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Concrete Limits

A sociometabolic analysis of the feasibility of the Circular Economy approach for the concrete sector

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Those far way

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Those closer

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Abstract

The concrete sector is a major contributor to global greenhouse gas emissions; consumes substantial amounts of natural resources and serves as a significant source of global waste. The Circular Economy approach has been put forward as the solution to these environmental issues, but the overall effectiveness of the approach has been called into question by existing research. The aim of this thesis was to evaluate the potential effectiveness of the Circular Economy approach in the concrete sector, with a focus on the barriers for adoption of circular strategies, and how the approach can be adapted to increase its ability to reduce material and energy consumption. The sociometabolic regime framework was used to analyse the effectiveness of the concept. Literature on this framework guided an analysis of data on concrete production and in-use stocks as well as findings from interviews conducted with representatives from the concrete and building sectors and academic experts. The findings indicate that, from a sociometabolic perspective, the most significant barriers to undermine the effectiveness of the Circular Economy transition in the concrete sector are the continued expansion of concrete in-use stocks and the growth-oriented nature of the CE approach. Another finding was that part of what has made concrete a dominant building material is that it is easy to produce cheaply, and thus easy to profit from. This presents a clear barrier for implementing circularity, as this very attractive quality of concrete, its cheapness, would be eroded if the CE approach was implemented. Finally, the research concludes that the Circular Economy approach could be made more effective, in the case of concrete, by prioritising sufficiency and the contraction of in-use stocks. This would lead to greater effectiveness in bringing down levels of resource and energy use.

Keywords: concrete, Circular Economy, sociometabolic regime, in-use stock

Executive Summary

Background and Problem Definition

Concrete is the world's most used construction material, and second most used material in general, after water. (Xuan et al., 2018). There are several troubling environmental impacts associated with concrete, chief among them the greenhouse gas emissions generated during its production (Busch et al, 2022). Concrete manufacturing also makes use of natural resources such as sand, which once were considered ubiquitous throughout the world but are now facing issues of scarcity (Watari et al, 2023). Finally, concrete represents a major waste stream, with much of the material ending up in landfills around the world at the end-of-life stage (Mah et al, 2017).

The concept of Circular Economy (CE) has become a dominant policy approach adopted to solve many of the above-mentioned sustainability issues. It aims to achieve this by transitioning from the conventional take-make-dispose form of production and consumption to a circular system which makes use of waste streams as secondary material inputs (Ellen MacArthur Foundation, n.d). The building and construction sector is one of many identified by the EU as being a target for transition to a Circular Economy and was highlighted in 2020 Circular Economy Action Plan as being a resource intensive industry which will be targeted by forthcoming measures aimed to increase circularity.

While the CE has been championed by many governments, academics and think-tanks around the world, there have also been critiques levelled at the concept (Skene, 2022; Valenzuela & Böhm, 2017; Korhonen et al 2018; Millar et al., 2018). Much of the research exploring the limitations of the circular economy either takes a detailed approach to analysing technical or practical barriers of implementing circular strategies and how to overcome them (Ritzén & Sandström, 2017; Kirchherr et al, 2018; Govindan & Hasanagic, 2018), or interrogates the epistemological underpinnings of the approach itself (Corvellec et al., 2022;Skene 2022; Korhonen et al., 2018). For the Circular Economy policy approach to successfully achieving widespread, long-lasting changes in patterns of resource and energy use, barriers for implementation need not just be identified, but considered when evaluating the possible effectiveness of policy approach. Such evaluations can then be used to suggest how the CE approach can be further developed to ensure absolute reductions in material and resource use that bring us within planetary boundaries.

The theory of sociometabolic regimes, from the field of ecological economics, is a powerful tool which has been used to understand the biophysical basis of human societies and has been put forward as a macro-level paradigm for evaluating sustainable development strategies (Pauliuk & Hertwich, 2015). Sociometabolic regime theory is in many ways primarily concerned with changes in energy systems and patterns of material use (Fischer-Kowalski, 2011), and so is well suited to the task of perceiving the extent to which policy approaches such as the CE can truly transform societies in a way that has them operating within planetary boundaries.

Aim and Research Questions

The aim of this research is to evaluate the barriers of transitioning to a Circular Economy in the concrete sector. The barriers identified will be used to understand how viable this policy approach is in terms of its ability to bring about a transition to a more stable sociometabolic regime.

The following research question and sub-question will be addressed in an attempt to achieve this research aim:

How effective can the CE policy approach be for bringing down material and fossil-based energy use in the concrete sector?

a. *What are the barriers to transitioning to a CE in the concrete sector?*
b. *What would need to change about the approach for material and fossil-based energy use to decrease in the concrete sector?*

Methodology

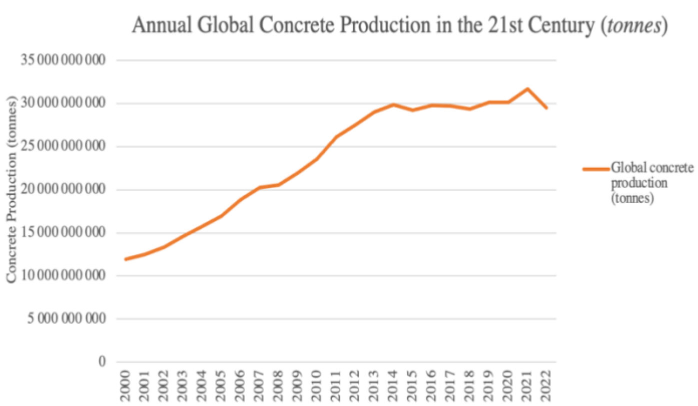
The first phase of research into the barriers of the concrete industry transitioning to a CE involved collating publicly available data on global in-use stocks of concrete and production of concrete to understand the trends in production and stock accumulation in recent history. Ultimately a simple calculation was made to determine the extent to which current stocks could be used to meet demand for new concrete.

The next stage of research involved carrying out interviews with practitioners and academic experts with intention of gathering data in the form of expert-opinions and reflections on professional experience on the driving factors of the success of concrete, barriers for concretes transition to a CE and finally factors which would need to change for the CE approach in the concrete sector to be more effective at bringing down material and energy use.

Interviews were then coded thematically and the implications of the findings were analysed using literature on the framework of sociometabolic regimes.

Findings

RQ 1a: What are the barriers to transitioning to a CE in the concrete sector?



The first barrier inidentified was that the rapid expansion of in-use stocks of concrete along with rates of concrete production suggests that in-use stocks cannot be relied on as a long-term source for secondary materials. Over the past few decades, in-use stocks and production of concrete have steadily increased, and this trend is expected to continue and even increase in severity, especially as developing nations undergo rapid urbanisation and development. However, this expansion of concrete stocks is incompatible with the principles of circularity. Circular economy principles advocate for the use of secondary materials from previous years' stocks, reducing the reliance on primary resources. If physical stocks expand every year, demands for materials needed for stock growth will not be able to be met by secondary materials from previous years stocks. Essentially, growing stocks necessitate growing resource use and less demand met by secondary materials.

The second barrier identified in this research is that the current dominance of neoliberal capitalist principles works to discourage the uptake of circular strategies. It was also found that the current CE approach aims to decouple economic growth from environmental harm, particularly when it comes to resource depletion and climate change. However, this notion has proven to be unfeasible and presents a challenge when implementing the circular economy within a neoliberal capitalist system. Unfortunately, one of the intrinsic characteristics of concrete is that it is cheap to produce, being made of abundant raw materials and created in processes fired by fossil fuels. Concrete, as it is now, is profitable. For this reason, introducing circularity to the production of this cheap resource within a system that prioritises economic growth over reducing resource and energy use is particularly challenging.

RQ1b: What would need to change about the approach for material and fossil-based energy use to decrease in the concrete sector?

Significant changes are required to overcome the previously identified barriers and promote the adoption of a circular economy concept which achieves reductions in material and energy use in the concrete sector. Firstly, there must be a contraction of the physical stocks of concrete. This necessitates a fundamental shift from focusing solely on efficiency and growth to emphasising sufficiency. A sufficiency-driven CE approach would entail re-evaluating how much concrete is truly necessary and promoting responsible consumption and production practices. This would also involve updating policy to remove any legal and bureaucratic barriers faced by concrete producers. The main focus, however, would be a change in attitudes related to how much concrete is actually needed to meet society's needs.

Conclusions and Recommendations

In summary, the findings of this thesis highlight the barriers limiting the potential effectiveness of the CE strategy at reducing energy and resource use in the production and consumption of concrete. The continual expansion of concrete stocks and the emphasis on economic growth present significant barriers for achieving this aim. However, by reorienting the CE approach to one which prioritises sufficiency and contraction of in-use stocks, it is possible that it can become more effective in bringing down levels of resource and energy use.

The practical implications of this research highlight the need to reassess the theoretical underpinnings of the CE approach and its policy implications. To further knowledge on the effectiveness of circularity and adapt the CE approach to one which would contribute to real reductions in energy and resource use, there are several topics which warrant further research.

Recommendations for non academic audiences:

- **The adoption of a sufficiency-driven CE approach**
  By shifting policy priorities away from economic growth to sufficiency, policymakers can pave the way for a sustainability transition which actually produces significant changes to our sociometabolic profiles.

- **The utilisation of the sociometabolic regime analytical framework in policy making.**
  By considering the sociometabolic dimensions of human activities policymakers can gain a deeper understanding of the resource flows, energy use, and environmental impacts associated with different sectors and industries.

Recommendations for further academic research:

- **Research is needed on more up-to-date and accurate in-use stocks of concrete and other materials.**

This data would provide valuable insights into the amount of contraction required in the stock, enabling policymakers and stakeholders to make informed decisions on reducing the consumption of concrete.

- **Researchers should work to identify policy mechanisms and incentives that can encourage reduced concrete use, extended lifespan of structures, and the use of alternative materials.**
  This would assist policy makers in instating a CE approach which focuses on attaining sufficiency.

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Abbreviations

CDW - Construction and Demolition Waste

CE - Circular Economy

CEAP - Circular Economy Action Plan

EU - European Union

OPC - Ordinary Portland Cement

SMR - sociometabolic regime

USGS United States Geological Survey

1 Introduction

"Why do you keep saying there is no alternative, when there really is no alternative?"

- Erik Swyngedouw and Japhy Wilson, 2014

Throughout history, human relationships with nature have undergone many changes. These relationships have caused varying levels of harm to the environment. For example, contemporary society's patterns of energy and resource use have brought about major negative consequences for nature. The theory of sociometabolic regimes divides human societies according to their patterns of material and energy resources and designates that most of modern-day society exists in the industrial sociometabolic regime, associated with high per capita consumption of materials and energy, mainly in the form of fossil fuels (Haberl et al., 2011).

The industrial sociometabolic regime is dominated by several sustainability issues including pollution, climate change and the depletion of natural resources (Krausmann et al, 2016). These are mainly due to enormously high levels of material and energy use. One characteristic of industrial society which contributes largely to these high levels is the development and maintenance of physical infrastructure (Krausmann et al., 2008). Construction materials currently dominate global resource use. They are the most used resource group in the world by weight and are a major source of waste (Haas et al, 2016).

Concrete is the world's most used construction material, and second most used material in general, after water. (Xuan et al., 2018). There are several troubling environmental impacts associated with concrete, chief among them the greenhouse gas emissions generated during its production (Busch et al, 2022). Concrete manufacturing also makes use of natural resources such as sand, which once were considered ubiquitous throughout the world but are now facing issues of scarcity (Watari et al, 2023). Finally, concrete represents a major waste stream, with much of the material ending up in landfills around the world at the end-of-life stage (Mah et al, 2017). The exact amount of waste concrete produced each year is unclear, but construction and demolition waste (CDW) represents 40% of all global waste (Ahmed et al, 2020), and around a third of the European Union's annual waste (European Commission, n.d). There is little data available on the exact share of Europe's CDW that can be attributed to concrete, but overall it is a major contributor (ibid.), as in other regions such as North America, where concrete takes up 67.5% and 52% of CDW in the United States and Canada, respectively (EPA, 2018; Ahmed et al., 2020).

The concept of Circular Economy (CE) has become a dominant policy approach adopted to solve many of the above-mentioned sustainability issues. It aims to achieve this by transitioning from the conventional take-make-dispose form of production and consumption to a circular system which makes use of waste streams as secondary material inputs (Ellen MacArthur Foundation, n.d). The building and construction sector is one of many identified by the EU as being a target for transition to a Circular Economy and was highlighted in 2020 Circular Economy Action Plan as being a resource intensive industry which will be targeted by forthcoming measures aimed to increase circularity.

While the CE has been championed by many governments, academics and think-tanks around the world, there have also been critiques levelled at the concept (Skene, 2022; Valenzuela & Böhm, 2017; Korhonen et al 2018; Millar et al., 2018). Scholars have questioned the concept's theoretical underpinnings and goals(Corvellec et al., 2022). In addition to epistemological challenges, major barriers to the implementation of a circular economy have been identified, although admittedly much scholarship on barriers has been conducted with the expressed intention of finding ways to overcome said challenges (Jaeger & Upadhyay, 2020; Kirchherr et al, 2018; Ritzén & Sandström, 2017). The theory of sociometabolic regimes, from the field of ecological economics, is a powerful tool which has been used to understand the biophysical basis of human societies and has been put forward as a macro-level paradigm for evaluating sustainable development strategies (Pauliuk & Hertwich, 2015). Sociometabolic regime theory is in many ways primarily concerned with changes in energy systems and patterns of material use (Fischer-Kowalski, 2011), and so is well suited to the task of perceiving the extent to which policy approaches such as the CE can truly transform societies in a way that has them operating within planetary boundaries.

1.1 Problem Definition

As previously explained, the CE is one of the main strategies currently being pursued by the European Union to solve problems related to natural resource depletion and energy use (European Commission, n.d). Despite this firm uptake of the policy approach, recent scholarship has levelled several critiques of the CE (Corvellec et al., 2022; Skene 2022; Korhonen et al., 2018). Bearing this in mind, there needs to be a clearer understanding of the obstacles preventing this approach from being implemented successfully in specific sectors, such as concrete. Furthermore, it is vital that the CE approach itself is evaluated, bearing in mind the challenges of its implementation, in the context of discerning whether it has the potential to bring about a global shift of resource and energy use that would bring society's activities within planetary boundaries.

As the concrete sector has such significant environmental impacts, in terms of its contribution to GHG emissions, contribution to waste production and use of global resources, it is particularly important to understand what obstacles need to be overcome for the current dominant policy approach to be properly implemented. There is an urgent need to transform this sector. According to the International Energy Agency, the cement industry, which produces concrete's key ingredient, is currently not on track to meet its Net Zero Emissions Scenario (IEA, 2022). The sector is set to face even more challenges as global demands for the material increase, as more parts of the world experience urbanisation and economic development (Chatham House, 2018). Any barriers for implementing policies used to tackle the environmental problems associated with this sector need to be understood, in order to help and encourage it implement wide-reaching changes. The presence of such obstacles needs then to be taken into consideration when coming to a more nuanced understanding of what potential issues exist within the CE approach itself.

Much of the research exploring the limitations of the circular economy either takes a detailed approach to analysing technical or practical barriers of implementing circular strategies and how to overcome them (Ritzén & Sandström, 2017; Kirchherr et al, 2018; Govindan & Hasanagic, 2018), or interrogates the epistemological underpinnings of the approach itself (Corvellec et al., 2022; Skene 2022; Korhonen et al., 2018). There has been less focus on identifying what the CE approach, with all its barriers, can offer in terms of establishing a pathway to a more sustainable sociometabolic regime.

For the Circular Economy policy approach to successfully achieving widespread, long-lasting changes in patterns of resource and energy use, barriers for implementation need not just be identified, but considered when evaluating the possible effectiveness of policy approach. It is well established that the CE is an idea which lacks a solid, agreed-upon definition (Kirchherr et al., 2017). In general, though, materials taken from government bodies and think-tanks promoting its adoption suggest that the CE is not only conceived as a series of waste management and prevention techniques such as those presented in the waste hierarchy. Instead, the CE is presented as a strategy which can be used to achieve "green" economic growth, wherein sustained economic growth can be achieved without causing environmental harm (Korhonen et al., 2018). Much of the criticism levelled at the CE's theoretical principles is related to this proposition. Examining the barriers faced by a specific sector can help to highlight whether these criticisms are warranted, and what can be done to overcome them.

1.2 Aim and Research Questions

The aim of this research is to evaluate the barriers of transitioning to a Circular Economy in the concrete sector. The barriers identified will be used to understand how viable this policy approach is in terms of its ability to bring about a transition to a more stable sociometabolic regime.

The following research question and sub-question will be addressed to achieve this research aim:

1. *How effective is the CE policy approach for bringing down material and fossil-based energy use in the concrete sector?*
    a. *What are the barriers to transitioning to a CE in the concrete sector?*
    b. *What would need to change about the approach for material and fossil-based energy use to decrease in the concrete sector?*

1.3 Scope and Delimitations

The sectoral scope for this thesis is the EU's concrete industry. All the research questions first and foremost aim to understand how the Circular Economy policy approach can be implemented in this sector. The findings are then used to make broader conclusions about the Circular Economy as a whole, but these are all grounded in findings from the concrete sector. Concrete was chosen as being a sector worthy of focus due to its major contribution to climate change and natural resource use, and for the fact that it can be considered an emblematic material of the industrial sociometabolic regime, due to its significant contribution to the production of infrastructure, and its part played in societies use of non-biobased materials.

The geographical focus of this research can broadly be defined as the European Union. This is because different conceptions of the CE exist as a policy approach (McDowall et al., 2017), and the conception focused on and evaluated in this research is the European perspective on the Circular Economy. Some concrete in-use stock estimates used were related to physical stocks present on a global scale, and not just the EU. This was because precise regional data was not available.

1.4 Ethical Considerations

This research involved conducting interviews with experts and practitioners associated with concrete or building materials more broadly. Participants agreed to be interviewed via email, and it was made clear that their participation in the research was voluntary, pending their time and interest. Consent to record and transcribe the interview proceedings was obtained verbally at the start of the interview, which were all conducted online, using a popular video conferencing application. Interviewees were informed that in the write up of findings from interviews their responses would be anonymised, and they would be identified only by a code referring to their industry or field of expertise.

Interview recordings and transcriptions were stored offline on a password protected computer which only I can access. These files will be kept for a period of ten years, as is the policy outlined by Lund University.

Overall, the research design has been reviewed against the criteria for research requiring an ethics board review at Lund University and has been found to not require a statement from the ethics committee.

1.5 Audience

As this research aims to identify barriers for reaching circularity and comment on how the policy approach can be improved based on said barriers, the primary intended audience of this thesis are policy makers involved in policy formation and implementation related to the circular economy.

This thesis may also be of interest to academic researchers as it seeks to add to a burgeoning field of research which seeks to critically examine and refine the Circular Economy concept to strengthen the approach in a way that can help it tackle issues related to unsustainable energy and material use in a concrete way. This research may also be beneficial to those employing the sociometabolic regime framework, as it furthers an understanding of how this framework can be used as a form of policy evaluation.

1.6 Disposition

Chapter one provided a brief overview of the background of the research topic and refined the research problem. It went on to state the aim of the research and RQs used to conduct the study. It also outlined the scope and intended audience for the research. Ethical considerations of the research are also presented in this section.

Chapter two provides a detailed overview of literature relevant to the study. It focuses on reviewing literature related to the topic of focus in this study, namely, concrete and the Circular Economy policy approach. It also explains the chosen analytical framework, sociometabolic regimes. The section ends with an explanation of the main research gaps this thesis attempts to fill.

Chapter three explains the methodology of the thesis. It presents the various methods used to collect and analyse data.

Chapter four presents the findings of the thesis.

Chapter five analyses the research findings from the previous chapter, using the chosen analytical framework, sociometabolic regime theory.

Chapter six contains a discussion on the findings in relation to the initial RQs posed. It then goes on to discuss these findings in the context of existing research. Finally, limitations regarding methodology, legitimacy and generalisability.

Chapter seven outlines the main conclusions of the research before going on to provide recommendations for both academic and non-academic audiences.

2 Literature Review

The following literature review aims to give an overview of the conceptual framework used to analyse the results of this study, namely sociometabolic regime theory. It goes on to use this framework to trace the development of the building material concrete, while giving an overview of the materials properties and environmental impacts associated with its production. It then goes on to present a summary of the factors which have made concrete the dominant building material it is today. Next, the Circular Economy, the policy approach which is being examined in this thesis is explained and positioned in the context of the concrete industry. Finally, this chapter ends with a discussion of the research gaps present in the literature reviewed.

2.1 The Theory of Sociometabolic Regimes

The theory of socio-metabolic regimes is an attempt to understand human-nature interactions throughout history (Fischer-Kowalski 2011). The theory divides human societies into categories, referred to as "regimes", according to their main dominant patterns of energy and material use (ibid.) Transitions between stages are given great attention, with efforts made to understand what circumstances led to shifts in energy and resource consumption (See Figure 2-1). Within this framework researchers tend to divide human history into three regimes: hunter gatherer, agrarian and industrial (Krausmann et al.,2016, 65). The first two regimes span the majority of human history wherein people lived lives which were relatively sustainable in terms of energy and resource use. In hunter-gatherer societies energy is taken from "trophic energy flows in ecosystems" by collecting plants and hunting animals in their natural environment (Haberl et al., 2017). Theirs is referred to as an "uncontrolled solar energy system", as they received energy from biomass which grows using solar energy, but this growth is not a result of human cultivation (Krausman et al. 2016, 65). The hunter-gatherer regime is further characterised by having several limits on population size and complexity, as well as the ability of people to accumulate belongings and maintain permanent settlements (ibid.). The transition from hunter-gatherer regime to agrarian regime is referred to as the neolithic transition, as shown in Figure 2-1.

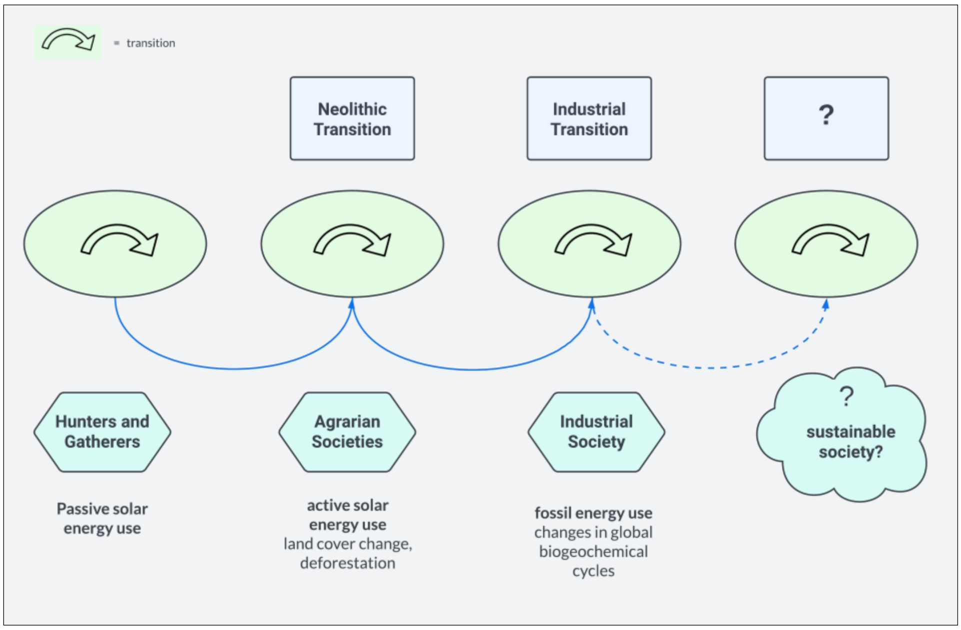

Figure 2-1: Transitions in Sociometabolic Regimes

Source: Adapted from Fischer-Kowalski et al., 2011

Agrarian societies, by contrast, have what is referred to as "controlled" solar energy system (Krausmann et al., 2008). This is because people in this regime actively manage ecosystems to increase the amount of biomass available. Doing this enables them to increase the amount of energy per unit of land (Krausmann et al., 2016, 70). The actual composition of the energy and material throughput of this system does not differ much from the previous regime. Most of the energy and materials needed still come from biomass (ibid.). During this regime there is a gradual increase in population, but generally there are several limits placed on population growth and density. This is due to several factors, but mainly the fact that over the long term, material and energy outputs per capita reach a limit (ibid.).

Finally, the industrial regime presents a drastic shift in terms of natural resource and energy use. After the industrial transition, fossil resources become the dominant energy sources. This leads to the decoupling of the energy system from land use, as biomass, which is suddenly no longer the main source of energy, is replaced by "area independent" energy in the form of fossil fuels (Krausmann et al., 2016, 80). Furthermore, in this system, agriculture is, through mechanisation and fertilisation, industrialised. In the industrial sociometabolic regime, population and resource use increase dramatically (ibid., 83). It is not just the number of resources that changes, however, but the composition as well. Suddenly biomass only represents between 10-30% of total resource inputs (Haberl et al., 2011.). A vast share, around 50%, of materials are needed for non-energy purposes, due to changed patterns of consumption (ibid.). Mineral resource use takes up a significant overall share. This regime overall is characterised by an abundance of infrastructure, high mobility of people and resources and mass production and consumption (85-7). The underlying "logic" and goal of societies in this system is economic growth.

A useful aspect of the sociometabolic regime theory as a conceptual framework is the fact that it pays great attention to the transitions between sociometabolic regimes. This allows for the future, much needed transition away from industrial regimes to be imagined in a tangible way, with real targets related to energy use and material use, among other considerations. It is for this reason that this analytical framework is deployed in this thesis, as it allows for the material concrete to be followed throughout agrarian and industrial regimes, and for its place in the next, more stable sociometabolic regime to be better understood.

2.2 Concrete

Apart from water, concrete is the most used material on earth. (Xuan et al., 2018). An estimated 30 billion tonnes of concrete are produced annually, and as the world's population grows and more people move to cities, the demand for this building material will only increase (Monteiro et al. 2017). The exact ingredients and production methods have evolved over time. Essentially, its production involves coarse, chemically-inert filler particles known as aggregates, which generally come in form of sand and crushed stone, being held together with cement and water (Encyclopedia Britannica, 2023). Cement, another man-made material, is composed mainly of limestone, clay, sand and water (Portland Cement Association, n.d).

Concrete has a long history which stretches back thousands of years, and first came into use in the agrarian sociometabolic regime. It was not until the industrial regime however, where it took dominance as the most used building material on earth. The following sections trace the material throughout its history in the agrarian and industrial socioeconomic regimes, with a view of understanding how the use and production of the material changed with each transformation of society. This review aims at foregrounding the findings of this thesis, which aims to understand how the CE approach can be better leveraged to ameliorate the environmental impacts of concrete production in such a way that can pave a way for its place in the next, more stable sociometabolic regime.

2.2.1 Concrete in the Agrarian Regime

The origins of concrete production are uncertain due to evolving composition and techniques. Around 7000 BCE, houses in Jericho had floors made of lime plaster. Stone Age Syrians discovered a glue-like substance near their cooking hearths, which had strong binding properties and solidified into a stable material. In Lepenski Vir, Serbia, concrete floors dating back to 5600 BCE were found. Concrete use is also evident in ancient China, Egypt, and Greece between 3000 and 600 BCE. Concrete making techniques were advanced significantly by the Romans. They had access to abundant resources and used pozzolana cement, made from volcanic ash, to create strong and durable concrete. Roman concrete was utilised in various structures, including buildings, bridges, and harbours.

In the agrarian sociometabolic regime, the production process gone through to produce concrete was fuelled by biomass, in a so-called "organic economy". In an organic economy, material and energy needs are largely met with products derived from biomass (Wrigley, 2010, p.9). Before the industrial revolution, concrete production processes, particularly the calcination stage, where calcium carbonate and clay or ash are heated to high temperatures, took place in wood or charcoal-fired kilns (Cook, 2021). Data on the physical stocks of concrete accumulated by agrarian societies does not exist, as even estimates on total material stocks are difficult to make (Haberl et al., 2017). What is known, however, is that per capita physical stocks were not large, at least compared to the succeeding industrial regime: material stocks for agrarian regimes stood at under 10 tons per capita, while in the current industrial regime they range from around 100 - 1000 (ibid.)

2.2.2 Concrete in the Industrial Regime

In around the 13th Century, the British began to produce lime outside of the organic economy (Cook, 2021). The British Isles were rich in limestone and coal, and when used in conjunction, the lime, and by extension concrete industries were afforded the ability to expand, exponentially, as long as stock of both last (ibid.). This transition in how concrete was produced, the bringing together of two types of fossilised resources, allowed for British cities to overcome environmental limits to growth, as there was no longer a need to depend on biomass in the form of firewood for the energy required in the production of concrete.

Concrete began to be widely used in British construction in the late 18th Century. An act came into place in 1774 prohibiting the use of exposed timber on buildings to limit the number of fires in the city (Wilkie, 2019). This led to a period of experimentation with cement and concrete manufacturing, and caused construction with the material to become much more widespread (ibid.). In 1828 the form of cement which dominates use today, Portland Cement, was first made and patented by English bricklayer Joseph Aspdin (Waters & Zalasiewicz, 2018, p.76). It was composed of limestone and clay, and over time also began to incorporate tricalcium silicate, which improved the mix's strength and water resistance (ibid.). As concrete manufacturing entered the industrial economy, technological innovation and inventions came one after another, with the invention of breezeblocks, and crucially, reinforced concrete.

Reinforced concrete is concrete which has steel reinforcing bars (also referred to as rebars) embedded to improve it's tensile strength. This solves the only characterstic of concrete which until this point was found wanting: its low tensile strength, which poses an issue when it comes to building very tall structures, like skyscrapers. The addition of twisted steel bars within the body of the concrete hugely improves its tensile strength and has allowed for many of the world's great cities to fill their skylines with concrete towers (Cook, 2021). Reinfoced concrete was developed in France in the latter half of the 19th century by French horticulturist Joseph Monier, who, while building plant pots and tubs, experimented by adding steel mesh iron rods and chicken wire to his concrete mixes as a form of reinforcement (Moussard et al., 2018). Along with Monier's initial attempts to combine metal and concrete to form a stronger material came many others, with patents being registered for specific products such as floor panels, boats and troughs, among others (ibid.). In the late 1800s, architects and engineers began using reinforced concrete for larger structural elements for bridges, buildings and other structures.

Although modern reinforced concrete is much stronger material than earlier forms of concrete, there are several complications which arise with the addition of steel to concrete structures. Firstly, adding steel to concrete can impact the longevity of the material (Mehta, 2001). When concrete cracks and the internal steel rebars are exposed, they begin to rust and expand, which leads to the formation of yet more cracks (ibid.) This effect, known as "concrete spalling" or "concrete cancer" leads to modern-day concrete structures having far shorter lifespans than many examples from the agrarian industrial which are still standing today (Cook, 2021).

2.2.2.1 The Success of Concrete in the Industrial Sociometabolic Regime

There are several reasons why concrete has achieved dominance in the industrial sociometabolic regime. Overall these can be divided into three categories. Firstly, there are its physical properties. Concrete is strong and durable; it is resistant to fire and adverse weather conditions; it is highly flexible: it can be moulded into any shape or design. Next come questions of economics and practicality. The raw materials used to produce concrete are abundant in most parts of the world. Calcium carbonate can be found in many types of sedimentary rock, including limestone, chalk and some forms of marble (Cook, 2021). Failing that, marine sediment is also rich in calcium carbonate can be used instead (ibid.). Aggregate in the form of rocks and sand are also for the most part plentiful, despite recent worries that we are running out of sand (Vaughan, 2022). The fossil energy used to produce concrete is also cheap, and abundant. This all means that concrete is cheap. Finally, an overarching, sociological perspective can be taken when considering the success of concrete. Concrete has, in many ways, paved the way for modernity, and allowed for a very successful human control of nature.

Physical Properties

Concrete is strong (Arum & Olotuah, 2006). It is, when made properly, long-lasting (ibid.). Its physical properties mean that architects and engineers can transform the material into previously impossible structures, stretching high up in the sky or taking on all varieties of shapes. Sources ranging from engineering manuals to concrete industry literature to works describing the history of the construction material agree that its strength, resistance to adverse weather and fire and versatility make it an exemplary material with which to construct buildings and infrastructure. One source written in 1877 around the time when concrete was taking off as *the* modern construction material, proclaims:

There is nothing can be so easily and economically moulded into any shape or form for architectural purposes without distortion, and that will bear exposure to the vicissitudes of our own or any other climate; and there is no other material that can be applied to so many various requirements in building with such satisfactory results. (Potter, 2014, p.5).

The physical properties of concrete do indeed set it apart from many other building materials, and this is what in many cases makes it the material choice for most modern-day construction. This alone however was not enough to propel its use to today's epic proportions. We know that even in the agrarian regime there was knowledge of the calcination process, and the hard, rock-like substance it produced. In order to become the second most used substance in the world, it had to be cheap and easy to produce.

Economic factors

Environmental historian Travis Cook explains that it is the combination of its physical properties and its relative cheapness which allowed for concrete to become "primary material used to transform the possibilities of human geography" (2021). Engineering manuals for concrete construction also highlight this important benefit, stating that concrete is economical (Surayo, 2019, p.4; Kind-Barkauskas et al, 2013; Cardarelli, 2019, p. 1422). Grey literature from the cement industry also highlights this main attraction, with Concrete Europe, an umbrella organisation representing the concrete industry stating that concrete offers unparalleled value-for-money and affordability (Concrete Europe, n.d).

Dominion over Nature

In many ways, concrete has been the main material used to control nature in the industrial sociometabolic regime. Wilson (2015) states that concrete: " allowed us to recreate natural landscapes into human constructed systems based on large scale infrastructure". Cook puts forward the idea that concrete has allowed us to surpass natural bounds imposed by nature (2021). The idea here is that many of the natural phenomena which humans would naturally fall victim to have been stopped in a major way with this material. These range all the way from flooding, as concrete seawalls hold back the sea; to disease, as concrete sanitation infrastructure allows us to live in densely populated urban centres without fear of regular outbreaks of disease (ibid). As Adrian Forty writes in his book Concrete and Culture, nature is "reworked" by concrete (Forty, 2013 p.59). He describes examples of massive hydraulic projects such as the Hoover Dam in the United States, road networks such as the German autobahn are examples of urban "incursions" into nature (ibid., p.63). Figure 2-3 shows Kasusabe's Metropolitan Area Outer Underground Discharge Channel, located around 30km from Tokyo (Japan National Tourism Organisation, n.d). This is the world's largest underground discharge tunnel, capable of discharging around 180 tonnes of water a second from Tokyo's watershed towards the Edogawa River, keeping the city streets free from flooding (Hall, 2012). Structures such as these exist all over the world and are examples of the concrete infrastructure emblematic of the industrial sociometabolic regime. Infrastructure such as this allows human populations to grow in urban enclaves, protected from previous limits put in place by nature.

Figure 2-2: Metropolitan Area Outer Underground Discharge Channel. Kasukabe, Japan.

Source: (dddeco, Wikimedia Commons, 2007)

2.3 Environmental Impacts of Concrete Production

Currently there are many different environmental impacts associated with concrete, chief among them being the greenhouse gas emissions which are released during its production. The concrete industry accounts for 8% of global greenhouse gas emissions (Habert et al., 2020; Lehne & Preston, 2018). The vast majority of these emissions, around 77%, come from the production of concrete's principal ingredient: cement (Busch et al, 2022). For every tonne of cement produced, 561-622 kg of carbon dioxide is emitted into the atmosphere (Fennell et al., 2021). Cement's high carbon footprint can be largely attributed to the calcination process, whereby calcium carbonate, usually in the form of limestone, as well as small quantities of other materials including clay, are heated to temperatures of around 1500 degrees Celsius. A chemical reaction then takes place whereby calcium carbonate ($CaCO3$) transforms into calcium oxide, also known as lime, and carbon dioxide, which is released into the atmosphere (Cook, 2021, p.11). The lime then reacts with the other ingredients in the kiln and forms clinker (CEMBUREAU, n.d). The clinker is then cooled to around 100–200 degrees, ground together with small quantities of gypsum to produce a very fine powder, which is the final product: Ordinary Portland Cement (OPC) (ibid.). An estimated 55% of the Co2 emissions from cement production come from carbonate decomposition, when carbon dioxide is released as a by-product of the chemical reaction which occurs when limestone is heated to high temperatures (Busch et al, 2022). The remaining emissions come from the fossil fuel combustion which takes place to heat the materials to such temperatures, which makes up around 31% of total emissions (ibid.). The final 14% comes from electricity usage in the production process (ibid.).

Other environmental issues linked to concrete production include high levels of water use and pollution. In the case of water use, a 2018 study by Miller et al. found that in 2012, 9% of global industrial withdrawals, and 1.7% of total water withdrawal were used in concrete production. They further concluded that by 2050 75% of water demand for concrete will be felt in water-stressed regions (Miller et al. 2018). Pollution is also a concerning, although less studied, environmental impact of concrete production. Research has found that concrete production and use has led to the leaching of pollutants, such as hydrocarbons and heavy metals, from slurry produced as a by-product during production as well as demolished concrete material into waterways (Glavind, 2009).

Modern-day reinforced steel has it's own set of extra negative environmental implications associated with its production and use. The added steel in the material adds to the embodied carbon of the material (Purnell, 2013), and makes recycling the material more complicated, as steel components need to be separated from the surrounding concrete (Gorgolewski et al, 2006).

These factors all point to the fact that there are significant sustainability issues related to the production, use and disposal of concrete, which relate to broader issues associated with material and energy usage in the industrial sociometabolic regime. It is vital that steps are taken to address these issues. One of the dominant policy approaches being put forward to do so currently in the EU is that of the Circular Economy.

2.4 The Circular Economy: Concept and Limitations

The Circular Economy aims to replace current systems of production with processes which reduce, reuse, recycle and recover materials, thus turning a linear "take-make-dispose" system into a circular one (Merli et al., 2018). The CE itself is difficult to define in concrete terms, owing to the fact that there exist a huge variety of different understandings of the term (Kirchherr et al., 2017). Many scholars have remarked that the circular economy concept is rife with ambiguity, that no clear vision or definitions exist of it. That it, at best, should be treated as an "umbrella term " (Blomsma & Brenna, 2017), or a "floating signifier" (Swyngedouw & Wilson, 2014). This lack of clarity has been criticised, for several reasons, among them for the fact that it turns the concept into something which can be "depoliticised", as it does not allow for the encompassing of any radical aims. a less defined concept which is more palatable to the current power structures in our system, as the concept is not defined by any promulgations of real systemic change (Berry et al., 2022).

Apparent from critiques aimed at the theoretical basis for the CE approach, research has also highlighted several barriers for the uptake of circular strategies by industry and businesses, related to practicality and technical feasibility. Practical barriers include, among others: the high costs associated with actors transitioning to circularity; lack of knowledge and technical skills and added complexity to supply chains (Jaeger & Upadhyay, 2020). Technical limits pointed out in the literature often revolve around the implications of the second law of theromodynamics: entropy. Research explains that complete cycling of materials through the economic system is impossible, as circular processes themselves require energy and resources, generate waste, and produce side-products (Korhonen et al., 2018).

2.4.1 The Circular Approach for the Concrete Sector

As highlighted by the United Nation's twelfth Sustainable Development Goal pertaining to responsible production and consumption, there is currently a global need to address our patterns of natural resource use and waste production (A/RES/70/1). The world's total material footprint is increasing every year (UN Environment, n.d). The amount of waste being generated is also escalating and is expected to increase by 70% by 2050 (Kaza et al., 2018). The environmental impacts associated with unsustainable consumption and disposal are difficult to understate, which is why there are ongoing efforts around the world, and in the European Union (EU) in particular, to transition away from linear forms of production and consumption in favour of systems built around circularity.

The European Union's current strategy for tackling pressing environmental problems is grounded in the EU Green Deal, an action plan launched in 2019, which puts forward multiple policies which aim to help the Union transition to a carbon-neutral, circular economy which restores and protects biodiversity and limits pollution (Nugent et al., 2022). A central part of this EU Green Deal is the Circular Economy Action Plan (CEAP). Presented in March 2020, the CEAP puts forward a series of legislative and non-legislative actions which aim to achieve the following four core aims: to create more sustainable products; empower customers; prolong product lifetimes and finally minimise waste (WBCSD, 2020). The CEAP identifies 35 actions corresponding to the different goals put forward in the action plan, along with dates by which these actions must be carried out (Annex, COM(2020) 98 final). These actions are grouped into 7 sections: A Sustainable Product Policy Framework; Key Product Value Chains; Less Waste, More Value; Making the Circular Economy Work for People, Regions and Cities; Crosscutting actions; Leading Efforts at a Global Level and Monitoring the Progress. The CEAP contains sections which focus on specific resource intensive industries, one of which is the construction industry. The section states that a Strategy for a Sustainable Built Environment will be launched, as well as a "Renovation Wave" initiative, which aims to promote the widespread renovation of public and private buildings throughout the EU to increase the energy efficiency of the built environment. The action plan also highlights that the Commission will consider revising targets for material recovery for construction and demolition waste (ibid).

Despite the European Commission committing to releasing a sustainable built environment strategy which falls in line with Circular Economy Action Plan in 2020 there has still been no such policy released. In March 2021, a year after the commitment was made, an open letter signed by 30 signatories including the Climate Action Network, Local Governments for Sustainability and the European Environmental Bureau, urging for the strategy to be released (MIO-ECSDE, 2021). As of mid-2023, the strategy has still not been published, though the Commission outlines that it is expected to "promote circular economy principles for buildings design and the development of digital logbooks for buildings" (Ragonnaud, 2023).

Although there is not yet any EU-level legislation or actions related to reuse and recovery of concrete products, there is a growing interest in the potential of reusing concrete by academia and amongst think-tanks and policymakers. This is reflected in recent academic literature exploring the feasibility of introducing circularity into concrete construction (Küpfer et al., 2023). Generally it is concluded that of all the circular strategies for dealing with materials at their end-of-life, reuse of concrete elements would offer the most environmental benefit, due to their large overall contribution to a building's embodied energy (ibid). The Ellen MacArthur Foundation, a network of private and public actors working to transition to a circular economy also champions the cause of reuse when it comes to concrete, putting forward the argument that apart from making better use of existing buildings by using them for longer, reuse and recycling need to be promoted as the go-to solutions before demolishing for landfill (Ellen MacArthur Foundation, 2021). Other organisations such as Metabolic, another member-based organisation which purportedly uses systems-thinking to tackle sustainability issues, have been steady proponents of introducing circularity into the built environment, working to publish a report which identifies the obstacles and opportunities for achieving this transition (Streefland, 2022).

Apart from actual policies, EU funded projects have in recent years explored ways to add circularity to the construction and demolition sector in general, and in the case of concrete. The EU Horizon 2020 project ReCreate, for example, has been funded 12.5 million euros over four years, with the aim of understanding how to reuse concrete elements in new buildings, and "turn the process into a profitable business" (ReCreate, n.d). Another Horizon 2020 project, VEEP, investigates discovering technological solutions to building refurbishment and recladding, using majority recycled construction and demolition waste. The project also aims to research and develop business models for upcycling concrete waste (VEEP, n.d).

2.5 Circularity Strategies for Concrete

There are various circular strategies that can be introduced to the concrete sector to assist with material cycling and the use of secondary materials. The main strategies are described in this section.

Recycling

Recycled concrete is a more sustainably alternative traditional concrete. It involves crushing and processing old concrete structures and using the resulting material as aggregate to replace natural aggregates in new concrete production. By recycling concrete, we reduce the need for extracting and processing virgin materials, such as gravel and sand, which helps conserve natural resources and minimize environmental impact. One Life Cycle Assessment found that if all the co-products, such as steel scrap, are considered in the lifecycle of recycled concrete, then the environmental impacts of concrete can be reduced by up to 70% (Knoeri et al., 2013). The same study found however that the Global Warming Potential of recycled concrete is comparable to conventional concrete. It is suggested that this is due to that the environmental benefits associated with recycling being outweighed by the fact that, when using recycled aggregate, more cement needs to be used in the concrete mix to compensate for decreased structural strength associated with the use of recycled aggregate (ibid.). This is particularly the case when there are long transport distances for recovered concrete (ibid.).

Reuse of Elements

Reusing concrete elements in buildings is another method of sustainable construction. Instead of demolishing entire concrete structures, certain elements like walls, beams, and columns can be salvaged and repurposed (Devènes et al, 2022). This approach not only reduces construction waste but also saves energy and resources required for producing new materials (Salama, 2017). Reusing concrete elements often involves careful dismantling and assessing the structural integrity of the salvaged components (Küpfer, 2022). These elements can then be integrated into new building projects, providing a unique aesthetic, and preserving the character of the original structure (Devènes et al., 2022).

Repurposing Buildings

Repurposing concrete buildings offers an innovative way to give new life to existing structures. Rather than tearing down concrete buildings, repurposing involves adapting and transforming them to serve different functions or accommodate changing needs (Foster, 2020). This leads to an overall decrease in energy consumption, material usage and waste production (Assefa & Ambler, 2017). Repurposed concrete buildings can be converted into various facilities such as offices, residential spaces, cultural centres, or recreational areas, breathing new life into urban environments while minimizing waste and environmental impact (Misirlisoy & Günçe, 2016).

2.6 Research Gap

There is limited available literature which comprehensively overviews the barriers associated with implementing circular strategies in the concrete industry. A particularly overlooked potential barrier which has not been sufficiently researched is the consideration of in-use stocks, as well as what inherent qualities of concrete affect the industry's motivation for introducing circularity measures. The use and production of concrete in the industrial sociometabolic regime has several characteristics that contribute to its success and wide-scale adoption, and these characteristics may be able to provide insights into the feasibility of this sector transitioning to a Circular Economy.

Much of the existing research which reviews barriers to CE implementation in general primarily focuses on addressing technical barriers and proposing short-term policy recommendations to promote circularity, often through market-based mechanisms (Dolinsky & Maier, 2015). This research aims to assist in overcome obstacles and facilitate the adoption of circular solutions by suggesting incremental changes which comply with existing societal and economic structures, without delving into the underlying systemic issues. Recognising this research gap, this thesis attempts to critically examine the circularity concept using the sociometabolic regime framework in a way that can produce suggestions on wide-reaching changes necessary for a more stable regime of human-nature relationships to be achieved.

Finally, this thesis also attempts to fill the gap presented by the fact that in existing research there is a lack of literature which explores the sociometabolic implications of barriers to implementing circular economy strategies. Literature which currently uses the lens of sociometabolic regimes to comment on the limitations of the CE approach often rely on quantitative data related to material flows and stocks and do not use qualitative data on why various sectors are reticent to transition away from a linear economy. By combining these approaches, it is hoped that more thorough understanding of the sociometabolic implications of limits to CE approach can be identified, as well as ways to further develop the CE approach in a way which can lead to absolute reductions in material and energy use.

3 Research design and Methodology

This thesis deployed a mixed methods approach, collecting and analysing both qualitative and quantitative data. This approach was chosen largely due to the theoretical framework which underpins this research, sociometabolic regime theory. Research on sociometabolic regimes, and in the wider field of ecological economics relies heavily on the use of data on material stocks, population, and energy use in order to make wider conclusions about the metabolic profiles of different societies (Pauliuk and Hertwich, 2015). A gap which was revealed in the literature review, however, was that research on transitions in sociometabolic regimes often neglects qualitative data on barriers for transformation. So far, research in the concept largely focuses on observing patterns of material and energy use in the three sociometabolic regimes and is not employed as a tool to analyse the effectiveness of sustainability attempts. Therefore, for this thesis, a highly simplified version of more typical analysis of stocks is performed to understand the barriers involved in introducing circularity to the concrete sector. In addition, however, qualitative data from interviews will also be used to understand what barriers exist. These findings will be analysed in the context of literature on sustainability in sociometabolic regimes. That is, barriers identified will be discussed in relation to sociometabolic regime literature on regime transformations.

3.1 Quantitative Methods

The first phase of research into the barriers of the concrete industry transitioning to a CE involved collating publicly available data on global in-use stocks of concrete and production of concrete to understand the trends in production and stock accumulation in recent history. Ultimately a simple calculation was made to determine the extent to which current stocks could be used to meet demand for new concrete.

3.1.1 Methods used to collect data

To produce an estimate of the extent to which global in-use stocks of concrete could meet current demand, a literature review of both academic literature and grey literature (including industry reports) was conducted to collect data pertaining to in-use stocks of concrete; current concrete use; projected future demand of concrete. Academic literature containing this data were obtained using the academic search engine Google Scholar. Grey literature, including industry reports as well as government documents were found using the Google search engine.

Search-terms used for gathering data on production were: “concrete production statistics” and “concrete production data”. These were used on the Google search engine. This was found to yield limited results, and therefore the search terms “cement production data and “cement production statistics” were used instead, as this was found to recover more data. The US Geological Survey’s annually published Mineral Commodities Summaries and Minerals Yearbook were determined as being high-quality, trustworthy sources of data, and so were the main sources of information for this dataset.

To gather data on in-use stocks of concrete the search terms “in-use concrete stock” and “in-use cement stock” were used to search for data using the Google Scholar search engine, which was determined to be a more appropriate search engine due to the fact that “in-use stock” is a technical term used in the field of industrial ecology, and thus academic literature was expected to contain more data than non-academic literature.

3.1.2 Materials Collected

In-use stocks

During the data collection stage, it was found that there are relatively few academic, industry or government attempts to quantify in-use stocks, at any scale. In fact, only five sources estimating in-use concrete or cement stocks were identified. Both concrete and cement estimates were included to allow for more data to be collected as both types of data were useable given the fact that a simple calculation can be made to derive a figure for estimated concrete stock given the value of in-use cement, as concrete is generally composed of 10-15% cement, by weight (Portland Cement Association, n.d a). Of these five identified sources of data, only two were eventually used in the subsequent calculation stages as main estimates for in use as the geographic scope of the remaining three studies was determined to be too limited. Two were conducted on a country level, and the remaining study estimated in-use stocks in one city.

Data on global concrete in-use stocks were based on figures obtained from a 2017 article by Fridolin Krausmann and colleagues entitled: "Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use", which provides estimations of various material stocks from 1900 to 2010.

Concrete production

Data on concrete production was obtained primarily from the United States Geological Survey's (USGS) annual Mineral Commodity Surveys and Minerals Yearbook on cement. Again, data on cement was included due to the simple conversion which takes place to determine the amount of concrete produced. In this case, a standard conversion factor of 12.5% was used to determine the amount of concrete being produced annually. This figure is rounded down to the nearest billion to account for uses of cement other than concrete, for example masonry mortar and grout, leaving the final figure for global concrete production for a given year.

Regional data corresponding to the same regions in the above-mentioned Cao et al. paper estimating regional in-use stocks were also obtained by combining the production data from the USGS country specific data to form the regions as laid-out by Cao and colleagues (2017).

3.1.3 Methods used to process and analyse data

Data on global in-use stocks and concrete production were first used to make a simple calculation about the amount of secondary available could potentially be made available for primary material replacement in concrete production.

The first step taken to be able to compare the figures for total in-stock concrete and demand was to perform necessary conversions so that both in-stock and production figures were expressed as metric tons. This involved converting both converting between various measures of weight such as petatons, as well as converting figures denoting the volume of concrete to weight. Finally, many of the data collected on both in-use stocks and production were on cement, not concrete. These figures were converted to corresponding estimates of weight of concrete, based on the knowledge that in general concrete contains between 10-15% cement (Caltrans, 2013). This conversion was undertaken with the following calculation:

$$C = \left(\frac{\alpha}{12.5}\right) * 100$$

Where: $C =$ weight of concrete

$\alpha =$ weight of cement

12.5= figure representing average proportion of cement in concrete

Once the data was homogenised, the in-use stocks were compared to yearly production and the number of years in-use stocks can satisfy current global demand can be calculated by dividing production by stock. This allowed for the determination of the extent to which reuse or recycling would be a feasible way to bring down the need for new production.

Apart from this rudimentary analysis of global stock potential for the circular economy, sociometabolic regime literature on in-use stocks and their relation to sustainability transitions in general and the Circular Economy was used to make further comments on any potential barriers which presented by the data.

3.2 Qualitative Methods

The next stage of research involved carrying out interviews with practitioners and academic experts with intention of gathering data in the form of expert-opinions and reflections on professional experience on the driving factors of the success of concrete, barriers for concretes transition to a CE and finally factors which would need to change for the CE approach in the concrete sector to be more effective at bringing down material and energy use.

Interviews were then coded thematically and the implications of the findings were analysed using literature on the framework of sociometabolic regimes.

3.2.1 Methods used to collect data

Three groups of interviewees were interviewed in this phase of the research: practitioners from the concrete industry; practitioners working in the field of construction/architecture and academic experts on building circularity, particularly those who have been involved in research on concrete (See List of Interviewees in Appendix A). These groups were chosen because they were thought to be able to comment on the feasibility of transitioning to a Circular Economy in the concrete sector from different perspectives, and comment on a range of issues in terms of practical issues and technical feasibility of circularity in the sector.

Questions were prepared in a way which encouraged interviewees to use their knowledge and experiences related to their work to divulge insights on the feasibility of circularity in the concrete industry and the barriers involved in transitioning to a Circular Economy in this sector (See Interview Guide in Appendix B) . Additionally, interviewees were asked to comment on what they believed would need to change for circularity to be more widely adopted. Finally, the characteristics of concrete which allowed for the material to become successful were discussed, to determine whether any of these characteristics posed an innate challenge to achieving circularity.

The interviews were all conducted via Zoom and lasted for around half an hour. Interviews were recorded and transcribed first using the online transcription tool Otter.ai, and then checked by the researcher by comparing the transcript to the original recording.

3.2.2 Methods used to analyse data

Interview transcripts were thematically analysed using an abductive approach based on Jamie Thompson's proposed eight step process for abductive coding (2022). After the first transcription phase, interviews were coded. Coding refers to the categorisation of data into groups which share similar characteristics. Coding was conducted twice, as recommended by Thompson's guide. Next, themes were developed for the classification of codes. The choice of themes for this analysis was heavily influenced by the research aim, as there was a need to gather data on insights participants had on the concrete sectors transition to a circular economy. The following themes were established for analysis, based on the codes: Barriers; Changes Needed; Feasibility of Transition and finally Reasons for Concrete Success as Building Material.

To determine implications of the findings which arose from the thematic analysis stage, results were analysed using literature pertaining to sociometabolic regimes, particularly sources addressing sustainability transitions. Some supplementary literature further exploring the themes uncovered by this investigation was also used to provide more depth to the analysis.

4 Findings

The following section presents the findings from this research. Firstly, the results of the investigation into the physical feasibility of utilising secondary concrete to meet current demand will be presented. Next data from interviews will be explained, including findings on factors which contribute to the success of concrete; barriers for introducing circularity and interviewees general opinions on the feasibility of the concrete industry transitioning to a Circular Economy.

4.1 A Concrete Production and In-use Stocks Perspective on the Feasibility of Circularity

In this section the findings from an investigation into current global production of concrete, as well as global and EU in-use stocks of concrete are presented. The extent to which stocks could potentially satisfy demand is commented on, based on this data.

4.1.1 Production

Spurred on by urbanisation and population growth, concrete production rapidly increased in the 21st century, with an average yearly growth rate of 5%. From the year 2000 until 2022, the world saw concrete production increase by 147% (see Figure 4-1), from an estimated 10.8 billion to around 30.4 billion tonnes (for tabulated data on production, see Appendix C). China is the world's largest producer of the material, manufacturing an estimated 15.1 billion tonnes in 2022, accounting for just over half of the total global production for that year (USGS, 2022).

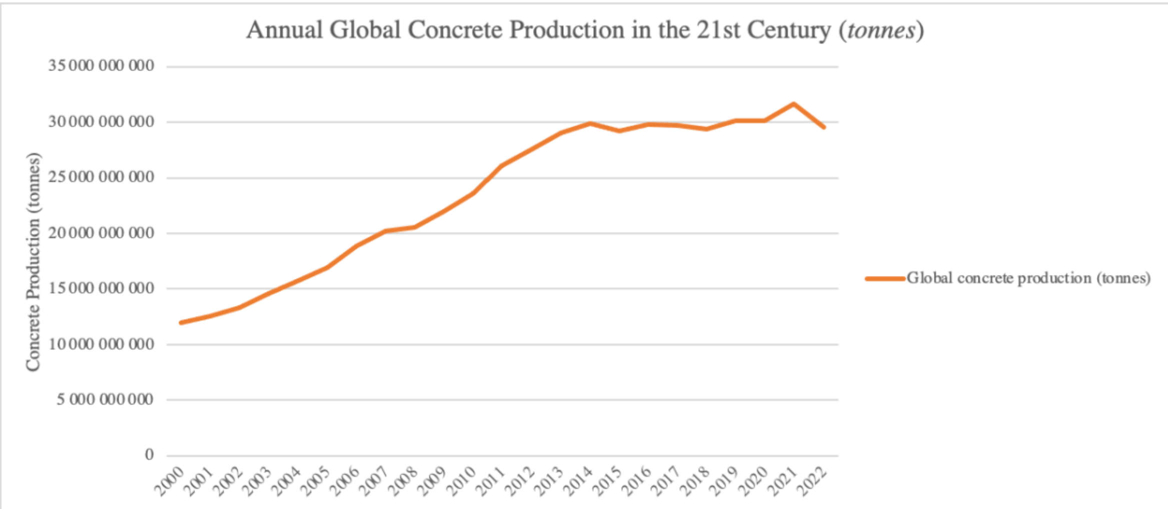

Figure 4-1: Annual Global Concrete Production in the 21st Century

Source: (USGS 1999b; USGS 2000b, USGS 2001b; USGS 2002b; USGS 2003b; USGS 2004b; USGS 2005b; USGS 2006b; USGS 2007b; USGS 2008b; USGS 2009b; USGS 2010b; USGS 2011b; USGS 2012b; USGS 2013b; USGS 2014b; USGS 2015b; USGS 2016b; USGS 2017b; USGS 2018b; USGS 2019b; USGS 2020b; USGS 2023).

4.1.2 In-use stock

In industrial ecology, the concept of in-use stocks is used to understand the physical capital supply available in the entire anthroposphere (Pauliuk, 2017). Data on global in-use stocks of specific materials is patchy and difficult to obtain, and this is no different when it comes to concrete. The best available information comes from a Krausmann et al. study on global socioeconomic material stocks. From this study it is possible to data on estimated global in-use stocks from 1900 to 2010. This dataset shows us that, logically, as global production of concrete has increased and concrete structures are added to the built environment, stocks of in-use concrete have expanded correspondingly.

Between the years 1900 and 2000, a total of 313 billion tonnes of concrete have been added to the global in-use stock. The global in-use stock has expanded by an estimated average of 4.6% per year. When compared to recent production figures, we can see that while in the year 2010 there was already a substantial stock of concrete in the anthroposphere, the pace of production has meant that any attempt to rely on this stock for secondary materials would mean that demand would only be met for a very short period. Despite not having data on in-use stocks after the year 2010, it is clear that stocks have continued to increase. In the ten-year period between 2010 and 2020, roughly 314 billion tonnes of concrete were produced. As already stated, the in-use stock in 2010 was 213 billion tonnes. This means that in just ten years, more concrete was produced than added into the anthroposphere in the 110 years between 1900-2010.

To understand how much production demand could be met with secondary materials from the current concrete stock, an average stock addition rate was calculated, by using the percentage increase in stock tonnage from the years 2000-2010, which yielded a figure of 4.6%. The projected concrete stock figures from 2011-2022 were compared with production from those years to see how many years demand could be met (results shown in Table 4-1). If we assume ideal-world conditions where all available stock would be available and appropriate for reuse and recycling and that there would be no thermodynamic losses in the process, the projected stock could meet the average annual production demand of concrete in the last ten years, which is around 29.3 billion tonnes, for around 18.8 years.

Table 4-1: Table showing global in-use concrete stocks, global concrete production and the number of years stock can meet global demand for concrete production. (Numbers in red are based on projects calculated by the author, and do not come from literature.)

Year	In-use stock of concrete (tonnes)	New stock addition rate	Annual global production of concrete (tonnes)	Number of years stock can meet demand
2000	196 990 976 000	-	11 952 000 000	16.5
2001	204 987 152 000	4%	12 528 000 000	16.4
2002	213 525 984 000	4%	13 320 000 000	16.0
2003	223 054 368 000	4%	14 616 000 000	15.3
2004	233 518 352 000	5%	15 768 000 000	14.8

2005	244 857 424 000	5%	16 920 000 000	14.5
2006	257 782 208 000	5%	18 864 000 000	13.7
2007	271 751 616 000	5%	20 232 000 000	13.4
2008	285 815 808 000	5%	20 520 000 000	13.9
2009	300 970 752 000	5%	21 960 000 000	13.7
2010	315 843 904 000	5%	23 616 000 000	13.4
2011	**330 878 073 830**	**4.76%**	26 136 000 000	**12.7**
2012	**346 627 870 145**	**4.76%**	27 504 000 000	**12.6**
2013	**363 127 356 764**	**4.76%**	29 016 000 000	**12.5**
2014	**380 412 218 946**	**4.76%**	29 880 000 000	**12.7**
2015	**398 519 840 567**	**4.76%**	29 232 000 000	**13.6**
2016	**417 489 384 978**	**4.76%**	29 808 000 000	**14.0**
2017	**437 361 879 703**	**4.76%**	29 736 000 000	**14.7**
2018	**458 180 305 177**	**4.76%**	29 376 000 000	**15.6**
2019	**479 989 687 704**	**4.76%**	30 168 000 000	**15.9**
2020	**502 837 196 838**	**4.76%**	30 168 000 000	**16.7**
2021	**526 772 247 408**	**4.76%**	31 680 000 000	**16.6**
2022	**551 846 606 384**	**4.76%**	29 520 000 000	**18.7**

Sources: In-use stock data: (Krausmann et al., 2017) Production data: (USGS 1999b; USGS 2000b, USGS 2001b; USGS 2002b; USGS 2003b; USGS 2004b; USGS 2005b; USGS 2006b; USGS 2007b; USGS 2008b; USGS 2009b; USGS 2010b; USGS 2011b; USGS 2012b; USGS 2013b; USGS 2014b; USGS 2015b; USGS 2016b; USGS 2017b; USGS 2018b; USGS 2019b; USGS 2020b; USGS 2023).

This figure is of course limited in value as: first of all, in-stock values after the year 2010 are roughly estimated, and not based on in-depth calculations. However, even if we calculate how many years the 2010 stocks could be used to compensate for 2010 production, we see that they would last 13 years, which is also a fairly limited amount of time (See Table 4-1). Secondly, and more importantly, it is unreasonable to assume that all concrete would be available and appropriate for reason, due to the relatively long lifetime of concrete structures. Regardless, what we can gather from this is that, despite the fact that we have accumulated a vast amount of concrete in global stocks over the past 100 years or so, our demand for concrete in the industrial socio-metabolic regime would mean that circularity could not satisfy production needs. In fact, this is assuming that demand would stay the same. While it would appear that since around 2013 global demand is stabilising at around 30 billion tons a year, it is expected that as populations increase in more countries and regions around the world, and rates of urbanisation continue to rise, demand for building materials will grow. For example, according to the World Green Building Council, Africa's population is set to increase by an estimated 1.1 billion by 2050 (WGBC, 2022). 80 percent of the buildings required to meet the needs of this expanded population have not been built yet. Globally, total building floor area is projected to grow by 20% by 2030 (Delmastro, 2022). These projections would suggest that overall production of concrete will also increase, as there is little evidence to suggest that more economically developed countries with already high concrete use rates will use less to make up for an upsurge of usage in countries which are yet to substantially expand building stocks.

Regional Stocks

There are significant variations in the amount of in-use concrete stocks in various regions around the world, although not much research has been done to estimate the amounts present. To date, one study by Cao et al., produced per capita in-use stock estimates for 10 regions for the year 2015. Although cement is only a component of concrete, it is reasonable to assume that these estimates can give a picture of what regional variations exist (see Figure 4-2). The regions with the highest estimated amount of cement were the European Union, China and the Former Soviet Union. The least were India, Africa and "Other Asia", which is comprised of Asian countries apart from China and India.

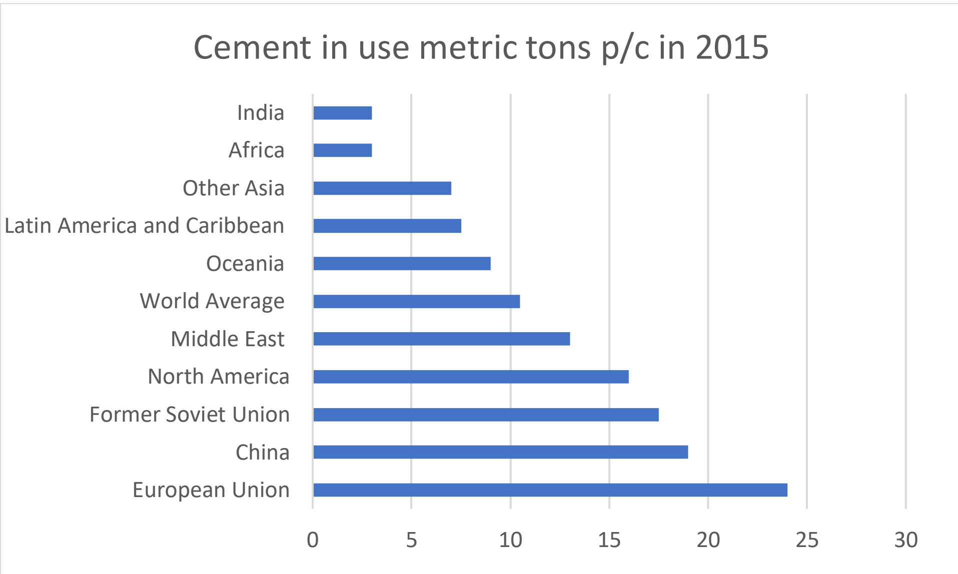

Figure 4-2: Per capita in-use cement stocks of 10 regions

Source: Cao et al., 2017

4.2 Factors Contributing to Concrete Success

In general, interviewees cited two main groups of reasons for concrete being a widely-used construction material: it's physical properties, and the fact that it is cheap.

Every person interviewed was quick to admit that concrete was a physically exemplary material, suitable for building strong, safe and long-lasting structures. As Concrete Industry 2 put it:

> *it's well-suited to sustain all the different requirements that you have on the structures in both buildings, and also infrastructure applications. And that relates to high durability in terms of moisture and all kinds of weather impact. And it's very amendable to different shapes. So, you can use it in many different ways; it's not restricted by geometry or behaviour.*

All the requirements for strong, safe durable housing which can keep fire and extreme weather at bay seem to be met with concrete. The safety offered by concrete was underlined by some interviewees, when explaining it as a material of choice. One concrete industry representative (Concrete Industry 3), used the following analogy to explain why we generally resort to concrete in building operations and are unlikely to move away from it:

> *There's a big debate at the moment, isn't there, about housing and wooden housing and yeah, okay: There's the story of the three little pigs, if you remember, from your childhood. The house built of straw and wood got blown over. And the house built of bricks defeated him in the end, like concrete would.*

The idea here being that no other material is up for the job of creating safe, durable housing that fulfils our needs. This interviewee went on to say: *"that's what's kept it going for so many years is that you know, there is no alternative."*

Of all the factors mentioned by interviewees, the cheapness of concrete was the most cited reason for its success. Interviewees pointed out that the materials were available "almost everywhere on earth" (Concrete Industry 2); and that concrete is a economical material for all countries, especially countries which do not have abundant access to other natural resources which can be used for construction, as Architect 1 explained: "*when a country does not have like access to steel or like wood, you know, concrete is very cheap in relation to anything else that this specific country could produce."*

4.3 Barriers

The interviewees discussed several barriers for transitioning to a more circular concrete sector (barriers are tabulated in Table 4-2). Apart from technical considerations such as quality issues when looking for aggregate suitable for recycling, or poured concrete not being suitable for reuse, participants highlighted several systemic issues which also play a role in preventing a move to more circular concrete production and consumption.

Table 4-2: Barriers for concrete industry transitioning to Circular Economy identified by interviewees

Interviewee	***Barriers Identified for circularity in concrete***
Concrete Industry 1	• It is extremely **difficult to make money** with recycled concrete because it is more expensive to produce than concrete made with virgin materials. • **Robust supply chains for good quality aggregate** have not been established. • Regulations limiting the amount of aggregate in recycled concrete that can be replaced with recycled aggregate are **too stringent.** • **Lack of well-developed demolition industry** that can reliably supply good quality recycled aggregate.

Concrete Industry 2	• Recycling is **not economically competitive.** • **Inflexible standards** for recycled aggregate replacement, which lead to the need for extra certification. Companies view this as an impractical hurdle.
Concrete Industry 3	• Need to **compensate for impurities** in recycled aggregates with more cement. • **Fragmented nature of demolition industry** means it is difficult to obtain good quality recycled aggregate. • **Downcycling** (crushing concrete and using as subbase) is the cheapest way to deal with demolition waste – this disincentivises "inner" circularity strategies.
Architect 1	• **Cost** of using more sustainable materials is higher than conventional ones.
Academic Expert 1	• **Difficult to assess the quality** of used concrete elements.
Academic Expert 2	• Difficult to make circularity common when the **market dictates** what choices producers and consumers make.
Academic Expert 3	• For reuse of concrete elements to become a reality, demolition companies need to **transition into becoming deconstruction** companies.
Academic Expert 4	• **Inflexible standards** on the amount of recycled aggregate can be used in producing recycled concrete.

Economically Uncompetitive

The idea that circularity strategies in the concrete sector was economically uncompetitive in today's economic system was put forward in five out of six of the interviews as being one of the main reasons why material cycling of concrete is not a common practice. As one interviewee put it "There's[...] still, I think, a sort of gap between the intentions and how the market is working. The market is so big, and it's driving everything. It's so difficult to make the market move a little bit in one direction or in another" (Academic Expert 2). The idea here being that the only way for real change to come about in our system would be if the change were seen to be economically profitable. Reuse and recycling are currently not considered activities which would add economic value to the sector and are therefore not pursued as much as if they were.

Interviewees from the concrete sector mainly discussed the barriers of recycling concrete, as this was the circularity strategy they worked with the most closely and had opinions on. All three of the concrete sector representatives interviewed cited economic barriers to increasing recycling in their sector. Respondents explained that using recycled aggregate made their concrete products more expensive to produce, and thus limited profits. One respondent (Concrete Industry 1) said on this: "it's very difficult to make any money in the recycling business. So, it is to a certain extent, *the* barrier, because you know, we, if there is no real business case, there, you will not get the full value or the quick development that you could get." Overall, several interviewees emphasised that the lack of business cases for recycling was because using new materials was cheaper than using recycled aggregates. With recycled aggregates, they explained, the added logistics involved in transporting recycled material from demolition sites to concrete manufacturing sites made the process much more expensive than using virgin materials.

This result confirms research done by the European Environment Agency on barriers and opportunities for circular economy strategies in the CDW, where in their report they concluded that the main obstacle for recycling concrete was the low cost of virgin aggregates and the high cost of waste processing (EEA, 2020). The report outlines that when buildings are demolished with the intention of recycling or reusing waste, more care needs to be taken with separating waste and identifying parts which can be used for recycling, or indeed for reuse. More time and expertise are needed than when a building is simply demolished and waste is sent to landfill (ibid.).

Quality

Three of the interviewees, two concrete sector (Concrete Industry 1 and 3, Academic Expert 1) representatives and one academic expert, mentioned quality as a major barrier to reuse and recycling for concrete. In terms of recycling, concrete sector representatives explained that recycled aggregate must be of a very high quality, with few impurities, in order to be used to create strong, safe concrete. The interviewees explained that high quality material was hard to come by as most demolished material is contaminated with other products. One explained (Concrete Industry 3) that due to the fact that recycled aggregates were lower quality than virgin materials, more cement had to be added to the mix to compensate for the impurities it contains.

Academic Expert 2 also touched on the topic of quality when it comes to the reuse of concrete elements. He explained that it is very difficult to understand when a concrete element can suitably be reused due to the fact that it's quality is unknown. He elaborated: "You can mix concrete every day and get very similar properties and so on. When you start to reuse elements, I mean, each of them is different, because they all have a different history. They were, you know, subjected to different conditions, they were carrying different loads, and so on. So each element becomes unique."

Transport

The issue of transport came up in four interviews, again with all three of concrete sector employees, as well as with an academic expert on circularity in building materials. Three instances where transport were mentioned was to give an example of why using recycled concrete to replace natural aggregate comes with higher costs – as a Concrete Industry 1 put it: "the transport of materials is expensive and so, you cannot travel very far. So, up to 30-40 kilometres around the place you recycle the materials but not much further".

Another reason transport was brought up as a barrier was to do with the environmental drawbacks of transporting heavy construction materials long distances. Interviewees explained that if recycled aggregate must be transported for a long distance from demolition sites to concrete production centres, environmental benefits of reusing material may be outweighed with carbon emission associated with the transportation. One interviewee explained that there is even a commonly accepted distance by which environmental impacts are reversed by long distance transport:

> *"I think there's this thing called the 15 mile rule. Which is it was a colloquialism, I guess, but if you have to move the material more than 15 miles to a recycling point, and recycle it and then ship it back to another point of sale, then the then the co2 output associated with those activities outweighs any benefit from the CO2."*

Regulations

Regulations on the amount of course or fine recycled aggregate that can be used to replace natural aggregate differs from country to country to a large degree. Portugal and Spain are examples of countries which have a low threshold for the amount of aggregate that can be replaced with recycled concrete, with a range of 20-25% being allowed in Portugal, and 20% in Spain (Gonçalves & de Brito, 2010). In the Netherlands up to between 50-100% of aggregate replacement is allowed, depending on the type of concrete being produced (FIR, n.d). In Denmark, however, 100% of coarse aggregate can be replaced with recycled aggregate, and up to 20% of coarse aggregate (Gonçalves & de Brito, 2010).

Such regulations were cited as a barrier for circularity in three of the interviews, two from the concrete industry and one academic expert (Concrete Industry 1, Concrete Industry 2, Academic Expert 2). Regulations were cited as a barrier in the context of recycling concrete to use as a replacement for aggregate. The interviewees explained that the amount of recycled aggregate, as opposed to virgin aggregate, that is allowed to be used in concrete production is strictly controlled by government policy, and the percentage that is allowed to be used is often lower than what could technically be used to produce good quality concrete. Another problem explained is that regulations often stipulate that if above a certain threshold of recycled aggregates are used in concrete making, the manufacturer must obtain a special certification for the resulting product by proving that it is of good quality. This additional hurdle present in producing recycled concrete adds a burden to producers, making it a less desirable form of production. As Concrete Industry 2 explained:

> *"Today, 5% is not the problem, you can do that without any special actions. But if you go higher, you have to certify the crushed concrete."*

Demolition Companies

Another barrier put forward by some interviewees (Concrete Industry 1, Concrete Industry 3, Academic Expert 3) was that the current state of the demolition sector does not meet the requirements for large scale reuse and recycling. The main challenge is the fact that this sector is, in Europe, dominated by small, sometimes family-run businesses. Because they are operating on a small scale, they often struggle to provide the quantity of materials required to either contribute to producing large volumes of concrete or supply the amount of reused elements needed to make reuse a prevalent practice. The scale that demolition companies operate on also poses issues in terms of consistency in terms of the having elements or waste available over time.

Furthermore, because the demolition sector has not yet developed to focus on retaining parts, or collecting for recycling, there are issues to do with quality. Demolition companies lack experience in this field, and so concrete companies wishing to obtain used concrete to make recycled aggregate have issues obtaining materials that are of a high quality. This leads to concrete producers are reluctant to incorporate them into their processes, fearing potential inconsistencies and compromises in the final product. Adding to the complexity, according to one concrete industry representative (Concrete Industry 3), the demolition industry itself is very fragmented and this leads to difficulties coordinating efforts, best practices and establishing standardised procedures for concrete material recovery.

One academic expert (Academic Expert 3) pointed out that a transformation needs to take place where traditional demolition companies transition to becoming deconstruction companies. Unlike the current activities carried out the demolition sector, deconstruction would involve carefully disassembling buildings, and recovering materials and concrete elements. This adoption of deconstruction practices would aid in the adoption of circular strategies.

4.4 What needs to change?

In the interviews, participants were asked to reflect on their perspectives on the changes needed for the concrete sector to be able to transition to circularity. Two primary solutions were identified, one related to structural changes in existing policy for circularity and the other to do with more systematic changes to how concrete usage and circularity is perceived (changes needed are outlined in Table 4-3). Firstly, the interviewees emphasised the need for the create new policies, and adaptation of existing regulations, to incentivise the adoption of circular strategies. Secondly, some interviewees proposed that a re-evaluation of the quantity of concrete required in the built environment is needed to ensure a decreased use of material resources. By questioning the actual necessity of excessive concrete usage, they advocated for a shift towards prioritising a shift in consumption behaviour where sufficiency is emphasised, rather than overaccumulation.

Table 4-3: Changes needed to better implement Circular Economy approach in the concrete sector as identified by interviewees

Interviewee	***Changes Needed for Transition to Circular Concrete Industry Identified***
Concrete Industry 1	• Policy: **Economic incentives** to encourage production of recycled concrete such as placing a **tax on natural aggregates**. • Policy: **Adjust norms** to allow for **higher proportions of recycled aggregate** to be used in concrete production.
Concrete Industry 2	• Policy: **Economic incentives** to encourage concrete recycling. • Attitudes: Resources used in production of concrete need to be viewed as **valuable and finite**. • Attitudes: **Re-evaluate the building of new structures** and strive for prolonging lifetime of existing buildings and reuse elements, with **a focus on sufficiency**.
Concrete Industry 3	• Attitudes: **More commitment** and desire to reusing elements on the part of the construction sector.
Architect 1	• Policy: **Introduce requirements** on minimum amount of secondary materials used in building projects. Such policies should consider the context of each country and their ability to implement circularity. • Attitudes: **Move away from culture of consumerism** and focus more on prolonging product lives. This is a complex issue, due to socio-economic differences in society.
Academic Expert 1	• Policy: **More standards** should be introduced which guide the concrete industry on concrete recycling.
Academic Expert 2	• Attitudes: Need to find a way **of changing attitudes to motivate circularity,** this could be in the form of providing financial incentives or underlining the environmental benefit.

Academic Expert 3	• Policy: **Regulations governing reuse** of concrete elements need to be introduced.
Academic Expert 4	• Policy: **More flexible standards** need to be established for concrete recycling. • Attitudes: **Re-evaluate the amount of concrete that is actually needed**, keeping it for complex load-bearing structures such as bridges, but replacing it in other structures.

Policy

The transition towards a more circular concrete industry requires policies to be introduced which encourage industry actors to introduce more circularity to production processes. Firstly, some (Concrete Industry 1, Concrete Industry 2) interviewees suggested that governments should implement policies that incentivise circularity, such as imposing taxes on virgin aggregates. They explained that this would make recycling more a more economically competitive practice, compared to what it is now.

Furthermore, some interviewees (Concrete Industry 1, Architect 1) also claimed that regulations should be established to enforce a minimum requirement of secondary materials in building projects. This would involve engaging all stakeholders involved in the construction process, including concrete sector professionals, designers, builders, and building owners. By making circularity a mandatory aspect of projects, all actors would be compelled to incorporate circular practices into new projects. One interviewee, Architect 1, pointed out that it would be crucial, when developing such policies, to acknowledge the varying capacities of different countries to achieve circularity. Imposing a one-size-fits-all EU law mandating fully circular concrete systems could create challenges for economies with limited capabilities. Such regulations could lead to an increase in illegal construction and production practices, as well as corruption, undermining the desired objectives. Therefore, policymakers must carefully consider local contexts and develop policies that are appropriate for each country's specific circumstances.

Finally, some interviewees (Concrete Industry 1, Concrete Industry 2, Academic Expert 4) underlined that the existing standards governing the permissible amount of recycled material replacing natural aggregate need to be revised. It was suggested that the current standards should be made more flexible to accommodate a higher proportion of recycled materials in concrete production. Academic Expert 3 explained that in the context of the reuse of concrete elements, laws and standards do not exist yet, and until these regulations are developed there will be very little progress made in terms of increasing circularity using this strategies.

Attitude Adjustments, and a shift towards sufficiency

In order to develop a more circular concrete industry, some interviewees, representing all "sectors" interviewed (Concrete Industry 2, Architect 1, Academic Expert 4) suggested that attitudes and approaches to concrete and expectations of how much concrete should be used, need to change in order for the industry to become more circular. One concrete industry representative (Concrete Industry 2) believed that there should be more emphasis placed on sufficiency when it comes to the use of concrete, meaning that instead of continuing the trend of increased usage, more should be done to evaluate the actual amount of concrete society needs. By consciously assessing our construction requirements, we can reduce unnecessary concrete consumption. He underlined the need to recognise that the natural resources used in the production of concrete are finite.

Two interviewees (Concrete Industry 2, Architect 1) believed that we should strive to construct buildings and structures with longer lifetimes and adapt them over time to meet new requirements. Rather than defaulting to demolition when a building falls out of use, our priority, they believed, should be the reuse of building components. Crushing and converting concrete into new aggregate should be considered as a last resort. In the discussion surrounding what needs to happen for the concrete sector to be more circular, the architect interviewed focused on the consumerism which drives a lot of material usage today. She stated that, in her opinion, our perspectives on material usage needs a fundamental shift. We should prioritise the creation of durable products and materials and challenge our prevailing culture of consumerism. She admitted that such a change would be complicated to achieve as there exist a wide range of lifestyles, from extremely affluent individuals leading wasteful lives to those who, out of necessity, adopt circular practices to save money. She concluded her thoughts by stating that this complex task can only be tackled collectively.

Finally, when it came to changing attitudes and adopting new approaches to construction, Academic Expert 4 was also adamant that we need to rethink our reliance on concrete. She suggested that while it is crucial to retain concrete where its structural properties are truly necessary, such as in challenging constructions like bridges and load-bearing structures, non-essential uses of concrete should be replaced with alternative materials or techniques, or constructed using reused concrete elements or adapted buildings.

4.5 Perceptions on the Feasibility of Transitioning to a Circular Concrete Sector

There was a diverse set of answers when it came to discussing whether it was feasible to transition to circular concrete use (tabulated opinions outlined in Table 4-4). Most interviewees chose to focus on a particular form of circularity which is possible with concrete, including: recycling crushed concrete as aggregate in new concrete production; reusing prefabricated concrete elements; using recycled cement paste in the creation of new cement; and the repurposing of existing concrete buildings and structures. Overall, the level of technical feasibility perceived by the interviewees increased as more "interior" circular strategies were considered.

Table 4-4: Interviewee opinions on the feasibility of concrete sector adopting circular economy approach

Interviewee	***Opinion on the Feasibility of Concrete Sector Adopting Circular Economy Approach***
Concrete Industry 1	• Recycling is partially feasible. 30-40% of aggregate needs could come from recycling or circular sourcing
Concrete Industry 2	• It would be possible to increase current recycling rates for aggregate, up to 30%
Concrete Industry 3	• Recycling is technologically straightforward by replacing aggregate and through recycling of recycled cement paste

Architect 1	• Reuse is possible in countries where prefabricated concrete is/has been used; not possible for places which mainly use site-cast concrete
Academic Expert 1	• There is a need to increase the amount of concrete recycled, but it is not possible to build new construction with only recycled concrete
Academic Expert 2	• Primary materials will always be needed to meet demand, particularly as demand is set to increase in developing regions of the world.
Academic Expert 3	• There is a high potential for reuse of structures containing prefabricated concrete elements
Academic Expert 4	• Circularity is largely tenable for domestic structures, if we start to re-purpose and rehabilitate existing buildings

The circular economy is often represented as having "inner" and "outer" circles. Essentially, the various strategies regarding stock management in a circular economy can be imagined as a set of concentric circles, as seen in figure 4-3, where circular strategies for concrete are presented. The innermost strategies consist of sharing products, or maintaining them and prolonging their lives. Next comes reuse, which sits roughly in the middle of the series of circles, which involves products which are not waste being used again for their original intended purpose (European Environment Agency, 2016). Finally, the outermost circles are taken up by remanufacturing, and recycling. Generally, it is accepted that the more interior the circle, the less harmful environmental externalities are produced, such as greenhouse gas emissions or pollution, as can be the case with recycling (Wieser & Tröger, 2018).

4.5.1 Concrete Recycling for Aggregate Replacement

In the interviews, three separate circular strategies were discussed when it came to concrete: recycling concrete for aggregate replacement, reuse of concrete elements and repurposing buildings. The three interviewees working in the concrete industry focused on recycling in their interviews. This could be due to the fact that, as they are in the business of manufacturing concrete from scratch, they have little power over whether or not those heading construction projects would consider using reused concrete elements. Recycling, then, is the only circular economy strategy within reach in the context of manufacturing concrete. While one interviewee (Concrete Industry 3) was very positive about the technical feasibility of recycling, all three concrete industry representatives stated that while the amount of recycling must increase for the industry to become more sustainable, there is an upper limit to the amount of aggregate which can be replaced with recycled concrete (Concrete Industry 1, 2 and 3). Two representatives stated that the upper limit was around 30-40% (Concrete Industry 1,2). The reason behind this limit is due to issues with the quality of the recycled concrete. The aggregates used in concrete production need to be of a certain quality to ensure that the concrete can be produced to the desired standard. The interviewees also explained that there is a lot of uncertainty when it comes to the quality of recycled concrete, as it is difficult to know whether or not the recycled products contain any impurities.

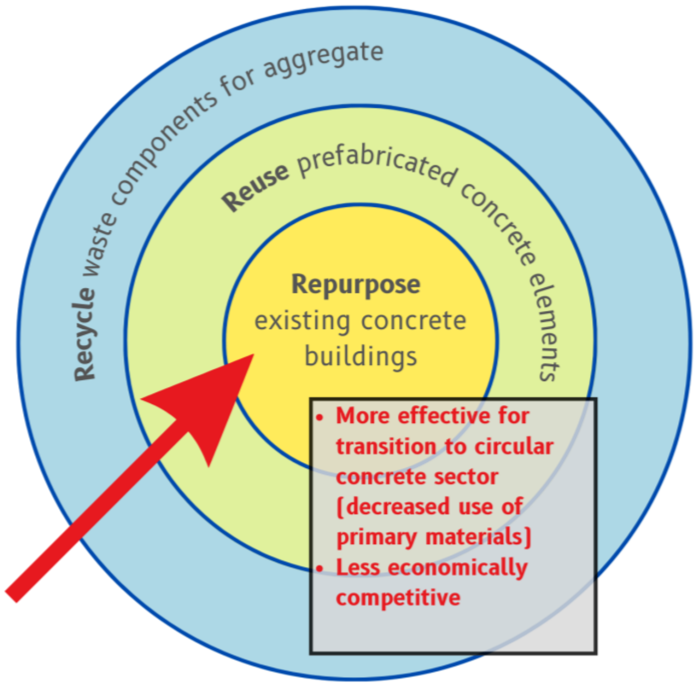

Figure 4-3: Circular concrete strategies from exterior to interior

4.5.2 Reuse of prefabricated elements

Precast concrete, also known as prefabricated concrete, is concrete that is cast away from construction sites and then transported to such sites for building assembly (Richardson, 2003, p. 21/4). This makes it a mobile material, and is usually made to standardised shapes and dimensions (Ochshorn, 2010, p.71). Precast concrete differs from the more common onsite concrete, where concrete is transported to building sites in an unhardened state in a concrete truck, and then poured into removable moulds called "forms", which also contain steel reinforcing bars (PCA, n.d).

There are many benefits associated with working with precast concrete. Some studies have shown that casting structural elements off site reduces the amount of time and labour required to create the elements, which leads to them being cheaper(Hong, 2020, p.1). The process also lends itself to higher levels of quality control than conventional onsite pouring (ibid.). Apart from these economic benefits, there are also important environmental advantages of using precast elements in construction, chiefly that their manufacturing produces less carbon emissions (Dong et al., 2015) and generates less waste (Shen et al., 2009). An environmental benefit of using prefabricated elements relevant for this study is the fact that they can in many cases be reused, with some slabs being suitable for reuse two or even three times (ibid.).

Two of the interviewees spoke of the possibility of introducing circularity in the concrete industry through reuse of fabricated elements. One of the participants, Academic Expert 3, is directly involved in an EU funded project which focuses on reuse of concrete elements. The other interviewee who shared their thoughts on this form of reuse was Architect 1, an architect working in Germany, where, according to the interviewee, use of prefabricated elements is widespread.

Both interviews were very positive about the possibilities offered by reusing prefabricated elements. Academic Expert 3 emphasised the large amount of material available in the building stock, and pointed out that some parts of the world are witnessing the phenomenon of "shrinking cities", where population loss has meant that more and more buildings and infrastructure are falling out of use. The interviewee put forward an example of abundance of material available from a piece of research he had conducted:

> *We looked at what's being demolished today. So we looked at 1300 demolition permits in Stockholm and we could see that, out of those 250 or so were kind of on the building size and, and I think it was 63 of them were actually large buildings with prefabricated components. And with a very rough calculation, this could cover 30% of one year's production of housing in Stockholm. So the material is out there. (Academic Expert 3, 5 April, 2023).*

This interviewee estimated that in the next ten years or so models will be developed which will allow for the rate of reuse to increase from zero, where it is now, to a "few percent of reuse". He predicted that new companies would be established which will specialise in this type of construction. He explained that he thought that due to the conservatism present in the building industry, reuse will probably never represent the majority of materials used in new construction, but re-emphasised that there is an abundance of material available around the world which is available for reuse, and that this should be taken advantage of.

Architect 1 talked about reuse of prefabricated concrete mainly in the context of explaining her opinion that how feasible it is to introduce circularity into concrete use would vary depending on the country. She explained that in Germany, where she works, prefabricated elements are the norm: "they already have, you know, a very [...] developed industry with very specific standards for everything. So basically, all the materials are precast, or predefined in a factory. So you just attach it." (31 March, 2023). She explains that in the case of these types of materials, she "sees a lot of potential for reuse (ibid.). However, in other countries which mainly rely on conventional onsite concrete, she stated: " I don't see any way you could possibly reuse it. Other than gabions." Gabions are rectangular baskets, usually metal ones, filled with sand or aggregate. They are used in construction to create walls, on slopes for erosion control, foundation building or for several other purposes. Her point here, saying that onsite concrete can only be used again in gabions, underlines the idea that for this type of concrete, reuse, an inner circle of circularity, is not possible. The only option is recycling.

4.5.3 Repurposing buildings

Repurposing buildings involves keeping the main part of a building, such as its internal structure, and replacing other elements over time when needed (Assefa & Ambler, 2017) . This is in order to avoid generating more waste by demolishing the entire structure. Additional benefits are that it greatly reduces the amount of natural resources required for new construction, as well as land required for new construction projects (ibid.).

The fourth academic expert interviewed was extremely positive about the potential impact of repurposing buildings. She believed that transitioning to a circular built environment would be possible through adaptive reuse of existing buildings. She stated: "For me, we have finished building new houses. I think all the concrete that will be used in the future will be on infrastructure projects." When asked about the overall feasibility of transitioning to a circular building sector, she stated that she believed the sector could reach 90% circularity, with more linear take-make-dispose modes of construction and demolition being reserved solely for infrastructure projects such as bridges.

5 Analysis

In this analysis, literature from industrial ecology, particularly that pertaining to sociometabolic regimes, is utilised to expand on some of the main findings derived from the interviews and literature review conducted as a part of the research. The insights and principles of sociometabolic regime theory allow a close examination of how effective the current approaches to introducing circularity in the production and use of concrete are, with a particular focus on the trends of concrete production and in-use stocks, barriers for implementing circular strategies, and the characteristics of concrete that allowed it to achieve its current level of use.

5.1 Stock Expansion and Circularity

The investigation on the feasibility of meeting concrete production demands through use of secondary materials yielded significant findings. The research revealed that there has been continuous growth in the in-use stock of concrete over the past few decades, as well as a simultaneous increase in production. This trend is expected to persist and intensify as global development and urbanisation escalate in various regions across the world.

In recent years, there has been a discernible trend of expanding physical stocks of anthropogenic mass, which encompasses a wide range of materials and products generated by human activities. A 2020 study found that the total weight of man-made materials, including metals, asphalt, bricks, aggregates and concrete has been doubling every twenty years and, as of 2020, physical stocks of human-made materials have come to exceed the mass of all living beings on earth (Elhacham et al., 2020). The accumulation of these stocks is propelled by factors such as population growth, over-consumption and urban development (Bradshaw et al., 2021).

Literature from the field of industrial ecology and the SMR concept has found that the expansion of physical stocks of materials presents many issues for circularity, as the continuous growth of stocks impedes the possibility of stabilising or reducing resource use (Wiedenhofer et al., 2021). Stock expansion has also been found to be simply incompatible with circularity – if there is a demand for continuous additions to the in-use stock, the demand for materials necessary to produce and maintain this stock cannot be met by secondary materials from smaller stocks of previous years and decades (Haas, 2022). We can see this from the example of concrete, where stocks continue to rise significantly each year, and are projected to keep doing so. If this trend continues unabated, then the feasibility of achieving circularity is very low, as there will not be enough concrete in the anthroposphere to provide secondary materials.

Another finding from the research into in-use stocks was that there is a high degree of variation in the amount of concrete stocks across different regions. This is due to varying levels of development and urbanisation across the globe. There are many implications for this variation, especially when it comes to in-use stock expansion in countries which until now have used less concrete. Commentary on regional variability of concrete stocks is limited, however there has been research done on the global disparity of metal stocks. One study found that the majority of metal stocks are concentrated among approximately 20% of population (ordered by total in-use stocks), who hold between 65-70% of the worlds metal stock, and the bottom 20% just 1% (Watari & Yokoi, 2021). This disparity is important to consider when it comes to implementing the concept of the circular economy, as waiting for developing countries to attain equivalent levels of metal stocks would have severe environmental consequences. To address this issue, a concept known as "contraction and convergence" has emerged as a potential solution (Watari et al., 2021). This approach entails a process whereby developed nations undertake reductions in per capita stocks, while developing nations strive to converge at a lower level. By adopting this approach, a more equitable and sustainable distribution of physical stocks can be achieved. This would potentially have more significant benefits than relying solely on circular economy strategies to take hold in developed countries. For environmental harm to be truly averted, concrete stocks in developed countries need to contract, and efforts need to be made to assist with the development of infrastructure and housing for growing populations in less developed countries in a way which allows for the development of green building stocks, which utilise sufficient, and not excessive amounts of concrete.

5.2 Circularity in a Growth-driven System

The most prevalent barrier cited by interviewees for transitioning to a Circular Economy of concrete was the economic cost of introducing circularity to concrete production and building and infrastructure construction. This barrier is arguably the most difficult to solve of all the factors identified, given that the cheapness of the raw materials used to produce concrete and a reliance on fossil fuels are part of how concrete became successful. All the interviewees agreed that concrete is cheap to produce, and that the materials are available everywhere. The literature review into how concrete came to dominate as a construction material found that concrete was only able to go through its most recent revolution into huge widespread adoption because it began to be produced outside the "organic economy" (Cook, 2021). That is, instead of production processes that were driven by energy derived from biomass, usually firewood, it began to be produced using fossil fuels. These core factors, which projected the material to success, define concrete. Working without these factors in a system which pushes for continuous economic growth does not bode well for a transition to circularity. If it were only those in the concrete sector prioritising growth alongside eliminating environmental harm, then economic steering could perhaps be enough to ensure that industries take the necessary steps to move towards circularity. Literature and policy documents on the subject, however, explain that the CE concept, at least in Europe, is championed as a policy which can ensure a decoupling of economic growth from environmental harm, an assertion which many researchers have taken issue with (Sorman, 2023; Hickel & Kallis, 2020; Wälti et al., 2012).

5.2.1 The Circular Economy's Preoccupation with Growth

A significant proportion of critiques laid out in the literature addressing the current conceptualisation of the Circular Economy transition reject the idea, commonly shared by the industry and government actors, that CE can solve environmental problems while simultaneously achieving sustained economic growth. The fact that interviewees identified the higher cost barrier as the most prominent one in impeding the transition of the concrete sector to a CE, is indicative of how much economic growth keeps on being prioritised over sustainability goals. The fact that one of the main findings from this research was that circularity is not being pursued due to the relatively higher costs associated with adopting circularity strategies confirms the idea that economic growth is being prioritised over the goal of decreasing material and energy usage.

This is consistent with a possible sociometabolic take on the CE as it is currently envisioned: that the CE approach in its current form is not able to bring down material and energy usage because it prioritises economic growth. As there is limited evidence to suggest that decoupling economic growth from material usage is physical possible, having this aim embedded within the goals of transitioning to a CE limits its potential for bringing forward a sociometabolic transition. The CE transition as it is currently conceived can be seen as a new manifestation of a form of sustainability policy which aims to maintain the status quo: a social and economic system driven by growth and high levels of consumption.

Much of the policy documents and literature on circular economy frame its adoption as a transition. A transition from linear "take-make-dispose" modes of production to one which tries to close material loops while maintaining growth. One which moves towards an economy where growth is decoupled from environmental harm. In the context of sociometabolic regimes, however, there is evidence to suggest that the policy approach is not geared towards transitioning to a new regime but instead is an attempt to stabilise the current one.

Many have put forward the idea that the circular economy idea is a rehashing of older approaches to sustainability such as eco-efficiency, where an attempt is made to provide competitively priced products while reducing ecological impacts and resource use during their production, use and disposal (Ehrenfeld, 2005). There is, of course, no reason not to pursue technologies and modes of production which limit environmental harm, but due to rebound effects and the pursuit of a continuously growing economy, the pursuit of eco-efficiency has not successfully curtailed overall resource and energy use (Parrique et al., 2019).

Like eco-efficiency, the circular economy concept promises to allow for lifestyles to remain largely the same, and even improve, while solving catastrophic environmental problems (Ellen Mac Arthur Foundation, n.d.) It has, in fact, been referred to as a: "win-win-win" scenario, where industry wins, by profiting; the planet wins, by being saved from harm; and society wins, with the creation of new jobs, a heightened sense of community which is to come out of creating a sharing economy and also strengthened equality, through the formation of democratic decision making structures (Korhonen et al., 2018). Viewed from this perspective, we can conclude that in many ways the circular economy is a remastering of neoliberal capitalism, which "requires no radical change to institutions, infrastructures, and markets" (Corvellec et al., 2022).

That the circular economy is a reimagining of ideas such as eco-efficiency already put forward in fields such as industrial ecology has been explored in the literature, alongside the idea that the circular economy is a continuation of a tradition of "depoliticising" environmental movements. Lisa Doeland (2022) links this to the concept of *capitalist realism*, where naturalisation and depoliticisation are used to create the illusion that capitalism is the only viable economic system (Fischer, 2009). Capitalism, and in this case the circular economy, is presented as something "natural, necessary and a-political" (Doeland, 2022). Many scholars have remarked that the circular economy concept is rife with ambiguity, that no clear vision or definitions exist of it. That it, at best, should be treated as an "umbrella term" (Blomsma & Brenna, 2017), or a "floating signifier" (Laclau & Mouffe, 2001). The apolitical nature of how the CE is put forward, in addition to its lack of an agreed upon meaning, leaves little room for radical change.

Environmental movements, in order to have the potential to challenge dominant systems and powerful actors, need to have been developed through discursive analysis and , have central, focusing tenets. What has tended to be the case with environmental movements, within the neoliberal capitalist system, is that a call for a change to the system becomes eroded of its political nature over time. What is left is a less defined concept which is more palatable to the current power structures in our system, as the concept is no longer defined by its promulgation of system change. Erik Swyngedouw explains this in the context of what Slovenian philosopher Slavoj Žižek refers to as the "post-political" (Swyngedouw, 2011). The post-political being politics in which political boundaries are dissolved and what is left of the political arena is reduced to:

> *[...] the sphere of consensual governing and policy-making, centred on the technical, managerial and consensual administration (policing) of environmental, social, economic or other domains, and they remain of course fully within the realm of the possible, of existing social relations (ibid.).*

Essentially the post-political describes a system where politics is no longer concerned with radical change. What philosopher Bulent Diken describes as "game-playing without the possibility of changing the game." (2014, 127), within a "society that cannot imagine radical events" (ibid., 128). It is far from the world of post-politics where current dominant solutions to urgent environmental issues arise. Instead of imagining solutions and a future which involves change, we look backwards. As with climate change, for example. The framing of the climate problem and the need to tackle it often takes the form of identifying a "negotiated, idealised point in history, to return to climatic status quo ex-ante" (Swyngedouw, 2011). Then we embrace technological, managerial solutions to achieve a return to this point. The "techno-managerial" apparatus being called upon to produce socio-ecological fixes (ibid.) act as front-line emergency services, stabilising our systems and allowing for us to continue, unmodified in behaviour or ideals. A political approach would be about imagining alternatives.

The idea of sustainability itself can be a useful example for understanding how an idea which pushed for real systemic change, became enfolded into the post-political. Sustainability, apart from being brought into mainstream use after being included in several UN projects and publications in the 1980s, it finds its roots in several influential works of ecological economics such as *Limits to Growth* (Meadows et al., 1972), E. F Schumacher's *Small is Beautiful* and Herman Daly's *Towards a Steady State Economics* (Caradonna, 2017, p.15). These works all challenged the constant pursuit of economic growth and argued that this goal must be dissolved in order for humans to be able to stop wreaking havoc on the natural environment. The concept of sustainability today is, much like CE, challenged for its appropriation by neoliberal capitalism (Cock, 2011). Sustainability and the CE are not a rallying cry for a reorientation of the goals of society, but rather an assurance that they can be firmly held onto.

What we are left with then, bearing all this all in mind, is the idea that Circular Economy is a vague, apolitical concept which bears the hallmarks of capitalist-realism. The circular economy is presented as a techno-managerial solution, which fixes our current system. With the circular economy then, there is no need to consider broad economic, social or behavioural changes which would move us into a new sociometabolic regime, and in any case any changes would be impossible, as when it comes to our socio-economic world system, there is no alternative.

In conclusion, the introduction of circularity to the concrete sector faces significant barriers, with the cost of implementing circular practices being the most prevalent challenge identified. The success of concrete as a construction material is deeply rooted in its affordability and reliance on fossil fuels, making a transition to circularity difficult. The Circular Economy approach, often presented as a solution to decouple economic growth from environmental harm, can be seen as a continuation of existing neoliberal capitalist structures rather than a radical change. The circular economy, like previous approaches such as eco-efficiency, promises to address environmental problems while maintaining current lifestyles. However, the lack of a clear and agreed-upon definition, coupled with its apolitical nature, limits the potential for transformative change. This concept aligns with the concept of the post-political, where politics is seen to be reduced to technocratic decision-making and governance within existing social relations and economic systems. It fails to envision alternative systems and relies on technological fixes to stabilise current structures. Moreover, the appropriation of sustainability and circular economy by neoliberal capitalism further diminishes their potential for systemic change. Ultimately, the circular economy appears as a vague and ambiguous concept that upholds the status quo, neglecting the need for broad economic, social, and behavioural transformations required for a new sociometabolic regime.

The example of concrete used in this thesis provides a solid insight into these ideas, as the current dominant imagining of prioritising of economic growth in environmental policy development can present a barrier which is very difficult to overcome when it comes to transitioning to circularity. As we have seen, there is a need for developed countries to decrease concrete stocks, and transition to thinking about sufficiency.

5.2.2 Concrete and Circularity Outside the Organic Economy

The concepts of sociometabolic regimes, metabolisms and transitions are guided by a consideration of humankind's use of energy, resources and "colonisation of nature" (Brand & Wissen, 2017, pp.3). There is significant focus given to how the adoption of different sources of energy contributes to a regime's overall effect on the natural environment. For example, SMR literature finds that before the industrial revolution, humans in the agrarian sociometabolic are bound by strict energy limits, because they depend on biomass for fuel (Krausmann et al., 2008). These limits place natural checks on economy growth (ibid.) Using the framework of SMRs to analyse the general feasibility of concrete becoming circular then requires an interrogation of the idea that concrete was only able to achieve its current status as most used building material on earth due to the fact that it was able to surpass biophysical limits – because of the reliance of the sector on fossil energy. When tracing back the history of concrete we see that when concrete started to be produced with coal in Britain, limitations associated with producing the material using biofuels, mainly wood, were overcome. Using fossil fuels, Britain's large reserves of cheap coal, to produce concrete allowed for a sustained, high level of production, uninterrupted by scarcity and impeded by the limits associated with timber. Unchecked growth in the sector was achieved then, with the use of fossil fuels.

This line of argument follows on naturally from previous analyses of the environmental history of energy use. Swedish ecologist Andreas Malm's study on the rise of steam power in the industrial revolution found that transitioning to coal as the main source of energy was driven by the pursuit of higher levels of profitability, as the adoption of coal-powered steam engines allowed industrialists to locate factories near population centres and away from rivers, which were required to produce the previously used watermills. This shift to towns and cities allowed factory owners to achieve maximum profits and a steady flow of production, as it guaranteed them of a high volume of labour which in turn allowed them to reduce wages (Malm, 2016, pp. 124).

Both of these analyses of the effects of production exiting the organic economy show that in the industrial revolution, fossil fuels allowed for the limits associated with operating within biophysical limits to be overcome, which lead to much higher levels of output which are sustained to this day. Concrete's success then as such a widely used material, is in many ways contingent on the fact that it is produced with fossil fuels. That is, if success is measured in terms of the accumulation of physical stock, and ever-expanding rates of production. The obvious issue with this measure of success is the very clear environmental implications associated with producing concrete in this way, at these volumes. For any changes in the sector to be introduced which would have a real positive effect on society's sociometabolic profile, we may have to accept that we need to change our expectations for how much concrete we truly need in our built environment, as the path which lead concrete to dominate our lives is paved with a reliance on fossil fuels. The factors which contribute to the attractiveness of concrete as a material in the industrial sociometabolic regime may not be able to be retained in the event of a real sociometabolic transition. There may be no place for the amount of concrete we currently use in a sustainable sociometabolic regime.

The analysis presented above effectively aligns with the notion put forth by interviewees regarding the necessity of transitioning towards a sufficiency-oriented approach in the realm of concrete usage. The recognition that developed countries, endowed with extensive building stocks, ought to critically evaluate the quantity of concrete they employ constitutes a pivotal system change. By undertaking this fundamental step, we lay the groundwork for implementing circularity strategies effectively. It is imperative to comprehend the actual amount of concrete required before embarking on circularity initiatives, as these strategies, while encumbered by technical and practical challenges, cannot bring about significant transformations to our sociometabolic profile without first addressing sufficiency.

6 Discussion

The following section will discuss the results obtained in this thesis and link them with the previously stated research questions. The outcomes of the analysis will be presented against existing research. This will be followed by discussion this study's contribution to research. Finally, the results of the thesis will be reflected upon with regards to their validity and legitimacy, with a particular focus on the limitations of the study.

6.1 Barriers for CE in Concrete Sector

RQ 1a: What are the barriers to transitioning to a CE in the concrete sector?

In answer to RQ 1a, the barriers identified from interviews and literature that have the most potential to undermine the effectiveness of CE transition in the concrete sector, from a sociometabolic regime perspective are: **stock expansion**, **growth-oriented circularity** and the idea **that introducing circularity would not allow concrete to retain characteristics that made it a successful building material.**

6.2 Stock Expansion

The results of this research found that that in-use stocks have been expanding for the last several decades, with levels of production also steadily rising. An analysis using literature on sociometbaolic regimes found that stock expansion is incompatible with circularity, as the materials needed to expand and maintain new stock cannot be met with secondary materials from the comparatively smaller stocks of previous years. Another finding related to concrete stocks was that they are very uneven around the world at present, but that there is to be an expected expansion of concrete stocks in developing countries, as countries develop and urbanise. This too presents a barrier in itself for circularity, as if countries are to follow similar growth trajectories as developed nations, and attain similar stocks of concrete, global stocks will continue to expand, and the demand will rise and become increasingly unable to be met with much smaller historic stocks. The expansion of stocks is also expected to lead to the emission of a large amount of greenhouse gasses, released in the manufacturing of concrete.

Other attempts have been undertaken to analyse the effects of stock expansion on circularity. For example, an important study by Haas and colleagues analysed patterns in overall circularity from 1900-2015, attempting to understand the role circularity has come to play in our sociometabolic regime (2020). Circularity was divided into two types, ecological cycling, which are processes where outputs from used biomass re-enter "biogeochemical cycles" and aid in the growth of new biomass. The second type of cycling considered in the study was socioeconomic cycling, which is all waste that is fed back into production systems as secondary materials. The study found that circularity has steadily decreased in the period studied. Input cycling was found to have dropped from 43% to 24% (Haas et al., 2020). One of the main identified structural barriers to improved socioeconomic cycling was that "closing material loops completely is not compatible with physical growth" (ibid.). In other words, efforts to increase circularity are blocked by the intentions to produce more goods. This aligns with the findings of this thesis, which concluded that one of the main barriers to increasing circularity in the concrete sector was that there was a robust trend of continuous stock expansion. Another finding from this piece of research into circularity over the last century is that the build-up of physical stocks presents an issue for circularity for another reason, that building up stocks withdraws materials from the system, and thus they cannot be cycled through as new inputs. This is particularly the case with concrete, as buildings and infrastructure have such long lifetimes (ibid.).

Another piece of research into the issue of stock expansion and sociometabolic profile transition discussed the climate implications of continued stock expansion (Krausmann et al., 2017). The authors put forward the climate implications of all countries expanding physical stocks to levels currently held by industrialised nations. In this scenario by 2050 total global physical stocks would quadruple, and result in 542 billion tonnes of carbon being emitted to the atmosphere – this number would go down to 303 billion tonnes if all energy systems would be decarbonised by 2050. To have a 50% or higher chance of keeping below 2 degrees of warming as put forward by the Paris Agreement, carbon emissions need for this period need to stay in the range of 234-417 billion tonnes. The climate change potential of converging physical stock levels at the levels of industrial nations is clearly enormous. This aligns with the conclusion drawn in this thesis, that stocks need to contract and converge at levels lower than current industrial levels.

6.3 Growth-Driven Circularity

Apart from stock expansion, the growth and profit-driven nature of the current dominant economic system was identified as a barrier for circularity in the concrete sector. Furthermore, it was found that the CE approach as it is currently put forward in Europe aims to decouple economic growth from material and resource use. This aspect of the CE is found to be a barrier, as it limits the scale of change that can occur in the sector. This is because profits are prioritised over the successful implementation of circular concrete strategies. Overall, interviewees reiterated the fact that circularity is not being implemented on a wide scale because circular concrete strategies: recycling, reuse and repurposing buildings are difficult to implement while maintaining profits. In the case of recycling, this is due to secondary materials in the form of recycled concrete being more expensive than virgin aggregates. Recycling also results in added costs, due to the need to transport materials from demolition sites to concrete production facilities and the fact that demolition takes more time and skill when materials are being recovered.

Economic issues, more specifically the idea that introducing circularity into the concrete sector makes concrete economically uncompetitive, have been identified as important barriers to circularity in the building materials sector. Research on challenges and opportunities for construction and demolition waste in a circular economy by the European Environment Agency found that the "economics of [circular strategies] are the overriding consideration in their uptake" (EEA, 2020). They cite the fact that virgin materials are cheaper than recycled aggregates and the added costs of labour for selective demolition and transportation as the main reasons for the added costs associated with CE strategies (ibid.). The study goes on to list a variety of market-based mechanisms which can work to create a business case for circularity, thereby making the implementation of such strategies an economically attractive option for businesses, such as placing taxes on natural aggregates. Measures such as these would work to create a market system where recycling is the more profitable option. This suggests that circularity will only be achieved if more profits, and economic growth, are guaranteed. Other studies on barriers to uptake of circular concrete solutions draw similar conclusions, that companies are reluctant to implement circular solutions due to high upfront investment costs and low prices for virgin materials compared to secondary materials (Hart et al., 2019; Adams et al., 2017; Hopkins et al., 2019).

When examined in the context of socio-metabolic regimes, the uptake of circularity being dependent on profitability is problematic, as research has found that limiting resource efficiency alone cannot ameliorate environmental problems, and that efforts must be coupled with limits on economic growth. For example, a study by Steinberger and Krausmann, investigating the relationship between material, energy, and carbon productivity and economic activity on a global scale found that relying solely on productivity targets would be an inadequate approach for achieving an absolute decrease in resource use and greenhouse gas emissions (2011). The study concluded that to make such reductions, which would guarantee a positive sustainable change in our sociometabolic profile, restrictions must be placed on economic growth (ibid.). Other studies using a SMR approach put forward similar conclusions, with a piece of research conducted by Shao and colleagues in 2017 finding that reductions in material use are not expected to occur unless economic growth is limited to a maximum of 2%, as illustrated by the fact that reductions in material usage has tended to only occur in times of recession (Shao et al., 2017). Moreover, there is a growing body of literature which calls for a reassessment of the growth paradigm if absolute material and energy consumption are to be decreased (Steinberger & Krausmann, 2011; Haberl et al., 2017; O'Neill et al., 2018). The results of this thesis offer an example which helps to support these claims, as the current dominant economic system does not seem allow for an industry such as concrete to uptake unprofitable practices such as recycling, reuse and repurposing buildings.

6.3.1 The Success of Concrete: Cheap, Abundant and Free from the Organic Economy

Following on from the idea that circularity strategies and their potential to make absolute reductions in material and energy use are hindered by the current need for actors to achieve profitability above environmental concerns, is the finding that introducing circularity into the production and use of concrete would erode the characteristics that made the material so dominant in the first place. The literature review and interviews yielded the result that some of the main reasons concrete became such a successful building material were that its raw materials are abundant and cheap, and its production, being fueled by fossil energy carriers, avoided the pitfalls of relying on biomass as a source of fuel. These pitfalls usually resulted in loss of profit for manufacturers. This would suggest that part of what made concrete a popular material was that it was easy to produce cheaply, and thus easy to profit from. This presents a clear barrier for implementing circularity strategies, as the very attractive quality of concrete, its cheapness, would be eroded if the CE approach was implemented.

There is limited literature exploring the factors which made concrete such a widespread material, and why it continues to retain its popularity today. The fact that the above-mentioned sources on economic barriers to circularity all cite the cheapness of virgin aggregate as a barrier for CE implementation, however, shows that this defining feature of concrete is seen to be in danger within the CE.

6.4 Changes Needed to Increase Utility of CE Approach

RQ1b: What would need to change about the approach for material and fossil-based energy use to decrease in the concrete sector?

In answer to this research question, the findings demonstrate that there are two main goals which should be adopted to better aid a transition to a circular concrete sector which accomplishes the goal of reducing material consumption and energy use. The first goal would be **developing and updating policy surrounding circularity in the building sector which incentivises CE strategies and removes institutional barriers for doing so.** This could be considered a short-term goal which should be implemented in the near-future to ensure the beginnings of a process of transition towards a more sustainable sector. The second goal more long-term goal which put forward by some interviewees and shown to be necessary with the zoom-in on concrete stocks and production **is that the total amount of concrete used in the built environment must be decreased, and stock reduction prioritised. An overall approach of eco-sufficiency can be adopted to ensure this goal can be met**, whereby production levels are governed by what is determined to an appropriate level to meet human needs (Robra et al., 2020).

6.4.1 Policy

The interview findings from this research highlighted that one of the main short term changes that must be made to overcome barriers related to implementing circular strategies in the concrete sector should be the development of policies that drive the transition towards a circular concrete industry. Interviewees recommended incentivising circularity through measures such as taxing virgin aggregates and establishing regulations that mandate the use of recycled materials in building projects. However, it was noted by one interviewee in particular (Architect 1) that policies should consider the varying capacities of different countries to achieve full circularity, avoiding a one-size-fits-all approach.

It was also found that in order to overcome current barriers related to regulations which inhibit concrete recycling, that existing standards governing recycled material usage in concrete production should be revised to accommodate higher proportions of recycled materials, facilitating the industry's shift towards circularity. Additionally, the development of laws and standards for reusing concrete elements was emphasised as crucial for progress in the transitioning to a circular concrete sector.

6.4.2 Sufficiency: an answer to the needs of stock reduction, and a shift away from growth

Long term goals identified in this study which would aid in the transition to a circular economy which would be effective in bringing down energy and resource use are a overall reduction in in-use stocks, as well as a shift to sufficiency when it comes to the built environment and concrete use

As previously discussed, the large and growing stocks of concrete present in the sociometabolic system of this industrial regime presents a challenge for circularity. The highly unequal spread of stocks across global regions also presents an issue in terms of future stock expansion, as it can be expected that if developing countries follow a similar growth trajectory as industrialised nations, stocks of concrete will expand at similar rates. This would increase barriers to circularity and lead to even higher levels of resource use and GHG emissions. There needs then to be an effort in developing countries to contract concrete stocks, and for stocks in developed and developing nations to converge at an appropriate level. This appropriate level can be determined through a focus on sufficiency rather than unremitting economic growth.

The results of this study suggest that considerations of sufficiency should be brought into the CE concept for it to be truly effective at bringing down material and energy usage. Sufficiency emphasises creating a world system where society operates within planetary boundaries by producing and consuming only what is “enough” to meet human needs (Jungell-Michelsson & Heikkurinen, 2022). Sufficiency is an often-neglected topic in research on sustainability in general, and particularly when it comes to research related to the building industry (Bierwirth &

Thomas, 2019). Generally, much more attention has been paid to eco-efficiency and technical solutions to environmental challenges (ibid.). While these factors are undoubtedly important, the broader consideration of sufficiency is crucial for achieving sustainable and environmentally responsible outcomes. A sufficiency approach can be applied to the issue of stock expansion, to tackle the need to contract current in-use stocks of concrete. Overall, it would appear that the addition of the concept of sufficiency to the CE concept would help to shift the approach as it is currently understood to one which aims to increase biological and socioeconomic cycling in a system that has in place limits on the amount of concrete needed to meet a population's needs. This would entail a move away from the current growth-oriented form of circularity as espoused in today's CE approach.

Research linking the ideas of CE and sufficiency are still emerging as the concept of sufficiency has only entered mainstream discussion in the early 2000s. There are studies however which have put forward the idea that the concept of sufficiency needs to be incorporated with the CE approach, as it helps to combat worrying rebound effects and limitations of the paradigm. One study put forward the idea that we need to move towards a sufficiency-based circular economy, which prioritises using less and avoiding unnecessary consumption over strategies which aimed at increasing circularity (Bocken et al., 2022). The researchers argue that an overall reduction of resource use can only be achieved with a CE approach which strives to limit consumption, instead of perpetuating the current trend of pursuing constant economic growth (ibid.). This is consistent with other research on this concept, which generally argues that the concept of sufficiency can be leveraged to overcome barriers to sustainability born out of neoclassical economic principles (Lamberton, 2005).

6.5 Reflections on Study

The following section aims to critically reflect on the worth and limitations of the research conducted in this thesis. The potential contributions that the study have made to existing literature are considered, especially with regards to the approach taken to understand the effectiveness of the CE from a sociometabolic perspective. Next, limitations of the study are discussed, with a specific focus on the study's analytical drawbacks, legitimacy, and generalisability of findings.

In the realm of sociometabolic regime scholarship, various criticisms have been put forth regarding the CE approach, particularly concerning technical limitations to various forms of circularity and the dubious notion of decoupling economic growth from environmental impact. This research builds upon these criticisms by utilizing qualitative data from on the barriers faced transitioning to circularity as a lens by which to gain a deeper understanding of what changes can be introduced to the concept for it to be more effective at reducing material and energy use.

Furthermore, my research contributes to the existing body of knowledge by examining the intrinsic appeal of concrete as a material, a perspective not taken in existing literature. This examination allows for the barriers for circular transition to be understood more clearly. It also works to justify the idea that an absolute reduction in reliance on concrete as a construction material may be needed in order to make real changes to society's metabolic profile, and transition to a new, more stable, sociometabolic regime.

Methodology

While my research offers valuable insights into the barriers of implementing CE strategies in the concrete industry, there are certain important limitations present in the research's methodology and analysis.

One limitation of the research is that the analytical framework was not consistently applied in a systematic manner in the analysis of the data obtained from interviews. Certain barriers raised in the interviews were not sufficiently analysed, given that they did not bear much relevance to the ideas presented in the theory of sociometabolic regimes. This presents an opportunity for future research to explore how the sociometabolic perspective can be used to conduct more comprehensive analyses of the transitional potential of environmental policies.

On the other hand, it should be noted that the chosen analytical framework was ultimately deemed to be have been appropriate for the study. While the methodology might have its own limitations, it provides a solid foundation for investigating the challenges and implications of circular economy strategies in the concrete sector. Therefore, it is recommended that this framework be utilised more frequently in future research to gain a broader understanding of the sociometabolic implications of environmental policies. This piece of research shows that sociometbaolic regime theory can be utilised in the formation of policy to provide a concrete understanding of the material and energy reductions necessary to transition to a more stable sociometabolic regime.

Another limitation of the study lies in the choice of interviewees. Due to the limited number of individuals interviewed, the results and conclusions drawn from their perspectives may not fully represent the diversity of the actors involved in the concrete, construction and design industries. For example, while three representatives of the concrete industry were interviewed, who all operate in different countries in the European Union, only one architect was spoken to. The insights obtained from a larger and more diverse sample could potentially provide a more comprehensive understanding of the barriers and motivations influencing the adoption of circular practices in this sector.

Legitimacy

The legitimacy of research lies in the validity and relevance of its research questions. By investigating the effectiveness of the CE approach to the concrete sector, the study contributes to the understanding of the overall feasibility of transitioning to a Circular Economy, as well as what changes need to be made for the approach to be successfully in achieving it's environmental goals.

To better understand the potential of recycling in the concrete industry, the study utilises data on in-use stocks and production. This data provides valuable insights into the feasibility of relying on current stocks to provide secondary materials for the sector. However, it is important to note that precise estimates of the amount of concrete elements that can be reused are currently lacking. Incorporating such estimates would significantly enhance the understanding of the potential for reusing concrete elements and further inform circular economy strategies in the industry.

In conclusion, the legitimacy of the research is supported by the formulation of valid research questions, the use of in-use stock data and production to understand the potential of circularity.

Generalisability

Main aspects that are generalisable are the barriers identified in the interviews, as literature shows that many of these barriers have been identified before. A limitation of the generalisability of this study is the analysis of said barriers. Using literature to analyse the limitations meant that a certain level of subjective interpretation had to go into framing the narrative of what implications of the barriers were. A more systematic use of the sociometabolic regime as an analytical framework would have allowed the results of this research to be more generalizable.

7 Conclusion

This thesis aimed to understand the effectiveness of the Circular Economy (CE) approach in reducing material and energy use in the concrete sector. Through a comprehensive investigation, the study identified two significant barriers that hinder the sector's transition to a circular economy. The research also identified changes which can be made to the current CE approach which would allow it to have more potential to solve dominant environmental problems.

The first barrier identified was that the rapid expansion of in-use stocks of concrete, along with rates of concrete production, suggests that in-use stocks cannot be relied on as a long-term source for secondary materials. Over the past few decades, in-use stocks and production of concrete have steadily increased, and this trend is expected to continue and even increase in severity, especially as developing nations undergo rapid urbanisation and development. However, this expansion of concrete stocks is incompatible with the principles of circularity. Circular economy principles advocate for the use of secondary materials from previous years' stocks, reducing the reliance on primary resources. If physical stocks expand every year, demands for materials needed for stock growth will not be able to be met by secondary materials from previous years stocks. Essentially, growing stocks necessitate growing resource use and less demand met by secondary materials.

The second barrier identified in this research is that the current dominance of neoliberal capitalist principles works to discourage the uptake of circular strategies. It was found that, the current CE approach, which aims to decouple economic growth from environmental harm presents a challenge when implementing the circular economy strategies. Unfortunately, one of the intrinsic characteristics of concrete is that it is cheap to produce, being made of abundant raw materials and created in processes fired by fossil fuels. Concrete, as it is now, is profitable. For this reason, introducing circularity into its production within a system that prioritises economic growth over reducing resource and energy use is particularly challenging.

To overcome these barriers and promote the adoption of circularity in the concrete sector, significant changes are required. Firstly, there must be a contraction of the physical stocks of concrete. This necessitates a fundamental shift from focusing solely on efficiency and growth to emphasising sufficiency. A sufficiency-driven CE approach would entail re-evaluating how much concrete is truly necessary and promoting responsible consumption and production practices. This would also involve updating policy to remove any legal and bureaucratic barriers faced by concrete producers when producing recycled concrete and formulating guidance on reusing concrete elements. The focus, however, would be a change in attitudes related to how much concrete is actually needed to meet society's needs.

In summary, the findings of this thesis highlight the barriers limiting the potential effectiveness of the CE strategy at reducing energy and resource use in the production and consumption of concrete. The continual expansion of concrete stocks and the emphasis on economic growth present significant barriers for achieving this aim. However, by reorienting the CE approach to one which prioritises sufficiency and contraction of in-use stocks, could be a decisive step towards bringing down levels of resource and energy use.

7.1 Practical implications and recommendations for non-academic audiences

The practical implications of this research highlight the need to reassess the theoretical underpinnings of the CE approach and its policy implications. Currently this policy approach attempts to help businesses and citizens carry on business as usual with as little change as possible to dominant power, institutional and economic structures. It would appear, from the results of this research, that the CE approach may fail, in its current form to address the environmental challenges we face. Therefore, there is a pressing need for policymakers to re-examine the objectives of the CE approach in a way which prioritises sustainability over continuous economic expansion.

A key practical implication is the integration of sufficiency considerations into CE policy frameworks. By shifting the focus away from economic growth to sufficiency, policymakers can pave the way for a sustainability transition that corresponds with real changes to our sociometabolic profiles. This would involve creating policy which attempts to place limits on the amount of concrete that is used after first determining how much is required to meet a population's needs. This would also entails fostering reduced production and consumption, as well as promoting the adoption of circular practices, despite being economically uncompetitive. Such a shift can gradually lead to reduced energy and resource use in the concrete sector.

Another practical implication of this research is the fact that the sociometabolic regime framework can prove useful in the formulation of environmental policy. By considering the sociometabolic dimensions of human activities policymakers can gain a deeper understanding of the resource flows, energy use, and environmental impacts associated with different sectors and industries. This analytical framework provides a valuable tool for formulating policies that align with the biophysical limits of our planet. By integrating the sociometabolic regime analytical framework into policy-making processes, policymakers can take concrete steps towards achieving a more sustainable and balanced relationship between human activity and the environment.

7.2 Recommendations for future research

To gain deeper knowledge on the effectiveness of circularity and adapt the CE approach to one which would contribute to real reductions in energy and resource use, there are several topics which warrant further research.

Firstly, there is a pressing need for data on in-use stocks of concrete, among other materials. This data would provide valuable insights into the amount of contraction required in the stock, enabling policymakers and stakeholders to make informed decisions on reducing the consumption of concrete. Additionally, it is recommended that researchers differentiate between traditional cast-in-place concrete and prefabricated elements within the stock. This would assist in determining the potential for reusing these components. Research also needs to be conducted to identify policy mechanisms and incentives that can encourage reduced concrete use, extended lifespan of structures, and the use of alternative materials. This would assist policy makers in instating a CE approach which focuses on attaining sufficiency.

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Appendix A: List of Interviewees

Code Name	Description	Date of Interview	Mode of Interview
Concrete Industry 1	General Manager for ready-mix subsidiary of major international concrete producer	24/03/2023	Personal communication via video call
Concrete Industry 2	Research and Development Specialist at a national Swedish building materials company which is a subsidiary of a major international cement manufacturer	30/03/2023	Personal communication via video call
Concrete Industry 3	Sustainability manager for major international building materials company specialising in manufacturing cement and concrete.	03/04/2023	Personal communication via video call
Architect 1	Architect and Landscape Architect for German architecture company	31/03/2023	Personal communication via video call
Academic Expert 1	Academic researcher conducting research developing ways to certify the quality of concrete	04/04/2023	Personal communication via video call
Academic Expert 2	Academic research conducting research on updating regulations for concrete recycling	04/04/2023	Personal communication via video call
Academic Expert 3	Academic research involved in EU project on reusing concrete elements	05/04/2023	Personal communication via video call
Academic Expert 4	Academic expert on circular construction	17/04/2023	Personal communication via video call

Appendix B: Interview Guide

Practitioners from concrete industry

1. Can you tell me a little bit about your role in __*name of company*___?
2. Are you aware of any sustainability goals that __*name of company*___ has?
3. To what extent does __*name of company*___ engage in activities related to the circularity with concrete?
4. What factors/ characteristics of concrete do you think allowed it to become such a successful/dominant building material?
5. Do you think that it is possible for a significant portion of concrete demand to be met by adopting circularity strategies? Why or why not?
6. What are some factors which act as barriers to implementing circular economy strategies for the production of concrete?
7. What are some specific factors that would need to change to make circularity strategies more widespread in the concrete industry?

Practitioners from field of architecture and design

1. Can you tell me a little bit about your role in __*name of company*___?
2. Are you aware of any sustainability goals that __*name of company*___ has?
3. To what extent does __*name of company*___ engage in activities related to circularity surrounding concrete?
4. What factors/ characteristics of concrete do you think allowed it to become such a successful/dominant building material?
5. Do you think that it is possible for a significant portion of concrete demand to be met by adopting circularity strategies for concrete? Why or why not?
6. What are some factors which act as barriers to implementing circular economy strategies for the concrete?
7. What are some specific factors that would need to change to make circularity strategies more widespread in the concrete industry?

Academic Experts on building materials/ reuse

1. Can you start by telling me a little bit about your academic background and research?
2. What factors/ characteristics of concrete do you think allowed it to become such a successful/dominant building material?
3. Do you think that it is possible for a significant portion of concrete demand to be met by adopting circularity strategies for concrete? Why or why not?
4. What are some factors which act as barriers to implementing circular economy strategies for the concrete?
5. What are some specific factors that would need to change to make circularity strategies more widespread in the concrete industry?

Appendix C: Table of Global Concrete Production in the 21st Century

Year	Annual global cement production (tonnes)	Annual global cement production after adjustment for other uses of cement (-10%)	Global concrete production (tonnes)	Percentage change
2000	1 660 000 000	1 494 000 000	11 952 000 000	
2001	1 740 000 000	1 566 000 000	12 528 000 000	5%
2002	1 850 000 000	1 665 000 000	13 320 000 000	6%
2003	2 030 000 000	1 827 000 000	14 616 000 000	10%
2004	2 190 000 000	1 971 000 000	15 768 000 000	8%
2005	2 350 000 000	2 115 000 000	16 920 000 000	7%
2006	2 620 000 000	2 358 000 000	18 864 000 000	11%
2007	2 810 000 000	2 529 000 000	20 232 000 000	7%
2008	2 850 000 000	2 565 000 000	20 520 000 000	1%
2009	3 050 000 000	2 745 000 000	21 960 000 000	7%
2010	3 280 000 000	2 952 000 000	23 616 000 000	8%
2011	3 630 000 000	3 267 000 000	26 136 000 000	11%
2012	3 820 000 000	3 438 000 000	27 504 000 000	5%
2013	4 030 000 000	3 627 000 000	29 016 000 000	5%
2014	4 150 000 000	3 735 000 000	29 880 000 000	3%
2015	4 060 000 000	3 654 000 000	29 232 000 000	-2%
2016	4 140 000 000	3 726 000 000	29 808 000 000	2%
2017	4 130 000 000	3 717 000 000	29 736 000 000	0%
2018	4 080 000 000	3 672 000 000	29 376 000 000	-1%
2019	4 190 000 000	3 771 000 000	30 168 000 000	3%

2020	4 190 000 000	3 771 000 000	30 168 000 000	0%
2021	4 400 000 000	3 960 000 000	31 680 000 000	5%
2022	4 100 000 000	3 690 000 000	29 520 000 000	-7%

Sources: (USGS 1999b; USGS 2000b, USGS 2001b; USGS 2002b; USGS 2003b; USGS 2004b; USGS 2005b; USGS 2006b; USGS 2007b; USGS 2008b; USGS 2009b; USGS 2010b; USGS 2011b; USGS 2012b; USGS 2013b; USGS 2014b; USGS 2015b; USGS 2016b; USGS 2017b; USGS 2018b; USGS 2019b; USGS 2020b; USGS 2023).