aggregate concrete utilization in China	Ding	2016	China	No	Cradle	Yes	Yes
21	Definition of an equivalent functional unit for structural concrete incorporating recycled aggregates	Dobbelaere	2016	NA	No	Grave	Yes	No
22	Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute	Evangelista	2018	Brazil	No	Gate	No	No
23	Reducing greenhouse gas emissions for prescribed concrete compressive strength	Fan	2018	NA	No	Gate	Yes	No

25	The role of concrete compressive strength on the service life and life cycle of a RC structure: Case study	Garcez M. R.	2017	Brazil	No	Grave	Yes	Yes
27	Sustainability-based decision support framework for choosing concrete mixture proportions	Gettu	2018	India	No	Grave	Yes	No
28	Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates	Guo	2018	China	No	Grave	Yes	Yes
29	A life-cycle approcach to environmental, mechanical and durability properties of "green" concrete mixes with rice husk ash	Gursel	2015	USA	Yes	Grave	Yes	No
33	Improved selection of the functional unit in environmental impact assessment of cement	Gutierrez	2017	NA	No	Grave	No	Yes
35	Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials	Haflinger	2017	Switzerland	No	Cradle	No	No
36	Rheological properties, compressive strength and life cycle assessment of self-compacting concrete containing natural pumice pozzolan	Hedayatinia	2019	Iran	No	Gate	Yes	Yes
39	Mechanical, environmental and economic performance of structural concrete containing silica fume and marble industry waste powder	Khodabakhshian	2018	Iran	Yes	Cradle	Yes	Yes
41	Product-specific Life Cycle Assessment of ready mix concrete: Comparison between a recycled and an ordinary concrete	Kleijer	2017	Switzerland	No	Grave	Yes	No
42	Optimizing recycled concrete containing high volume of fly ash in terms of the embodied energy and chloride ion resistance	Kurda	2018	Portugal	No	Grave	Yes	No
43	Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash	Kurda	2018	Portugal	No	Gate	Yes	Yes
44	Environmental impact analysis of blast furnace slag applied to ordinary Portland cement production	Li	2015	China	Yes	Cradle	No	Yes
46	Life cycle assessment for concrete kerbs manufactured with recycled aggregates	Lopez-Gayyare	2015	Spain	No	Gate	No	Yes
47	Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls	Maia de Souza D.	2016	Brazil	No	Grave	No	No
48	Environmental assessment of green concretes for structural use	Marinkovic	2017	Serbia	No	Gate	Yes	Yes
53	Comparison indices for design and proportioning of concrete mixtures taking environmental impacts into account	Miller	2016	NA	No	Gate	Yes	No
54	Concrete mixture proportioning for desired strength and reduced global warming potential	Miller	2016	NA	No	Gate	Yes	Yes
55	Life cycle assessment (LCA) of benchmark concrete products in Australia	Mohammadi J.	2017	Australia	No	Gate	Yes	No
56	Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime	Muller H. S.	2014	NA	No	Grave	Yes	Yes
57	Life Cycle Cost Assessment of Preventive Strategies Applied to Prestressed Concrete Bridges Exposed to Chlorides	Navarro I. J.	2018	Spain	Yes	Grave	Yes	No
58	Environmental impacts and mechanical properties of lightweight concrete containing bauxite residue (red mud)	Nikbin	2017	Iran	No	Gate	Yes	No
59	The influence of design variables and	Panesar D. K.	2010	Canada	No	Grave	Yes	No

	environmental factors on life-cycle cost assessment of concrete culverts							
60	Impact of the selection of functional unit on the life cycle assessment of green concrete	Panesar D. K.	2017	NA	No	Grave	No	No
61	Life cycle CO_2 assessment of concrete by compressive strength on construction site in Korea	Park J.	2012	South Korea	Yes	Gate	Yes	Yes
62	Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators	Passuello	2017	Brazil	No	Gate	Yes	No
63	Life cycle assessment of a hemp concrete wall: Impact of thickness and coating	Pretot S.	2014	France	No	Grave	Yes	No
65	Comparative sustainability assessment of binary blended concretes using Supplementary Cementitious Materials (SCMs) and Ordinary Portland Cement (OPC)	Rahla	2019	NA	Yes	Gate	Yes	Yes
66	Life cycle assessment (LCA) of an alkali-activated binary concrete based on natural volcanic pozzolanic: A comparative analysis to OPC concrete	Robayo-Slazar R.	2018	Colombia	No	Gate	Yes	Yes
67	Increasing the sustainability potential of a reinforced concrete building through design strategies: Casestudy	Rohden	2018	Brazil	No	Gate	Yes	Yes
68	Life Cycle Assessment of BioZEment concrete production based on bacteria	Royna F.	2017	Sweden	No	Gate	Yes	Yes
70	Life cycle assessment of geopolymer concrete	Salas D A	2018	Ecuador	No	Gate	Yes	No
71	Greenhouse gas emissions of different fly ash based geopolymer concretes in building construction	Sandanayake M	2018	Australia	No	Gate	Yes	Yes
74	Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures	Sayyagh S.	2009	France	No	Grave	No	No
75	Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment	Serres	2015	France	No	Gate	No	No
76	Influence of fly ash allocation approaches on the life cycle assessment of cement-based materials	Seto K. E.	2017	Canada	Yes	gate	No	No
77	Life cycle assessment of adoption of local recycled aggregates and green concrete in Singapore perspective	Shan	2017	Singapore	No	Gate	No	No
79	Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete	Sinka M.	2018	Latvia	No	Gate	No	No
80	Comparative process-based life-cycle assessment of bioconcrete and conventional concrete	Soleimani M.	2017	USA	No	Gate	No	No
82	Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: The case of Catalonia (Spain)	Suarez-Silgado S.	2018	Spain	Yes	Gate	Yes	Yes
83	Life cycle CO_2 evaluation on reinforced concrete structures with high-strength concrete	Tae S.	2010	South Korea	No	Grave	Yes	Yes
84	A comparative cradle-to-gate life cycle assessment of three concrete mix designs	Tait M. and Cheung W. M.	2016	UK	No	Gate	Yes	Yes
86	Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia	Teh S. H.	2017	Australia	Yes	Gate	No	No

87	Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material	Teixeira E. R.	2015	Portugal	Yes	Gate	Yes	Yes
88	Economic and life cycle assessment of recycling municipal glass as a pozzolanic in Portland cement concrete production	Tucker E. L.	2017	USA	No	Gate	No	No
89	Environmental evaluation of green concretes versus conventional concrete by means of LCA	Turk	2015	Slovenia	No	Gate	Yes	No
92	Service life and global warming potential of chloride exposed concrete with high volumes of fly ash	Van den Heede	2017	NA	No	Grave	Yes	No
94	Durability Related Functional Units for Life Cycle Assessment of High-Volume Fly Ash Concrete	Van den Heede and De Belie	2010	Belgium	No	Grave	Yes	No
95	Environmental performance of ordinary and new generation concrete structures—a comparative analysis	Walach D.	2018	NA	No	Gate	Yes	Yes
96	Life cycle sustainability assessment of fly ash concrete structures	Wang J.	2017	China	Yes	Grave	Yes	No
99	Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area	Yazdanbakhsh	2017	USA	No	Gate	Yes	No
102	Assessment of CO_2 emissions and cost in fly ash concrete	Zhang	2014	China	No	Gate	Yes	Yes

Appendix B

A summary of the inventory data for the selected concrete constituents and processes using the selected environmental impact indicators

Constituent	Unit	Source	Country	Year	Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication potential	Abiotic Depletion Potential	Photochemical ozone creation potential	Energy consumption	Fresh Water net use
					GWP (CML)	ODP (TRACI)	AP (TRACI)	EP (TRACI)	ADPE	POCP	CED	FW
					kg co$_2$	kg cfc-11	kg so2	kg po4	kg sb eq	kg c2H4 eq	MJ	m^3
Super Plasticizers	/kg	Bisawas		2017	1.13E+00							
		Chiaia		2014	7.20E-01						1.83E+01	
		Garcia Segura		2013	2.20E-01							
		Habert		2011	7.49E-01	8.48E-08		1.03E-03	8.56E-03	2.29E-04		
		Muller		2014	9.44E-01							
		Serres		2016			5.44E-02				1.83E+01	
		Walach		2018	1.84E+00	2.61E-10		9.81E-04	1.11E-06	2.47E-04	2.79E+01	5.70E-03
		Zhang		2014	7.20E-01							
		Eco-Invent	-	2019	5.66E-01	3.02E-08		7.59E-04	6.26E-03	8.92E-05	1.48E+01	1.39E+00
		Mean			8.61E-01	3.84E-08	5.44E-02	9.23E-04	4.94E-03	1.88E-04	1.98E+01	6.98E-01
		Standard deviation			4.76E-01	4.29E-08	#DIV/0!	1.44E-04	4.43E-03	8.64E-05	5.63E+00	9.80E-01
Sodium Hydroxide	/kg	Habert		2011	2.24E+00	1.38E-07		8.10E-04	1.64E-02	4.63E-04		
		Marinkovic		2017	1.04E+00	3.42E-04	2.93E-03	1.54E-04				
		Robayo-Slazar		2018	1.36E+00							
		Sandanayake		2018	1.43E+00							
		Eco-Invent	-	2019	3.04E-01	1.82E-08		1.03E-03	2.21E-03	5.92E-05	6.35E+00	2.24E+00
		Mean			1.27E+00	1.14E-04	2.93E-03	6.63E-04	9.30E-03	2.61E-04	6.35E+00	2.24E+00
		Standard deviation			7.00E-01	1.97E-04	#DIV/0!	4.54E-04	1.00E-02	2.86E-04	#DIV/0!	#DIV/0!
Sodium Silicate	/kg	Habert		2011	1.14E+00	8.82E-08		4.95E-04	7.22E-03	2.43E-04		

		Marinkovic		2017	5.62E-01	2.73E-04	1.66E-03	8.48E-05				
		Robayo-Slazar		2018	7.93E-01							
		Sandanayake		2018	7.80E-01							
		Eco-Invent	-	2019	8.40E-01	6.10E-08		1.02E-03	4.81E-03	1.63E-04	1.50E+01	2.17E+00
		Mean			8.23E-01	9.09E-05	1.66E-03	5.34E-04	6.02E-03	2.03E-04	1.50E+01	2.17E+00
		Standard deviation			2.07E-01	1.57E-04	#DIV/0!	4.69E-04	1.70E-03	5.69E-05	#DIV/0!	#DIV/0!
Water	/kg	Habert		2011	1.55E-04	1.36E-11		1.01E-07	1.93E-06	9.98E-08		1.00E-03
		Walach		2018	5.70E-04	2.35E-14		2.48E-07	2.44E-10	8.53E-08		1.00E-03
		Eco-Invent	-	2019	2.44E-05	3.08E-12		2.95E-08	1.19E-07	4.46E-09	2.95E-04	1.19E-03
		Mean			2.50E-04	5.57E-12		1.26E-07	6.83E-07	6.32E-08	2.95E-04	1.06E-03
		Standard deviation			2.85E-04	7.12E-12		1.11E-07	1.08E-06	5.14E-08	#DIV/0!	1.12E-04
Small truck	/tkm	Chiaia		2014	3.32E-01						4.97E+00	5.34E-01
		Guo		2018	7.05E-01	5.13E-04	9.58E-05	2.60E-04				
		Kurda		2018	6.57E-05			7.20E-05	2.62E-09	2.24E-05	9.27E-01	
		Marinkovic		2017	1.88E-01	5.73E-05	5.63E-05	6.56E-05				
		Eco-Invent		2019	2.23E-01	3.06E-07		2.69E-04	1.63E-03	9.97E-05	3.55E+00	1.90E-01
		Mean			2.90E-01	1.90E-04	7.60E-05	1.67E-04	8.14E-04	6.11E-05	3.15E+00	3.62E-01
		Standard deviation			2.61E-01	2.81E-04	2.80E-05	1.13E-04	1.15E-03	5.47E-05	2.05E+00	2.44E-01
Large truck	/tkm	Chiaia		2014	1.36E-01						2.00E+00	1.63E-01
		Colangelo		2018	8.05E-01	0.00E+00	1.10E-04	3.51E-04				
		Kurda		2018	4.98E-02			5.14E-05	1.98E-09	1.59E-05	6.73E-01	
		Tosic		2015	4.06E-01	1.35E-04	4.31E-04	1.27E-04				
		Eco-Invent		2019	1.47E-01	2.10E-07		1.65E-04	1.16E-03	8.78E-05	2.55E+00	1.73E-01
		Mean			3.09E-01	4.50E-05	2.71E-04	1.74E-04	5.79E-04	5.18E-05	1.74E+00	1.68E-01
		Standard deviation			3.08E-01	7.77E-05	2.27E-04	1.27E-04	8.19E-04	5.08E-05	9.67E-01	7.33E-03
Rail	/tkm	Guo		2018	1.19E-01	2.43E-04	3.32E-05	5.06E-05				
		Eco-Invent		2019	3.95E-02	2.72E-09		1.05E-04	2.78E-04	8.92E-06	7.51E-01	

		Mean			7.92E-02	1.21E-04	3.32E-05	7.76E-05	2.78E-04	8.92E-06	7.51E-01	#DIV/0!
		Standard deviation			5.62E-02	1.72E-04	#DIV/0!	3.82E-05	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Barge	/tkm	Marinkovic		2017	1.88E-01	5.74E-05	5.64E-05	6.56E-05				
		Tosic		2015	1.73E-01	8.60E-05	1.73E-04	5.59E-05				
		Eco-Invent		2019	4.63E-02	4.83E-09		8.82E-05	2.82E-04	6.51E-06	6.56E-01	4.64E-02
		Mean			1.36E-01	4.78E-05	1.15E-04	6.99E-05	2.82E-04	6.51E-06	6.56E-01	4.64E-02
		Standard deviation			7.78E-02	4.38E-05	8.24E-05	1.66E-05	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Electricity	/kWh	Gursel	China	2016	1.21E+00	1.30E-04	2.80E-03	2.21E-04			9.17E+00	
			Japan		9.58E-01	2.20E-04	2.40E-03	1.56E-04			9.18E+00	
			Indoneia		1.18E+00	1.44E-04	3.70E-03	2.08E-04			1.06E+01	
			Malaysia		1.02E+00	2.40E-04	2.00E-03	1.82E-04			9.36E+00	
			Singapore		7.27E-01	3.60E-04	7.00E-04	1.08E-04			9.13E+00	
			Taiwan		1.02E+00	1.80E-04	2.00E-03	1.82E-04			1.02E+01	
			Thailand		8.58E-01	3.00E-04	1.00E-03	1.43E-04			9.11E+00	
		Panesar	Canada	2017	1.12E+00	3.22E-04	3.67E-04	3.78E-04				
		Eco-Invent	China	2019	8.76E-02	5.00E-10		7.22E-05	5.26E-04	3.34E-05	8.55E-01	1.06E-01
		Eco-Invent	Japan	2019	4.11E-02	1.47E-09		6.80E-05	3.17E-04	7.25E-06	8.96E-01	2.85E-01
		Eco-Invent	Europe	2019	3.75E-02	1.59E-09		1.08E-04	2.79E-04	6.65E-06	8.30E-01	2.93E-01
		Eco-Invent	USA	2019	5.81E-02	1.53E-09		1.06E-04	4.32E-04	1.66E-05	9.72E-01	2.12E-01
		Mean			6.92E-01	1.58E-04	1.87E-03	1.61E-04	3.88E-04	1.60E-05	6.39E+00	2.24E-01
		Standard deviation			4.88E-01	1.35E-04	1.13E-03	8.48E-05	1.13E-04	1.25E-05	4.39E+00	8.64E-02

Appendix C

A summary of the sources for the database created for the regression model in chapter 5

Author	#	Year	FA	GGBS	SF	LP	CC	Slump	Strength	Chloride	Carbon
Adam	1	2009		1					1		
Akhtar uz Zaman	2	2014	1	1	1				1	1	
AlAmoudi	3	2009	1		1				1	1	
Alhassan and Ballim	4	2017		1				1	1		1
Al-Shamiri	5	2017							1		
Amaknwa	6	2015					1	1	1		
Angulo-Ramirez	7	2019		1					1		1
Arora	8	2019	1					1	1	1	1
Atis	9	2003	1						1		1
Balakrishnan and Abdul Awal	10	2014	1					1	1		
Baten	11	2020	1	1				1			
Berndt	12	2009	1	1				1	1		
Bilim	13	2008		1					1		
Bisawas	14	2017		1				1	1		
Bucher	15	2017	1	1		1	1		1		1
Burden	16	2006	1					1	1	1	1
Buss	17	2013	1	1					1	1	1
Celik	18	2015	1			1			1		
Chen	19	2018	1					1	1		
Cholampour	20	2017	1	1				1	1		
Collepardi	21	2004	1	1		1			1		1
Crouch	22	2007	1					1	1		
Czarnecki	23	2018	1	1				1	1		1
Dhandapani	24	2018				1	1	1	1		1
Dhanya	25	2018	1	1					1	1	
Diab	26	2016			1	1			1		
Dinakar	27	2012		1					1		
Dinakar	28	2006	1	1				1	1		
Divsholi	29	2014		1					1		1
Dong-Woo	30	2012		1					1		
Duan	31	2013		1			1		1		
Duran-Herrera	32	2014	1						1		1
Eguchi	33	2013		1			1	1	1		1
Einsfeld	34	2006			1				1		
Faleschini	35	2015	1					1	1		
Fanghui	36	2015	1						1		
Felekoglu	37	2007				1		1	1		
Garcez	38	2018			1				1		
Garcia - segura	39	2014	1	1					1		1
Gesoglu	40	2009	1	1	1				1		

Gettu	41	2018	1	1		1	1		1		1
Goleski	42	2018	1						1		
Guneyisi	43	2010	1	1	1		1		1		
Harrison	44	2012	1	1		1		1	1		1
Hawileh	45	2017		1					1		
Holt	46	2010	1	1							1
Hui-Sheng	47	2008	1	1					1		
Hussain	48	2017	1						1		
Inthata	49	2013	1					1	1	1	
Jalal	50	2015	1		1	1			1		
Jau	51	2004	1					1	1		
Jiang	52	2004	1						1		
Johari	53	2011	1	1				1	1		
Jones	54	1997	1	1	1			1	1		
Kaewmanee	55	2014	1			1		1	1	1	1
Karahan	56	2017	1	1					1	1	
Karri	57	2015		1				1	1		
Kavita	58	2016					1			1	
Khodair	59	2015	1	1					1	1	
Khodanakhshian	60	2018			1			1	1		
khunthongkeaw	61	2006	1								1
Kou	62	2007	1					1	1	1	
Kou*	63	2011	1	1	1		1	1	1	1	
Kurda	64	2018	1						1		
Kumar	65	2020	1		1					1	
Lee	66	2013	1						1		1
Leeman	67	2015	1			1		1	1		1
Leung	68	2016	1		1				1		
Lima	69	2013	1					1	1		
Limbachiya	70	2012						1	1		
Ling	71	2004		1				1	1		
Liu	72	2014		1				1	1	1	
Lofgren	73	2016		1					1	1	
Long	74	2015	1	1		1	1		1		
Long*	75	2017	1	1					1		
Lubeck	76	2012		1					1		
Marinkovic	77	2017	1					1	1		
Marques	78	2013	1			1			1		1
Mary and Kishore	79	2015		1					1	1	
Matos	80	2019	1						1	1	
McCarthy and Dhir	81	2005	1			1			1		
McNally amd Sheils	82	2012	1	1		1			1		1
Meddah	83	2014				1		1	1		
Miller	84	2016	1						1		
Mittal	85	2004	1					1	1		

Moffatt	86	2017	1					1	1		1
Mohamadi	87	2017	1	1				1	1		
Mohamed	88	2018	1	1	1					1	
Murad	89	2019	1		1				1		
Najimi	90	2019	1		1					1	
Navarro	91	2018	1		1				1		
Nepomuceno	92	2014	1						1		
Newlands	93	2012	1						1		1
Nochaiya	94	2009	1		1			1	1		
Oner	95	2005	1						1		
Oner*	96	2007		1				1	1		
Panesar	97	2013		1					1		
Panesar*	98	2019	1					1	1	1	
Park	99	2012	1	1					1		
Parron-Rubio	100	2019		1					1		
Patil	101	2013		1					1		
Pillai	102	2019	1			1	1		1		
Poon	103	2000	1						1		
Poon and Kou	104	2010	1					1	1		
Preez	105	2019	1	1					1		
Quan and Kasami	106	2014	1					1	1		1
Rathnarajan	107	2017		1					1		1
Roziere	108	2009	1						1		1
Ruixia	109	2010	1						1		1
Saha	110	2020	1						1		
Sahmaran	111	2009	1			1			1		
Samad	112	2017		1					1		
San Nicolas	113	2014					1	1	1		1
Sanjuan	114	2003	1					1	1		1
Shaikh and Supit	115	2015	1					1	1	1	
Siddique	116	2004	1						1		
Silva	117	2013		1					1		
Simcic	118	2015	1					1	1		
Sisomphon and Frunke	119	2007	1	1							1
Soja	120	2019		1					1		1
Sonebi	121	2008	1	1		1		1	1		
Song	122	2008	1	1	1				1	1	
Soutsos	123	2018	1	1				1	1		
Sugi	124	2013	1	1					1		
Sujjavanich	125	2017	1				1	1	1	1	
Tae	126	2011		1					1		
Teng	127	2016		1				1	1		
Turuallo	128	2013		1					1		
Uysal and Sumer	129	2011	1	1		1			1		
Vab den heede	130	2019	1		1			1	1		

Van den heede and de belie	131	2010	1					1	1		1
Van den heede*	132	2017	1					1	1		
Vejmelkova	133	2009		1					1		
Vejmelkova*	134	2011	1				1	1	1		
Vivek and Dhinkaran	135	2017		1	1		1		1		
Vollpracht	136	2017	1	1				1	1		
Vu	137	2001					1	1	1		
Walach	138	2018			1				1		
Wang	139	2019	1	1				1	1		1
Wang*	140	2019	1					1	1		1
Wongkeo	141	2014	1		1			1	1	1	
Woyciechowsk	142	2019	1						1		1
Wu	143	2001		1					1		
X Zhang	144	2013		1							1
Xu and Liu	145	2010	1					1	1		
Yazici	146	2008	1		1				1		
Yeau and Kim	147	2004		1				1	1		
Yoo	148	2015	1					1	1		
Younsi	149	2011	1						1		1
Younsi*	150	2013	1	1				1	1		1
Younsi**	151	2011	1						1		
Zhang	152	2015	1						1		
Zhao	153	2015	1	1					1		1