Addressing the challenges of reducing greenhouse gas emissions in the construction industry: a multi-perspective approach

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Declaration

The following sections of this thesis are based on work from jointly-authored papers:

Thesis sections	Jointly-authored papers
Chapter 2: The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector	Jackson, D. & Brander, M. (2019) The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector. *Journal of Cleaner Production*. 223. p739-746.
Chapter 3: Dirty works - enabling carbon management practices in the construction industry	Jackson, D. & Kaesehage, K. Dirty works - enabling carbon management practices in the construction industry. *Business Strategy and the Environment*. Under Review.
Chapter 4: Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities	Jackson, D. & Ascui, F. Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities. *Supply Chain Management: An International Journal*. Under Review.

The candidate confirms that they are the principal author of the papers listed above. For each article, the candidate undertook the literature review, data collection, analysis, drafting of the papers and made significant contributions to the conceptual frameworks used.

The candidate also confirms that this work has not been submitted for any other degree or professional qualification.

David Jackson

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Abstract

With average global temperatures rising and more extreme weather events recorded year on year, several counties have now declared a climate emergency. To address this emergency, 195 nations came together to sign the Paris Agreement, setting an ambitious target to keep the increase in global average temperature to well-below 2 ^{o}C, whist actively pursuing efforts to minimise the increase to 1.5 ^{o}C. Each nation was to determine its contributions to this target, stating how they would reduce carbon emissions within their control. Governments have in turn called for industry to significantly reduce their carbon emissions. Although the direct footprint of the construction industry is relatively small (for example, approximately 2.5% of the United Kingdom's (UK) annual emissions), these numbers rise drastically when the carbon embodied in the materials, the operation and use of the assets are also included. As an example, just over half the UK's emissions are directly or indirectly related to the construction and use of infrastructure assets. Given these figures, it is imperative that the construction industry takes steps to make deep cuts in its carbon emissions.

To help the industry along the carbon management journey, the CITT (Carbon Infrastructure Transformation Tool) Project has developed an embodied carbon calculation tool to aid decision makers in developing low-carbon solutions to reduce emissions on large infrastructure projects. The tool accounts for emissions from materials, transportation and construction of an asset. This scope was selected as it is what the contractor would have direct control over and is easier to gather accurate data for embodied emissions as opposed to the operation and use phases. However, the uptake of tools such as the CIT tool has been relatively slow in the industry.

This thesis takes a multi-perspective approach to understand the technological and social implications of developing and adopting an embodied carbon calculator within the construction industry. This is done first by assessing the risk of burden shifting where the use of an embodied carbon calculator may suggest emission reductions during the construction of an asset at the expense of increasing emissions elsewhere in the life cycle. Second, the thesis explores the barriers to the tool's adoption within the industry and provides recommendations for how to enable change within organisations to increase the use of carbon calculation tools. Finally, the thesis shows how collaboration can be improved to successfully reduce carbon emissions through the infrastructure supply chain.

Using a portfolio of papers, this thesis makes several important contributions. Although the risk of burden shifting has been discussed in the literature, there is little empirical evidence to support this. Paper 1 provides this evidence by studying four decision cases from a rail project. Paper 2 contributes to practice by developing a framework highlighting the steps required to overcome the barriers to the adoption of carbon calculators in the construction industry. Finally, Paper 3 brings together the literature on low-carbon supply chain management and collaboration success factors to understand how the industry can collaborate to reduce emissions through the infrastructure supply chain. Taken together, this thesis provides novel insights into the challenges of using carbon calculation tools, and advises policy and decision makers in how to improve carbon management practices within the construction industry.

Lay Summary

The impact of climate change is getting more severe by the year. Record temperatures are being exceeded annually, ice caps disappearing at alarming rates and extreme weather events are becoming more frequent and more intense. It has now been proven without doubt that climate change is a manmade issue caused by pumping vast quantities of greenhouse gases (GHG) into the atmosphere.

The construction industry has a major role to play with regards to GHG emissions. Embodied emissions (emissions from the extraction of raw materials, transportation and the construction of an asset) account for approximately 9% of the United Kingdom's (UK) total annual GHG emissions. This number rises significantly to just over half of the UK's annual emissions when the operation, use and maintenance of the constructed assets are accounted for. However, as well as being part of the problem, the industry is keen to be part of the solution by minimising the levels of GHG emitted during the construction of new assets.

The work of this thesis contributes to the Carbon Infrastructure Transformation Tool (CITT) Project. This project sought to develop an embodied carbon calculator to help designers, estimators and planners working on the development of large infrastructure projects to quantify carbon emissions quickly and accurately, with the aim of reducing embodied carbon emissions.

However, if the carbon calculator is only measuring embodied carbon emissions, is there a risk of burden shifting, where designed emission reductions during the construction of an asset lead to a net increase in emissions over the asset's lifetime? Paper 1 of this thesis explores this risk through a case study analysis. Four cases were examined to see if changes made to reduce embodied emissions during the design and construction phases led to emission changes in the operation and use phases of the asset. In three of the four cases assessed, the output from the tool suggested there was no evidence of burden shifting. In the final case (reducing the diameter of a railway tunnel) it was found that although building the smaller tunnel reduced GHG emissions during the construction phase, the extra energy required for each train to

pass through the tunnel led to a net increase in emissions in as little as six years of operation. For this reason, Paper 1 develops a set of guidelines to make sure that embodied carbon calculators are used with caution and recommends that going forward the industry starts to develop and use calculation tools that measure whole-of-life emissions.

The use of the carbon calculator detailed above can be described as a carbon management practice, defined as any practice or process that aids the management and reduction of carbon emissions. Paper 2 sought to understand the challenges of integrating carbon management within an organisation in the construction industry and show how these challenges could be overcome. Through a series of workshops and interviews conducted with practitioners and industry experts, this paper suggests that barriers to the adoption of carbon management practices can be classified as internal to the organisation (for example lack of buy in from leadership), external to the organisation (such as a lack of regulation), or shared by both the industry and the organisation (for example an individual's resistance to change). To overcome these barriers Paper 2 proposes a framework showing how to successfully integrate carbon management practices within an organisation. First, there must be a motivating factor external to the organisation incentivising them to adopt carbon management practices. Second, the organisation's leadership must take responsibility and are then able to develop strategies and processes around carbon management. Finally, carbon management must be integrated within each individual's job description rather than being the specific responsibility of a carbon manager.

As demonstrated in Paper 1, GHG emissions arise at several points during the construction and use of an asset. As such, the responsibility to manage those emissions will fall on a number of different stakeholders who will have to work together to reduce these emissions. Given the relatively low levels of collaboration in the industry, Paper 3 examines the challenges of collaboration and suggests how stakeholders can work together to reduce emissions through the lifetime of an asset. Case studies from different industries were examined where the principal aim was the reduction of GHG emissions through the supply chain. These studies highlight the importance of sharing information between parties and creating appropriate incentives to encourage each stakeholder to collaborate. The studies show that these mechanisms were supported by developing other competencies such as trust and leadership. Based upon these findings, the paper recommends the construction industry transitions from the traditional transaction model where work is often awarded to the lowest bidder, to a collaborative approach where the client acts as a facilitator encouraging different stakeholders to engage with emission reductions by building trust, developing incentive mechanisms and allowing information to be shared between the project teams.

Overall this research shows that there are several challenges involved in reducing carbon emissions on large infrastructure projects, from the choice of how emissions are calculated, how organisations manage carbon, and how supply chains collaborate to reduce carbon through the lifetime of the asset. This thesis provides practical recommendations on how to overcome these challenges to reduce the industry's GHG emissions going forward.

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Formal acknowledgement is made to the Construction Climate Challenge (CCC) – hosted by Volvo Construction Equipment, who have funded the CITT Project of which this thesis is part. Without your funding this research would not have been possible. Thank you for hosting us at your events and allowing us to contribute to your goal of increasing the awareness of environmental issues in the construction industry.

Special thanks also goes to Dr Noemi Arena and Damien Canning, who helped enormously in gathering data and introducing me to relevant people, and all those at Costain (and their PhD Community) who have provided support and feedback on my research. Thanks also to the participants who have taken part in workshops and interviews that allowed me to capture the data to make this study possible.

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Right now, we are facing a man-made disaster of global scale.

Our greatest threat in thousands of years.

Climate Change.

Sir. David Attenborough (2018)

Introduction

1 Initial Overview and Motivations

Since the start of the industrial revolution towards the end of the 18th century, there has been an unprecedented increase in the level carbon dioxide (CO_2) and other greenhouse gases (GHG) in our atmosphere. This increase in GHG emissions has led to the Earth's average temperature rising by more than one degree Celsius (^oC) over the past 100 years (IPCC, 2018), and if left unchecked, global temperatures could rise by more than 4.5 ^oC over the coming century (IPCC, 2013). Recently, at COP21 in Paris, there was a significant breakthrough with leaders from across the globe acknowledging that climate change is a common concern for humankind. They agreed that action should be taken to hold the increase in the global average temperature to well below 2 ^oC from pre-industrial levels with efforts made to limit warming to no more than 1.5 ^oC (UN, 2015).

The Climate Change Act of 2008 set a legally binding target for the United Kingdom (UK) stipulating that by 2050 GHG emissions will be at least 80% lower than the 1990 baseline (HM Government, 2008). Strengthening this target, in 2019, the UK became the first major economy to set in law targets to reduce the country's emissions to net zero by 2050 (BEIS, 2019). This decision was based on recommendations from the Committee on Climate Change (CCC) that called for every industry and sector within the UK economy to significantly reduce their emissions to help the UK reach this target (CCC, 2019).

During the industrial era, the construction industry has made significant contributions to the levels of GHG emissions in our atmosphere. For example, in the UK, power stations were erected across the country, buildings rose higher and higher, and cities and towns spread quicker than ever before. The construction and use of this infrastructure has been very carbon intensive, and today, more than 200 years from the start of the industrial revolution, emissions from the construction industry still make up a significant proportion of our overall emissions. Directly or indirectly, it is estimated that over half of the UK's carbon emissions are associated with infrastructure. A share that could rise to 80% by 2025 and 90% by 2050 if current practices are not changed (Mott MacDonald, 2013). In 1972, discussing the environmental impact of the construction industry, Pehr G. Gyllenhammer, the President and CEO of the Volvo Group stated 'we are part of the problem – but we are also part of the solution'. As part of the 'solution', the construction industry has started to take steps towards developing and implementing low-carbon practices. Following the Infrastructure Carbon Review (Mott MacDonald, 2013) and in line with the 2008 Climate Change Act, the Green Construction Board (GCB) issued a Low Carbon Routemap stating the aim of reducing carbon emissions in the sector by 80% by 2050 (GCB, 2013). The same year, Construction 2025 – a joint strategy from government and industry for the future of the UK construction industry – set an intermediary target of a 50% reduction in emissions by 2025 (HM Government, 2013).

To help the industry towards these targets, in 2016, PAS 2080 was released by the British Standards Institute (BSI) setting out a carbon management process for the infrastructure sector to aid the delivery of a carbon reduction programme for the whole carbon life cycle (BSI, 2016). PAS 2080 includes a number of components which make up this process including the quantification of GHG emissions, developing baselines, target setting and reporting. To help achieve these steps, carbon calculation tools are being developed for the construction industry. However, the uptake of such tools has been slow and several challenges exist due to the nature of the industry. For example, organisations tend to only report the emissions they have direct control over meaning that opportunities to reduce emissions further could be lost. Resistance to change can hinder organisations as they try to incorporate carbon management practices. Likewise, the vast number of stakeholders involved on a single project means there are challenges in developing consistent approaches between organisations and between different projects.

To that end, this thesis takes a multi-perspective approach to look at the development of a carbon calculation tool, shedding light on these challenges by asking how carbon emission baselines can be accurately reported, how organisations within the industry can adopt carbon management practices, and how the industry can work together to achieve deep cuts in carbon emissions. This thesis follows a portfolio of papers approach, where three papers are accompanied by introductory and concluding chapters which describe the overarching narrative of the thesis. The three papers which make up this portfolio are listed in Table 1.

Each of the papers in this thesis includes its own introduction, literature review and methodology. It is not the intention of this introductory chapter to replicate that content, unless doing so is particularly useful for highlighting the overarching aims of this thesis. The remainder of this introductory chapter is structured as follows: Section 2 provides an overview of the Carbon Infrastructure Transformation Tool (CITT) Project which the work of this thesis contributed towards, and the research questions answered in this thesis are also presented; Section 3 gives a brief overview of each of the papers; Section 4 provides an overview of the literature relevant to this research; Section 5 explores different theoretical perspectives considered; and

Table 1. A summary of the papers in this thesis.

Paper	Title	Authors	Publication	Status
Paper 1	The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector	Jackson and Brander	Journal of Cleaner Production	Published (2019)
Paper 2	Dirty Works - enabling carbon management practices in the construction industry	Jackson and Kaesehage	Business Strategy and the Environment	Revise and Resubmit
Paper 3	Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities	Jackson and Ascui	Supply Chain Management: An International Journal	Under review

Section 6 discusses methodological implications experienced throughout the research period.

2 The CITT Project

The work undertaken for this thesis was part of a larger research project between the University of Edinburgh Business School and the Costain Group (from now on referred to simply as Costain). Costain is a UK based contractor that specialises in providing smart infrastructure solutions to clients across a number of sectors including transport, water, energy and defence. They have over 3,500 members of staff and yearly revenues close to £1.5 billion (Costain, 2019). The section below provides an overview of the CITT project, giving details on the project objectives, the work performed and the contributions that are directly linked to this thesis.

With funding from the Construction Climate Challenge (an initiative hosted by Volvo CE to promote sustainability throughout the construction industry), the CITT Project was designed to deliver a step change in the way carbon emissions are managed on large infrastructure projects. This project contained five unique work packages based around the development of an embodied carbon calculator. Embodied carbon emissions are those associated with the build phase of a project, including the extraction of raw materials, transportation and the construction of an asset. Emissions from the operation, use, maintenance and decommission phases of a project are not accounted for in this tool.

The structure of the CITT Project is shown in Figure 1. The output for Work Package 1 was the completed CIT Tool. The deliverable for the four other work packages was an academic journal article. Although during the three years of the CITT Project contributions were made by the candidate towards Work Packages 1 and 5, the work directly undertaken for this thesis was focussed towards delivering the journal articles for Work Packages 2, 3 and 4 (which make up chapters 2, 3 and 4 of this thesis respectively). It should be noted that the candidate was recruited to complete this PhD as part of the CITT Project, and that although an outline of each work package existed prior to the recruitment, the candidate was responsible for creating a detailed

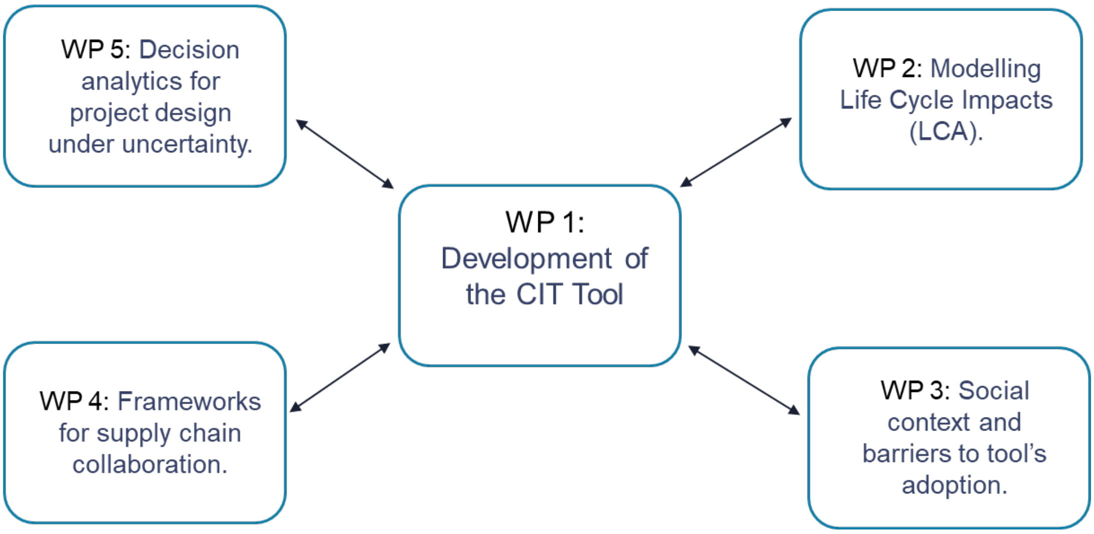


Figure 1. The structure of the CITT Project.

research design for Work Packages 2, 3 and 4. In the remainder of this section a brief overview of each work package is given, highlighting how the relevant research questions to this thesis fit with the associated work packages.

2.1 Work Package 1

Recently publications such as the Infrastructure Carbon Review (Mott MacDonald, 2013) and PAS 2080 (BSI, 2016) have provided evidence that reducing embodied carbon emissions can lead to reduced costs in procurement and delivery of infrastructure projects through design optimisation and improved efficiency. Work Package 1 (led by Costain) saw the development of an open access, web-based tool (the CIT Tool) designed to visualise and manage embodied carbon emissions. The tool uses a bill of quantities and a resource library to construct interactive dashboards to highlight the highest carbon and cost impacts across an infrastructure project. This then allows users to identify areas where efficiencies can be made to reduce the project's emissions.

2.2 Work Package 2

The CIT Tool has been designed to take account of embodied carbon emissions as this focuses on the emission sources within the control of the contractor and their supply chain partners, and avoids uncertainty with projecting use phase and end-of-life emissions. However, by omitting other life cycle stages there is a potential risk of ‘burden shifting’ where reductions in embodied emissions could lead to an increase in emissions elsewhere. Work Package 2 tested various scenarios designed to reduce embodied emissions to see if these led to an increase in emissions over the completed asset’s lifetime.

Research Question 1: Are there real-world situations in which burden shifting is likely to arise for infrastructure projects?

2.3 Work Package 3

The intention of making the CIT Tool open access was to engage and encourage the wider industry to use carbon calculators to manage and reduce their carbon emissions. However, several barriers prevent the use of such tools within the construction industry. Work Package 3 was designed to get a better understanding of the barriers to carbon management practices and the tool’s adoption within the construction industry, and to recommend steps to help organisations in the industry engage more with carbon management.

Research Question 2: Why have organisations in the construction industry been slow to implement carbon management practices?

Research Question 3: How can organisations in the construction industry improve the implementation of carbon management practices?

2.4 Work Package 4

Achieving carbon reductions in the most efficient way will require a high degree of collaboration between large numbers of diverse organisations. The output of the CIT Tool will highlight carbon hotspots that need to be addressed and will require supply chain members to work together to reduce their carbon emissions. However, it is highly unlikely that the costs associated with this will be split equally across all the parties involved. As such, collaborative frameworks will be required to achieve meaningful cuts in carbon emissions. Work Package 4 looks at the factors required to build successful collaborative partnerships within the construction industry.

Research Question 4: What factors are required for successful collaboration through the infrastructure supply chain?

2.5 Work Package 5

The aim of this work package was to understand decision analytics for infrastructure projects when there was uncertainty in the data, and explore the environmental and economic trade-offs associated with key design decisions in infrastructure projects. This was performed by investigating opportunities to incorporate uncertainty into the resource library designed in Work Package 1, and by developing a stochastic programming model to identify optimal environmental and economic performance.

3 Summary of Papers

The three papers written for this thesis address the technological and social challenges surrounding how to effectively reduce GHG emissions during the construction of large infrastructure projects. Each paper addresses these issues in a very different way: Paper 1 explores a technical issue with embodied carbon calculators; Paper 2 examines the challenges of adopting such tools within an organisation; and finally, Paper 3 describes how a collaborative approach amongst members of the infrastructure supply chain can help the industry to achieve deep cuts in GHG emissions. The remainder of this section provides a more detailed summary of the papers.

3.1 Paper 1

The title of Paper 1 is "The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector", which is now published in the *Journal of Cleaner Production* (2019).

The CIT Tool is an embodied carbon calculator, measuring emissions from the extraction of raw materials, the transportation of these materials and the construction of the asset. One of the motivations for undertaking a full life cycle assessment (LCA) is to avoid the risk of burden shifting, where decisions taken to reduce emissions in one stage of the assessment lead to an increase in emissions elsewhere in the project.

Paper 1 starts by challenging the proposed tool by testing four decision cases all aimed at reducing embodied emissions during the construction of a railway tunnel. In each case, the CIT Tool calculated a reduction in embodied emissions thus suggesting that the proposed changes should be implemented. Further examination showed that in three of the four cases no evidence of burden shifting was found, meaning that the efficiencies highlighted by the tool for reducing embodied emissions led to overall reductions in emissions during the asset's lifetime. However, an analysis of a decision case to reduce the diameter of a railway tunnel found that the initial savings in embodied emissions (due to less material and earthworks), were quickly outweighed by the increase in emissions during the use phase of the tunnel. This was due to the extra energy consumed by a train maintaining its speed going through the tunnel due to the increased friction and resistance in a smaller tunnel. Thus the decision should be to build the larger tunnel, contrary to the CIT Tool, even if this means greater emissions during the construction phase.

To overcome these issues, Paper 1 develops a heuristic set of guidelines that can be used to avoid the risk of burden shifting whilst using embodied carbon calculators. The paper then concludes by recommending that as the construction industry progresses with the skills and capacity to measure emissions, there should be a transition to incorporate whole-of-life assessments, and subsequently from whole-of-life attributional assessments to consequential assessments.

3.2 Paper 2

The title of Paper 2 is "Dirty Works - Enabling Carbon Management Practices in the Construction Industry", which has been submitted to *Business Strategy and the Environment* (under review).

Although there has been a growing awareness of the need to reduce emissions, the uptake of tools such as the CIT Tool, and other carbon management practices (which we define as any practice or process that aids the management and reduction of carbon emissions) has been relatively slow in the construction industry.

Paper 2 starts by examining the barriers to the adoption of carbon management practices within the construction industry, finding that barriers can be grouped into three categories: External Barriers; Internal Barriers; and Shared Barriers. External barriers are factors that an organisation has little or no control over, such as a lack of regulation on emission reductions or a client's willingness to incentivise change. Internal barriers are structural elements within an organisation that limit carbon management practices, such as the leadership's appetite to invest in low-carbon solutions or the organisation's internal processes. Finally, there are barriers that are shared, both within the organisation and the wider industry. These barriers, such as a resistance to change or a lack of collaboration need to be addressed both within the organisation and throughout the industry in general.

To overcome these barriers, the paper develops a three-step framework to ensure that carbon management practices can be adopted within an organisation. Firstly, external motivation in the form of regulation, incentives or industry pressure is required in order to encourage the organisation to act. Secondly, the organisation's senior leadership must be active in motivating change. This includes developing a carbon management strategy, overseeing changes to processes and seeking opportunities to collaborate with other industries. Finally, carbon management must be fully integrated into every team within the organisation (rather than having a specific carbon or sustainability team), with teams working together to develop the most efficient solutions.

3.3 Paper 3

The title of Paper 3 is "Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities", which has been submitted to *Supply Chain Management: An International Journal* (under review).

Infrastructure project emissions arise in many areas, including emissions embodied in the materials used, direct emissions from construction of the asset, and emissions resulting from the asset's use and decommissioning at end-of-life. Given the number of stakeholders involved in each of these stages, there is a need to work collaboratively to make sure emissions are minimised through the infrastructure supply chain. Paper 3 explores the challenges faced by the construction industry in reducing carbon emissions throughout the infrastructure supply chain and investigates how a collaborative approach can help overcome these challenges.

Based on a review of the literature on collaboration, the paper highlights eight success factors that are required for successful collaboration. These success factors were then tested through a meta-analysis of 16 academic and consultancy case studies that examined how organisations had collaborated to reduce emissions (or create energy efficiencies) throughout their supply chains. Based on these case studies, the paper reveals that information sharing and incentive mechanisms stand out as the main instruments for developing successful supply chain collaboration. These factors are then supported by building competencies in other factors such as leadership and trust.

To overcome the challenges of emission reduction and supply chain collaboration in the construction industry, the paper proposes the industry moves away from the traditional, transactional, project-based approach that the industry has used for years, and develops a client-centric framework where the client takes a leadership role, is able to be a trusted facilitator for information sharing, and has the ability to make sure collaborating partners are properly incentivised to reduce emissions.

4 Literature Review

As previously discussed, the three papers in this portfolio use a multi-perspective approach to understand the technological and social challenges relating to the use of carbon calculators in the construction industry with regards to driving down carbon emissions through the infrastructure supply chain. Within each paper, a review of the relevant literature is provided. The intention of this section is not to replicate those sections, but to provide a brief overview of the literature that binds the papers together, to provide further background literature that was not included in the papers due to space limitations, and discuss what overlap there is in the three areas of research.

4.1 The Construction Industry

The construction industry has been described as one of the most diverse and unstable sectors within the UK economy (Dainty et al., 2001), frequently suffering from cost overruns, programme delays and poor productivity (Briscoe et al., 2004). Behera et al. (2015) provide a useful diagram (shown in Figure 2) giving an overview of the phases of a typical construction project, identifying the work and stakeholders involved in each phase.

This traditional project framework has long been criticised by the industry. The Latham Report 'Constructing the Team' (Latham, 1994) was commissioned by the UK Government to understand the challenges faced by the industry. The report described the industry as ineffective and unable to deliver the needs of its customers. Four years later, the Egan Report 'Rethinking Construction' (Egan, 1998) raised deep concerns that the industry was still underachieving compared to other industries in the UK, highlighting that for the industry to advance, substantial changes were required in the industry's culture and structure to support improvement. However, a decade later in a speech at a Commons reception to mark the 10th anniversary of the report, Egan (2008) stated the industry was 'nowhere near the improvement we [the

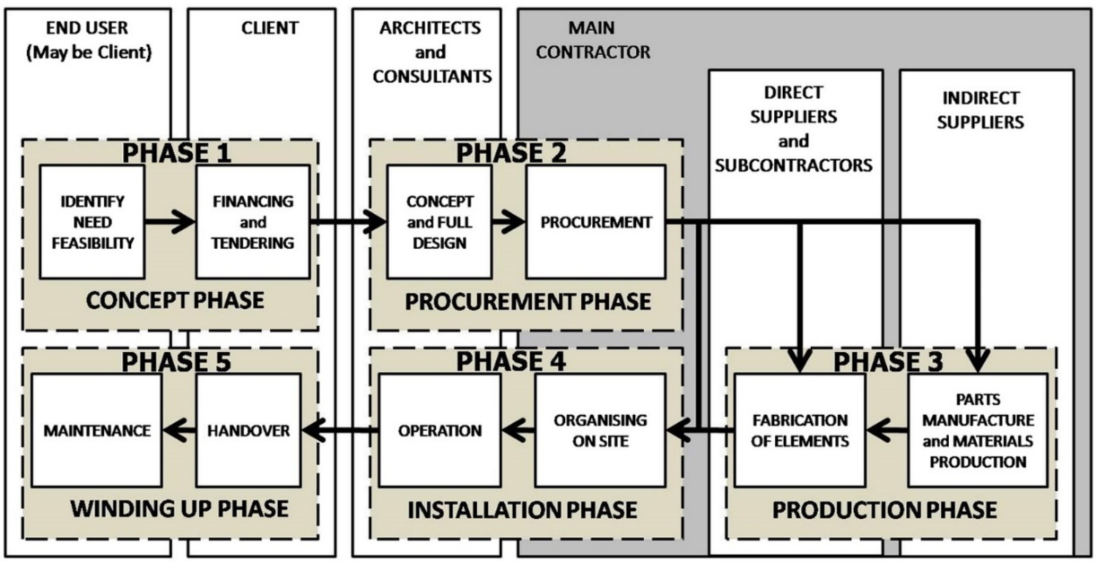


Figure 2. Phases in a typical construction project (Source Behera et al., 2015)

industry] could have achieved, or that I expected to achieve', concluding that he would only mark the industry at four out of 10 for effort. With concerns over how the industry was performing relating to cost and time overruns on projects, the UK Government (2011) published the 'Government Construction Strategy' to help reduce cost in the sector and stimulate growth. This led to the Infrastructure Cost and Infrastructure Carbon Reviews being released in 2013. Following this, the 'Farmer Review of the UK Construction Labour Model' (Farmer, 2016), also commissioned by the UK Government, concluded that the industry must 'modernise or die', stating that the current approach for designing and implementing assets was ineffective for the industry.

Although these reports span more than 20 years, it is worrying from the industry's perspective that a lot of the same issues appear throughout. For example, in 1994 and 2016, both Latham and Farmer are concerned with the level of fragmentation between the different stakeholders in the industry. Likewise, issues surrounding partnerships, collaboration, business strategies, costs and procurement models dominate these reports. As such, an important question to raise is what is making these things so difficult to achieve?

Scholars have looked to understand these challenges, both at an organisational and industry level. Within organisations, Vennström and Eriksson (2010) found that a resistance to change was an important barrier to overcome, both at an individual level, where an employee may have a short-term focus and will not want to engage in extra activities, and at an organisational level, where organisations are slow to adapt to new processes and technologies. Another issue is the work-winning process. Procurement strategies are based on competitive pricing where work is awarded to the lowest bidder rather than the best solution (Yuventi et al., 2013). This encourages a race to the bottom and leads to compromises in the quality of work (Hoonakker et al., 2010) in order to increase profit margins.

At an industry level, one of the most commonly described difficulties is the lack of long-term relationships in the construction supply chain, which can be contrasted with the situation in manufacturing (e.g. Fulford and Standing, 2014; Papadopulos et al., 2016; Skitmore and Smyth, 2009). Whereas supply chains in manufacturing are typically characterised by ongoing processes at a central location, aimed at creating efficiencies and reducing cost over a period of time, construction projects are often short-term, focussing on one-off designs which are built onsite. The short-term nature of project delivery means that organisations fail to develop meaningful relationships, which leads to short-term thinking where each stakeholder tries to do what is best for them rather than working together (Behera et al., 2015).

Another challenge is the degree of fragmentation in the construction industry, with a large proportion of small and medium sized enterprises (SMEs) which have entered the market due to low barriers to entry (King and Pitt, 2009). A typical large building project in the UK (£20-25 million range) may involve the main contractor managing over 70 sub-contracts, of which a large proportion may be for £50,000 or less (Mott MacDonald, 2013), and at times, the number of supply chain partners involved in a project can run into the hundreds (Wibowo et al., 2018). A lack of trust may also hinder relationships in the industry. In their study of the relationships between contractors and sub-contractors in the Netherlands, Broft et al. (2016) found that there was distrust between contractors and sub-contractors which led to a reluctance of each stakeholder to take the first step towards collaboration. Likewise Dainty et al. (2001) suggest there is mistrust between contractors and their suppliers, with the latter believing there will be no mutual benefits in collaborating.

More recently, there has been a growing need for the industry to take action to reduce its environmental impact, particularly with regards to reducing carbon emissions. Although the emissions from the construction process are relatively small (13.4 $MtCO_2e$ in 2017, or 2.4% of the UK's national GHG emissions on a production basis (ONS, 2019)), this rises to 48 $MtCO_2e$ when embodied emissions in construction materials are included (UK GBC, 2018), and up to 515 $MtCO_2e$ when emissions from the operation and use of all UK infrastructure are included – 53% of the UK's national emissions on a consumption basis (Mott MacDonald, 2013). Given these figures, it is important for each organisation to consider how they can most effectively reduce their emissions whilst overcoming resistance to change, and understanding how they can still maintain a profitable business model. At the same time, there is a need to develop collaborative partnerships that can help stakeholders work together to reduce the industry's carbon footprint. This will not be easy. As Behera et al.'s (2015) diagram shows (Figure 2), given the different stakeholders involved in each phase of the project, it becomes very difficult to manage emissions throughout the infrastructure supply chain. Therefore, it is important to develop an understanding of the challenges faced in reducing carbon emissions in the construction industry and how these can be overcome, both in organisations and the wider industry. This could also provide useful insight into how the industry can transition in the other issues stated above which may help to deliver the lasting change the industry has sought for so long.

To overcome some of these challenges, an important first step must be to measure, monitor and review all energy and GHG emissions that are expected from a project (Goggins et al., 2010), both at an organisational level and throughout the wider supply chain. Section 4.2 below details one framework designed to aid understanding of the environmental impact of a project, LCA.

4.2 LCA in the Construction Industry

As highlighted, there are several areas where emissions arise during the development and use of an infrastructure asset. LCA has become an important framework to understand the impact of these emissions through the lifetime of an asset. The LCA framework was designed to evaluate the environmental impact of a product, process or service through its lifetime, from inception to end-of-life (Monahan & J. C. Powell, 2011).

Several case studies have been carried out in the construction industry to assess the level of CO_2 emissions on certain construction activities (summarised in Table 2). Whilst some studies focus on specific materials, for example Purnell and Black (2012) perform a LCA for concrete, other studies assess the CO_2 emissions of a section of road (e.g. Biswas, 2014), or a whole building (e.g. Penaloza et al., 2016). The majority of studies use an LCA approach, however some of the case studies in Table 2 undertake an input-output (IO) analysis. Where an LCA approach gives results that are very specific to one project, which may then not be transferable to other projects

*Table 2. Summary of selected LCA case studies from literature. Values are blank if not stated. *Various if the paper provides more than one study. **If functional units not specified, then units of calculation are given.*

Author	Year	Approach	Building Type	Boundary	Lifespan (years)	Functional Units**
Cole and Kernan	1996	LCA	Office	C-2-Grave	50	GJ/m^2
Venkatarama Reddy and Jagadish	2003		Materials	C-2-Site		MJ/m^2
Treloar et al.	2004	Hybrid	Road	C-2- Use	40	GJ/m
Birgisdóttir et al.	2006	LCA	Road	C-2-Grave	100	1km of road for 100 years.
Asif et al.	2007	LCA	House	C-2-Site		GJ
Hacker et al.	2008	LCA	House	C-2-Use	100	kgCO_2/t
Huberman and Pearlmutter	2008	LCEA	Materials	C-2-Grave	50	The service provided by 4 28m^2 apartments over 50 years.
Langston and Langston	2008	Hybrid	Various*			GJ/unit and $/unit.
Chowdhury et al.	2010	LCA	Road	C-2-Site	20, 100, 200	mg/kg
Goggins et al.	2010	I-O	Office	C-2-Gate		GJ/kg or GJ/m^2
Monahan & Powell	2011	LCA	House	C-2-Site		The external, thermal envelope of a 3 bedroom, semi with a total foot print area of 45m^2 and total internal volume of 220.5m$^{3.}$
Zabalza Bribián et al.	2011	LCA	Materials	C-2-Site		1 kg of material.
Chang et al.	2012	Hybrid	School	C-2-Grave		kg/m^2 or GJ/m^2
Cuéllar-Franca & Azapagic	2012	LCA	House	C-2-Grave	50	Construction and occupation of a house over its lifetime.
Purnell	2012	LCA	Materials	C-2-Site		kgCO_2/m
Purnell & Black	2012		Concrete	C-2-Gate		eCO_2
Sansom & Pope	2012	LCA	Various	C-2-Grave		kgCO_2e/m^2
Stephan et al.	2012	LCEA	House	C-2-Use	50	GJ
Basbagill et al.	2013	LCA	House			kgCO_2e/kg

Biswas	2014	Hybrid	Road	C-2-Use	100	Tonne-kilometres (tkm).
Kumar et al.	2015	LCA	House	C-2-Grave	50	Living Area (m^2) *AND* no. people in house.
Zhang and Xu	2015		Dam	C-2-Use	50	gCO_2e
Kua and Maghimai	2016	LCA	Materials	C-2-Cradle		1 kg of structural steel.
Peñaloza et al	2016	LCA	House	C-2-Grave	50	Square metres of living area for 50 years.
Vieira & Horvath	2016	LCA	Concrete	C-2-Grave		mt

(Goggins et al., 2010), an IO analysis gives results that are much more general, usually the average of an entire sector, linking together the environmental data for all economic sectors where financial transactions occur between these sectors, and enables the allocation of the environmental data to the consumption of certain product groups (Miller & Blair, 2009). Bringing these approaches together, some studies use a combination of LCA and IO analysis (e.g. Biswas, 2014; Chang et al., 2012) as a hybrid, allowing for the integration of more reliable LCA data into the comprehensive I-O model (Treloar et al., 2004).

Although the case studies in Table 2 are not an exhaustive list of all case studies performed in this area, evidence of several challenges can be seen. For example, the system boundaries for each study are different. Whilst some studies complete a whole-of-life assessment (cradle-to-grave), others stop short of this measuring only emissions during the manufacturing and building of the asset (cradle-to-gate / -site). As well as differences in the boundaries, the functional units used in the assessments vary, as do the lifespans used to measure the operation and use phase emissions. Given all of these differences, it is perhaps not surprising that Dixit et al. (2013) found that it is difficult to compare the output of these assessments on a like-for-like basis.

The review of these case studies highlighted two important issues that are addressed through Paper 1. Firstly, of the 25 studies, the majority of assessments are undertaken for buildings or specific materials whilst only five look at infrastructure projects such as road and rail. Of the studies performed on infrastructure, the cases assess how changes to materials provide different emission scenarios rather than looking at how design changes to the asset affect CO_2 emissions. Secondly, out of the studies reviewed, only three (Hacker et al., 2008a; Huberman & Pearlmutter, 2008; Monahan & J. C. Powell, 2011) discuss the risk of burden shifting between life cycle stages, each focussing on housing rather than infrastructure projects. To this end, Paper 1 contributes by addressing this gap in the literature by providing empirical evidence of the risk of burden shifting on an infrastructure project.

4.3 Relation of Literature

The three papers which make up the portfolio of papers for this thesis share a common research object, a carbon calculation tool. Paper 1 provides an empirical test of the tool to determine its use in the construction industry, Paper 2 seeks to understand the barriers preventing the uptake of such tools within organisations in the industry, and Paper 3 investigates the challenges of gathering information for the tool and how collaboration amongst supply chain members can help overcome these challenges. The remainder of this section raises the question of overlap between the themes covered in these papers, asking what, if any, overlap there is in the literature?

A review of the literature finds a small number of papers that cover more than one of the themes of this thesis. For example, in their paper looking at greenhouse gas emissions in the construction industry, Arıoğlu Akan et al. (2018) undertake a LCA of the whole concrete supply chain in an attempt to look at how emissions can be reduced throughout the supply chain. They point to incentives and technology sharing between supply chain members as possible mechanisms to encourage emission reductions. As another example, Kogg (2003) looks at how environmental strategies can be implemented within a firm, but also show that it is possible to encourage supply chain organisations to consider their own environmental obligations. However, more commonly, the three areas of study tend to sit in their own domains. In total, papers from 73 different journals were cited between the three papers. Of these, only 10 journals crossed into more than one of the papers (some of which could have been the same article being cited in more than one of the papers in this thesis). Figure 3 shows the most common journals from which articles were cited in the three papers. It should be noted this figure only shows journals

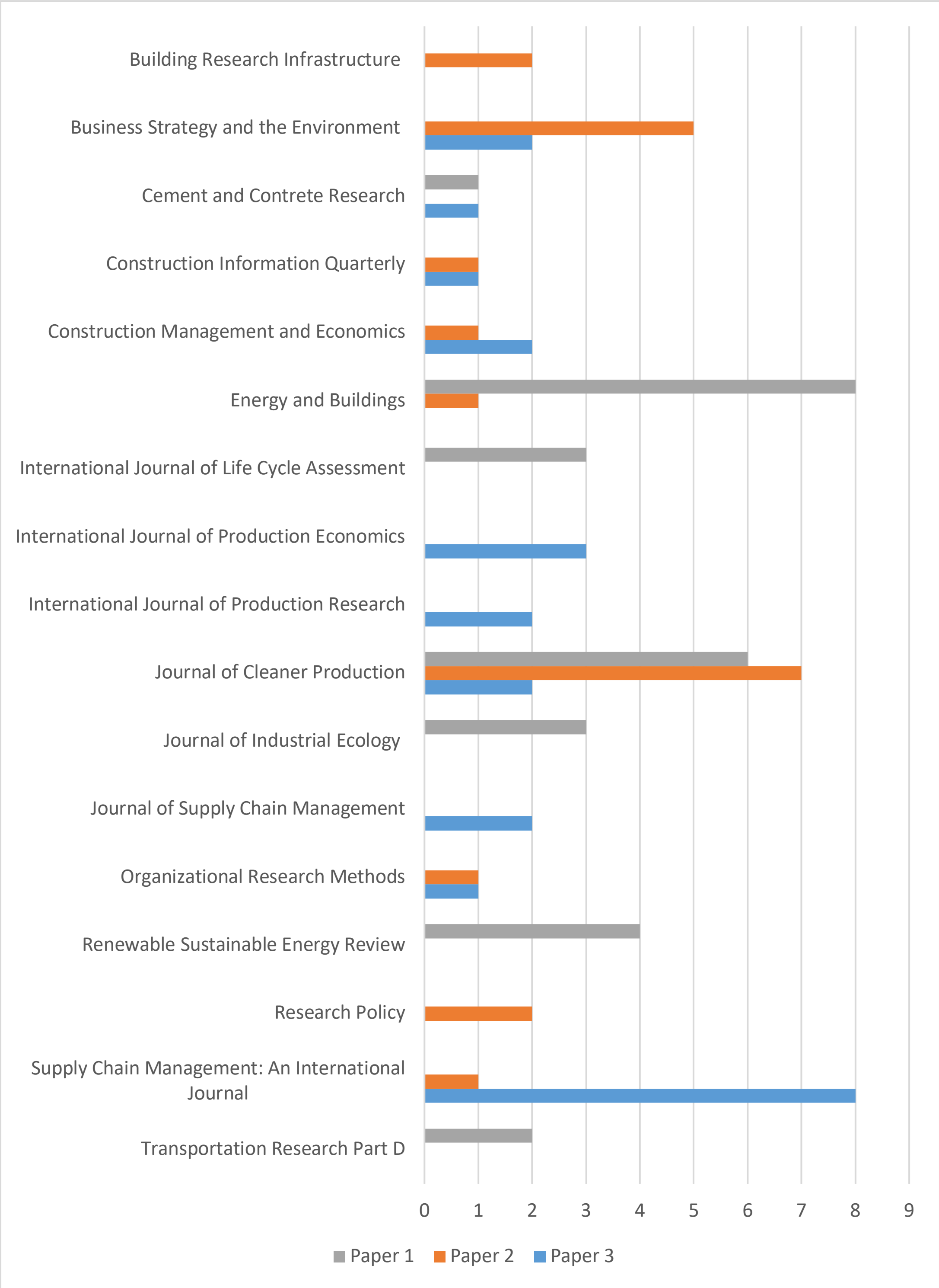


Figure 3. Summary of journals cited in Papers 1, 2 and 3.

where more than one paper from the journal was cited, either within the same paper, or distributed between the papers.

From Figure 3, it is clear to see the most common journals for each of the papers. For each of the papers, the most cited journals share the same theme as the paper they appear in, for example the International Journal of Life Cycle Assessment and the Journal of Industrial Ecology are often cited in Paper 1, whilst several journals about production and supply chain management are cited in Paper 3. A caveat that should be added is that the journals to which the three papers were submitted were more heavily cited than other journals in order to add to the discussions occurring in these journals.

It is more common that the journals that appear in more than one of the three papers relate to research methods (e.g. Organizational Research Methods) or to the construction industry (e.g. Cement and Concrete Research, Construction Information Quarterly or Construction Management and Economics). There is only one journal that is referenced in each of the three papers, the Journal of Cleaner Production, which had more than one article cited in each of the three papers. This journal describes itself as an 'international, transdisciplinary journal focusing on cleaner production, environmental, and sustainable research and practice' and given this description it is clear that the themes of the three papers all fit within this. However, a more thorough review of the articles cited from this journal would suggest that for the most part, the articles remain within their own disciplines in this journal without too much overlap with the other areas.

The purpose of this section was to discuss what, if any, overlap there is between the areas of literature that make up the three papers of this thesis. It is shown that there is very little literary cohesion between the themes covered in this thesis. As has been shown in Section 4.1 of this introduction, the construction industry has often been criticised for being slow to adopt new technologies, being resistant to change, and lacking collaboration and partnerships between organisations. Likewise, as will be shown throughout this thesis, there are several challenges that prevent the use of carbon calculation tools and carbon management practices being adopted throughout the industry. The challenges of integrating carbon calculators cannot be addressed simply by addressing the LCA, organisational change, or supply chain management literature, a multi-perspective approach is required. This thesis takes important first steps in bringing together these areas of literature which until now have been left to their own domains.

4.4 Mapping Exercise and Other Tools

In their review of the literature on embodied measurements, Dixit et al. (2012) raise a concern that there is no standard methodology for calculating embodied emissions. They highlight the need to develop a standard protocol and establish a robust dataset. The CIT Tool is not the first carbon calculator to be developed. Several other tools and databases have been created to try and address these issues. Many of these have been summarised in other academic literature (e.g. Cabeza et al., 2014; De Wolf et al., 2017; Haapio and Viitaniemi, 2008; Jrade and Abdulla, 2012; Lehtinen et al., 2011). The intention of this section is not to replicate these summaries, but to provide a more detailed review of a smaller number of tools that are specifically designed for infrastructure projects, summarised in Table 3. Whilst some of these tools are referred to in the introduction of Paper 1 (and in Table 4), the following describes in more detail some of the aspects of the tools which were not referred to in Paper 1 due to word count restrictions in the submitted manuscript.

Carbon calculation tools can be classified under two methodological approaches. The first approach has users build up their assessment by manually entering each item or material used in a spreadsheet and the tool then assigns a carbon emissions factor to that item (e.g. Scottish Water's CCAT and the Environment Agency's Carbon Planning Tool). The second approach is to take a pre-existing dataset which could be in the form of a bill of quantities or BIM (Building Information Modelling) data and automatically map the emissions next to each item (e.g. The CIT Tool or Mott MacDonald's Carbon Portal). The benefit of the second approach is that it

Table 3. Summary of other carbon calculators used in the infrastructure sector.

LCA Tool	Developer	Region
CCAT	Scottish Water	UK
Rail Carbon Tool	RSSB	UK
Carbon Planning Tool	Environment Agency	UK
Carbon Emissions Calculator	Highways England	UK
Carbon Footprint Calculator	Tarmac	UK
EToolLCD	ETool	UK / Australia
Klimatkallyl Tool	STA	Sweden
EC3	C-Change Labs	USA
Carbon Critical Knowledgebase	Atkins	Europe
Carbon Portal	Mott MacDonald	Worldwide
One Click LCA	Bionova	Worldwide

dramatically reduces the amount of time required to get a carbon assessment. Some tools, such as OneClick LCA, allow for both methods to be used depending on the level of assessment the user requires.

Haapio and Viitaniemi (2008) state that it is difficult, if not impossible, to compare tools due to the fact they are designed to assess different structures and take different life cycle stages into account. De Wolf et al. (2017) share these concerns and raise the issue of consistency amongst tools, highlighting the need for a standardised database so that the output from each tool is consistent. Whilst some tools are sector specific (e.g. RSSB's Rail Carbon Tool for rail or Highways England's Carbon Emission Calculator for road), and as such will require specific datasets to be used, others such as the Carbon Critical Knowledgebase from Atkins can be used across sectors. Most tools, including the CIT Tool have been developed using the ICE (Inventory of Carbon and Energy) database, a freely available embodied carbon and energy database for building materials (Hammond & Jones, 2008). A common concern of the industry was the age of this database as it had last been updated over a decade ago and as a result some of the figures were outdated. However, after the developers received additional funding it was updated during 2019 meaning it will likely be the 'go to' database for the construction industry for the coming years. Tools which cater for more than one country such as EToolLCD and OneClick LCA allow the user to choose the most relevant national database to meet their needs.

A common problem in LCA is the scope chosen for the assessment. Few of the tools reviewed actually complete a whole-of-life assessment. One reason for this is due to the long life of infrastructure assets and the fact that very few projects are decommissioned (Inui et al., 2011). As such, most tools assume that the completed structure will not be removed. Another reason for this is that other life cycle stages are not under the organisation's direct control, for example, Tarmac's Carbon Footprint Calculator only looks at cradle-to-gate emissions, because as a sub-contractor their concern is the product they develop rather than the whole project. Most tools summarised take into account cradle-to-completed construction, with some tools then allowing for operation and maintenance emissions to be entered, and others allowing for the manual entry of use phase emissions.

Whereas some tools have been designed by an organisation specifically for their own use, other organisations such as Mott MacDonald and Atkins have developed their tools and offer them as part of a consultancy package with a fee for the user. Tools developed by software developers such as EToolLDC and OneClick LCA are available to use online, or as an add-on to other software, for a fee. An intended unique feature of the CIT Tool was the fact that it was developed to be an open-access tool, freely available so that users would not have to use different tools. The motivation of this was to develop a standard approach across the industry. Recently however the EC3 tool, with backing from major organisations such as Skanska and Microsoft, has been developed offering a similar free-to-use format, publishing their code open source to allow integration with other software products.

It is worth noting that since the conception of the CITT Project in 2016, this landscape has changed significantly. Many of the tools discussed here have been developed during this period, and those that did exist prior to the project have changed from Excel spreadsheets to web-based platforms. Although there are still a few instances of Excel based tools (e.g. CCAT and the Carbon Planning Tool) most are now web-based tools offering a much quicker and more accurate calculation. The latest to make this transition was the Klimatkallyl Tool from STA. The scope of the tools has also changed during this time. The CIT Tool was designed as an embodied carbon calculator as at the time that was what the industry needed, while tools are now starting to take account of other life cycle stages. The speed at which these tools have changed and advanced highlights just how important accurate carbon calculations are to the industry.

5 Theoretical Perspectives

The term 'theory' is defined in the Oxford English Dictionary as a 'system of ideas intended to explain something, especially one based on general principles independent of the thing to be explained'. In an academic context, theories can be helpful in allowing the scholar to organise their thoughts, develop coherent explanations and improve predictions (Hambrick, 2007), and are important in knowledge accumulation, knowledge abstraction, creating new realities and legitimising knowledge (Suddaby, 2014). Colquitt and Zapata-Phelan (2007) allude to the fact that most of the top journals will 'demand' (p. 1281) that a paper contributes to theory, and although there are some scholars who think that theory can be overused (e.g. Hambrick, 2007; Pfeffer, 2014), most scholars would have a theoretical lens as the backbone of their research.

The remainder of this section provides an overview of some of the theoretical matters that arose during the period of study through the three papers. The main discussion points are around the requirement to emphasise theory in Paper 1, the choice of theory used in Paper 2, and of the contributions to collaboration theory made in Paper 3.

5.1 Paper 1

Within the LCA literature theory is rarely mentioned. If it is, it is in the sense of method development rather than explanatory theory. As an example, in the editorial opening of an edition of the International Journal of Life Cycle Assessment, Baitz et al. (2013) explore the 'harmony' of theory and practice in LCA. It is important to state here that the 'et al.' here lists 21 other co-authors which highlights that this is not just the view of one or two scholars in this field. Despite the use of the word 'theory', the discussion in the article is very much about balance between method development and LCA application. They state that method development can improve the application of LCA in practice, and at the same time the use of LCA can help provide feedback which will help scholars improve the methods.

Areas of method development discussed by Baitz et al. (2013) include determining the scope of the study, and the use of attributional or consequential LCA techniques. The goal of Paper 1 was to look at these issues and provide practical recommendations to enhance the methods used in LCA assessments. Thus, Paper 1 contributes to theory where theory is interpreted as method development. As the International Journal of Life Cycle Assessment is well regarded by scholars in the field that Paper 1 was written for, this supports the use of Baitz et al.'s (2013) classification of theoretical contribution for the purpose of this paper.

As a separate point, it was interesting that after submitting Paper 1 to the Journal of Cleaner Production, a publication that has a wide audience in the LCA community, that one comment from the editor stated the need to place greater emphasise the paper's contributions, both to theory and practice. It is interesting to see that the Journal of Cleaner Production seems to have followed other journals by expecting research to be theorised. Taking on board this comment, a small sub-section (Paper 1 – section 5.2) was added to clarify the practical and theoretical contributions for the approved manuscript.

5.2 Paper 2

The primary objective of Paper 2 was to understand the social barriers preventing carbon management practices being implemented within organisations, and how these could be overcome. Given the nature of this research there were several theoretical lenses that could be used to provide an explanatory framework, and an early problem at the start of my studies was in determining the 'right' lens to use. Advice on the approach to take varied significantly depending on who I spoke to. Accounting scholars saw challenges around how the data from the calculation tool was used and suggested integrated reporting (Eccles and Krzus, 2010) or the balanced scorecard (Kaplan and Norton, 1996) as possible approaches to use. Innovation scholars were interested in how the carbon calculator would spread through the industry and suggested theories including the diffusion of innovation theory (Rogers, 1995) and innovation systems theory (Edquist & Hommen, 1999). In the sub-sections below, more information is presented on some of the other theories considered, showing how Paper 2 could have been approached, and why the theoretical approach was, or was not, taken.

5.2.1 Institutional Theory

Organisational theory focuses on organisations, how they are shaped by their environments, how those environments effect intra-organisational functioning, and how organisations shape societies (Greenwood, 2016). Rather than studying individual organisations, institutional research focuses on field-level processes and institutional context. Meyer and Rowan (1977) found that within an industry, organisations followed similar forms and conventions to find acceptance within the industry. DiMaggio and Powell (1983) later highlighted institutional isomorphism, stating that institutions within a field act in the same way, and this is important to be seen as legitimate by others who are successful in that field. Since these conceptual foundations, As Lawrence and Suddaby (2006) allude to, there has been an emphasis in institutional studies to understand the role of actors in creating, transforming and maintaining institutions. Institutional theory has spread broadly to include several topics such as institutional entrepreneurship (e.g. Eisenstadt, 1980), institutional change (e.g. Leblebici et al., 1991), institutional logics (e.g. Friedland & Alford, 1991) and institutional work (e.g. Scott, 2001) to name a few.

One theoretical perspective considered for Paper 2 was to use institutional logics and hybrid organisations. Institutional logics are the beliefs and rules that shape the thoughts and behaviours of actors, and are the shared assumptions and ideas that provide a framework for reasoning and providing legitimacy (Dunn & Jones, 2010). Hybrid organisations are defined by combining two previously separate institutional logics (Battilana & Dorado, 2010), making them by nature 'arenas of contradiction' (Pache & Santos, 2013, p.972). For example, an impact investment organisation balances the need to make money (commercial logic) with wanting to improve services (development logic). Although hybrid organisations generally refer to organisations where the two logics are as important as each other, it would be very rare to find an organisation that does not have multiple logics.

Within the construction industry the dominant logic would be commercial values, such as profitability, however to a certain extent this would be balanced by the need to follow health and safety requirements. A smaller, but growing logic would be environmental and sustainability concerns and corporate social responsibilities (CSR). Prior research has looked at sustainability and hybrid organisations (e.g. York et al., 2016), but an interesting question for this paper could be how can a minor logic be amplified to become as dominant as the main logic within an organisation whose primary goal is not sustainability?

The decision not to move forward with this approach was based upon the fact that this would have been looking far more broadly at sustainability issues, whilst the focus of the paper was on the adoption of a carbon calculator which would not have been considered as a logic in itself. Although Paper 2 does go on to mention broader issues within the organisation and the industry, the primary objective of the paper was to understand the challenges to the adoption of the tool within an organisation.

5.2.2 Constructive Technology Assessment

Technology assessment (TA) developed in the 1960s and was a form of policy research used for examining the short- and long-term consequences of the application of technology (Banta, 2009). This could assess societal, economical, ethical or legal issues with the goal of providing policy makers with the information required to make decisions. TA is a wide-ranging field, not just assessing technology, but researching the diffusion of technology and the rate of acceptance of technology throughout society (Banta, 2009). TA had a 'two-track approach' (Rip et al., 1995) that separated promotion of technology from control and regulation. However, with this approach, the understanding of the development of technology could be overlooked until the product was already on the market.

To overcome this issue, a new form of TA was developed. Constructive technology assessment (CTA) was introduced in the 1980s in the Netherlands. Initially called the 'integration of science and technology in society' in a policy memorandum (1984), CTA developed to broaden the concept of technology assessment to take into account the design and development of new technologies, and also the actors using it (Rip et al., 1995). CTA activities can take the form of workshops, conferences or reports where the aim is to promote discussions between social actors and designers to develop the technology, however it is only after influencing design or technical changes that activities become CTA practices (Schot, 2005).

Socio-technical transition theories aim to understand the co-evolution of technological systems and societies (Lawhon & Murphy, 2011). Understanding socio-technical scenarios is very important for CTA as it allows the technology developers, at an early stage, to consider how the technological development will be used by actors once completed. In CTA, the use of socio-technical scenarios is not just an exercise for showing possible futures, it also embodies and articulates patterns and highlights patterns that actors tend to follow (Rip & Kulve, 2008). Schot and Rip (1996) describe three generic strategies for CTA: technology forcing, where regulation states the requirements and use of the technology; strategic niche management which reverses this idea and starts with technology developers finding out how their ideas can be introduced and expanded from the start of the process; and finally, alignment between the two strategies, where interactions between policy makers and technology developers are used to foster new ideas. This enables legitimacy, making sure that technological developments are aimed at meeting the desired requirements.

Many of the methods used for data collection in CTA were used for Paper 2, for example workshops aimed at getting feedback for the development of the CIT Tool. As a result of this feedback changes were made to the tool in future iterations. However, the interest of this paper is to go beyond the development of the carbon calculator and understand the barriers to its adoption in the industry. Many barriers were to do with the tool, and the way it can be used within organisations, but the majority of the barriers were unrelated to technology. As such, as a method of data collection, CTA has been very useful, but as a framework to support theoretical findings this approach was not taken forward.

5.2.3 Multi-Level Perspective

As described in the section above, Schot and Rip (1996) propose two strategies for the socio-technical transition: technological forcing where regulation is used to drive forward changes in technology, and strategic niche management, where developers innovate and successful ideas make it to market. Rip and Kemp (1998) built on this by proposing a third angle, the technical regime, which is described as an intermediary between specific innovations and the overall socio-technical landscape, and creates a multi-level framework. Nelson and Winter (1982) use the phrase 'technological regime' to define routines, or predictable patterns of behaviour within firms.

Building upon this further, Geels (2002; 2005) introduces the multi-level perspective (MLP), a framework for analysing socio-technical transitions and systems innovation at three levels: the landscape; the socio-technical regime; and the technological niche. The socio-technical regime varies slightly from the technical regime described by Nelson and Winter (1982) and Rip and Kemp (1998), and is defined as a 'semi-coherent set of rules carried by different social groups' that help to provide stability through their interactions (Geels, 2002, p.1260). These three levels together make a 'nested hierarchy', meaning that niches are embedded within regimes, and regimes are embedded in landscapes, as shown in Figure 4.

Technological transitions happen as an outcome of linked developments at multiple levels (Geels, 2002). Geels (2005) highlights four stages for a niche to become part of the mainstream. First novelties emerge in niches, within the context of the existing landscape and regime. Here there could be several different and opposing technical ideas competing with each other, with actors attempting to find the best solution. The second stage sees the novelty used in small market niches where technical specialisation is provided. Gradually a community comes together developing this new technology and refines it along a transition pathway where it is improved through learning processes. Through this stage a stabilisation of the new 'rules' (e.g. design or user preferences) are developed making sure the new technology will benefit the regime. The third stage sees a breakthrough of the new technology into the regime with wide diffusion and competition within the regime. The new technology challenges the existing regime, which can be aided when opportunities are created by the landscape putting pressure on the existing regime. Other

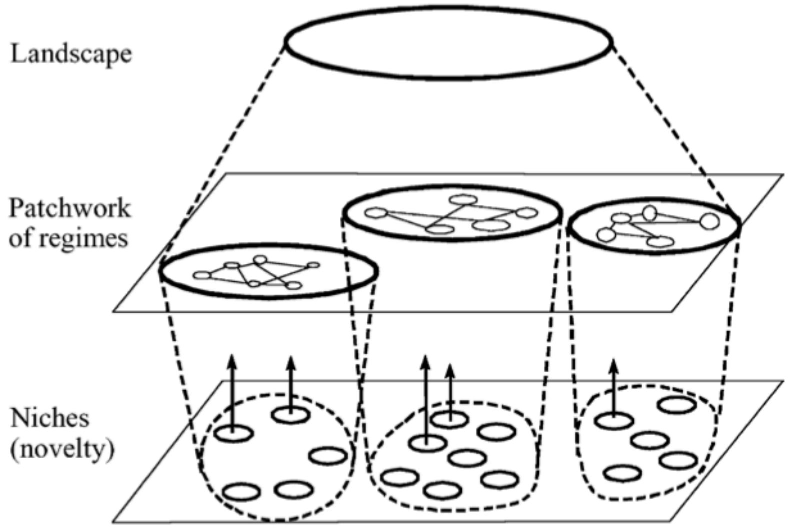


Figure 4. Multiple levels as a nested hierarchy (Source Geels, 2002).

pressures may come internally from the regime where current technology cannot provide a solution. The fourth and final stage is when the new technology replaces the old regime and is accompanied by wider changes to the socio-technical regime. These stages are summarised in Figure 5.

A criticism of the MLP is that the cases used by Geels to create the framework are historical and could be misleading if taken out of context (Genus & Coles, 2008). Likewise, Raven et al. (2012) question the temporal dynamics of transitions saying the framework does not take into account the interactions of actors in space and time. One approach for Paper 2 would have been to create a case study around the development of the CIT Tool and look at how this transitioned and changed the socio-technical regime within the construction industry. However, this would have required a longitudinal study, and as the tool was being developed alongside this research this proposal would have been outside the timeline for the project.

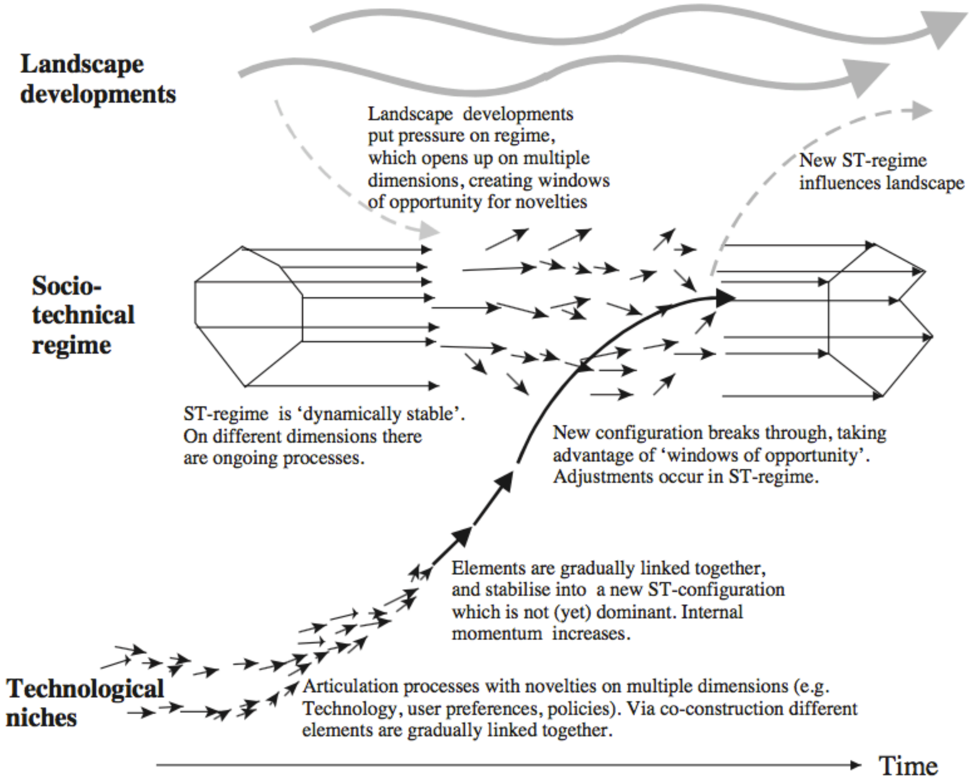


Figure 5. The multi-level perspective (Source Geels, 2005).

5.2.4 Eco-innovation

Another option considered for Paper 2 was to look at how eco-innovation could be implemented in the construction industry. Eco-innovation is considered to be one of the key factors for tackling the challenge of sustainability whilst at the same time improving the competitiveness of organisations (Tamayo-Orbegozo et al., 2017). Eco-innovation refers to new technologies (Carrillo-Hermosilla et al., 2009) as well as other organisational and social practices including the development of 'products (goods and services), processes, marketing methods, organisational structures and institutional arrangements' (OECD, 2008, p. 19), and is seen as a direct pathway for implementing the shift towards a low-carbon economy (Peiró-Signes & Segarra-Oña, 2018). Various scholars have tried to identify reasons and accelerators for eco-innovation. Horbach et al. (2012) and Zubeltzu-Jaka et al. (2018) highlight market pull, regulatory push/pull, technological push, and organisation-specific factors as important drivers. Del Río (2005) and Carrillo-Hermosilla et al. (2009) identified barriers and drivers to eco-innovation and group those in terms of internal (e.g. financial situation or technical capability) and external factors (e.g. policy) to an organisation as well as technological barriers. Internal drivers to the organisation may include the organisation's leadership (Arnold & Hockerts, 2011) or the organisation's environmental capabilities (Kesidou & Demirel, 2012), whilst external drivers include competitive pressures from rival organisations (Cai & Li, 2018) or regulations (Horbach et al., 2012).

One approach to Paper 2 could have been to explore the challenges of adopting eco-innovations within the construction industry. Conceptual models have been developed to understand the drivers for the adoption of eco-innovation (e.g. Bossle et al., 2016) but as Xavier et al. (2017) allude to, many of the models that have been developed in recent years have a degree of generalisation and often fail to give the level of detail required to show how an organisation can successfully incorporate these strategies, stating that there is no conclusive evidence to support these models. To that end, through a case of the construction industry, the paper could have provided empirical evidence to emphasise the requirements for eco-innovation to be adopted.

However, with the emphasis of the other two papers within this portfolio being on the development and use of a carbon calculator, it was decided that in order to maintain the theme throughout the thesis, that the focus of this paper should also be on the tool and carbon management practices, rather than broadening the conversation to look at eco-innovation.

5.2.5 Grounded / Inductive Approach

After investigating many different approaches, the decision made was to use an inductive research approach. Where deductive research has a theoretical structure in place prior to empirical testing (Gill & Johnson, 1997), inductive research follows a grounded approach (Glasser & Strauss, 1967) to develop general inferences out of observations (Bryman, 2008). Paper 2 uses the 'Gioia methodology' (Gioia et al., 2012) to analyse the barriers to the tool's adoption observed from the workshops and interviews. The barriers described by the participants became the first order concepts which are described by Gioia et al. (2012, p.18) as 'informant centric' data. Similar barriers were then grouped together by the candidate in second order themes which Gioia et al. (2012, p.18) describe as 'researcher centric' themes, before being grouped further into aggregate dimensions. These dimensions were then used to develop a framework to show how to overcome the barriers, and drive the adoption of carbon management practices in the construction industry.

Before finishing this section, it should be noted that by ruling out the use of some of the theories mentioned above was not to say that they would not have been of use and that my chosen route was the 'right' decision. Other approaches would have generated different insights which would have produced interesting research, however I felt the chosen approach was best suited to the research proposal put forward for Work Package 3 of the CITT Project.

5.3 Paper 3

Section 3 of Paper 3 touches upon several factors that make up the collaborative process. The point of this section is not to repeat that discussion, but to give some understanding of prior work on collaboration theory and show how Section 3 of Paper 3 contributes to this existing body of literature.

Collaboration between organisations aims to accomplish a desired outcome that no single organisation could achieve acting by themselves (Wood & Gray, 1991). In her seminal work on collaboration, Gray (1989, p.5) defines collaboration as:

> a process through which parties who see different aspects of a problem can constructively explore their differences and search for solutions that go beyond their own limited vision of what is possible.

Since then, many other definitions have been developed by researchers. From these definitions Bedwell et al. (2012, p.130) develop an overarching definition, describing collaboration as:

> an evolving process whereby two or more social entities actively and reciprocally engage in joint activities aimed at achieving at least one shared goal.

There are many strands of research in collaboration theory which can be divided into two main groups of literature, collaboration frameworks and interorganisational arrays and typologies (Williams, 2016). The majority of literature can be classified as system-based collaboration frameworks which assume that collaboration is a dynamic process. Wood and Gray (1991) develop one of the first collaboration frameworks. This framework was based on a linear antecedent-process-outcome framework, where the antecedent driver is either to resolve conflict or to advance shared visions between organisations and the expected output is joint agreement at the end of the collaborative process. Gray (1989) describes the collaborative process as three phases: problem setting; direction setting; and implementation, but as Wood and Gray (1991) state, it is the process element of collaboration that is least well understood (Thomson et al., 2009; Williams, 2016).

Developing our understanding of the collaborative process further, Ring and Van de Ven (1994) developed a cyclical process of cooperative interorganisational relationships. This involves a cycle of negotiations, commitments and executions, with assessments at each stage. If both parties assess that it is mutually beneficial to continue they will, but if not the next stage will not occur. This also highlights why collaborative arrangements develop and dissolve over time. Thomson and Perry (2006) also shed light on the collaboration process's 'black box'. They elaborate on Wood and Gray's (1991) framework and describe five dimensions of the collaboration process: governance; administration; organizational autonomy; mutuality; and trust, which when adhered to will increase the likelihood of successful collaboration.

As well as system-based frameworks, thematic frameworks have been developed which rather than discussing the dynamic process of collaboration discuss the key variables of interest in collaboration as themes (Williams, 2016). Huxham (2003) suggests five overlapping themes coming from issues that practitioners find in collaborative working: common aims; power; trust; membership structure; and leadership. Although this approach does not give detail on the processes involved in collaboration, it better identifies key aspects of collaboration that will be more intuitive and beneficial to a practitioner (Williams, 2016).

The second way that collaboration theory is conceptualised is by using interorganisational arrays and typologies. These are typically characterised by tables where the horizontal axis gives an interorganisational interaction, form or relationship while the vertical axis details specific organisational dimensions that merit study, such as leadership, strategy or organisation type (Williams, 2016). Gray (1989) classifies four forms of collaboration based on their expected outcomes, 'exploratory', 'advisory', 'confederative', and 'contractual' collaboration, while Margerum (2008) shows the functional differences between three types of collaborative approaches: 'action', 'organisational' and 'policy'. Similarly, McNamara (2012) highlights ten dimensions – or 'elements' – taken from the literature on interorganisational theory to distinguish between cooperation, coordination and collaboration: design; formality of the agreement; organisational autonomy; key personnel; information sharing; decision making; resolution of turf issues; resource allocation; systems thinking; and trust.

Williams (2016) concludes by offering a comparison between the two approaches. He states that frameworks highlight the complexity of collective action and give a better understanding of the processes involved in collaboration which typologies can miss. Typologies are better for showing the relationships between interaction terms, such as cooperation or collaboration. Finally, where typologies give detailed accounts that relate to specific cases, frameworks can be ambiguous when trying to make linkages across different types of collaboration.

As the intention of Paper 3 was to understand one specific form of collaboration, supply chain collaboration, and the factors involved in successful collaboration in this area, the paper uses a framework based approach to better understand the factors required in the collaborative processes for successful supply chain collaboration in the construction industry.

5.4 Summary

This section has explored some of the theoretical matters which arose during the past three years of study. To start, Section 5.1 touches upon an important question of what defines a theoretical contribution? I show that within the LCA community (e.g. Baitz et al., 2013), method development is classed as a form of theoretical contribution. As such, using this definition of theory, Paper 1 makes important contributions by addressing challenges associated with burden shifting when using embodied carbon calculators. Secondly, this section showed that there are several different theoretical perspectives that can be used to address a research area. In Section 5.2 I explore some of the theoretical lenses that could be been used to understand the barriers and enablers to the tool's adoption within the construction industry, highlighting that different approaches would have led to different insights and stating the reasons for choosing to adopt an inductive research approach. Finally, Section 5.3 provides important background on collaboration theory, to show how the testing of eight collaboration success factors in Paper 3 speaks to and advances this existing body of literature.

6 Methodology

6.1 Outline and Overarching Linkages

As with previous sections, it should be noted that each paper within this portfolio contains a methodology section which outlines in detail how data was collected and analysed. The following section is not intended to repeat this, but to provide more detail about the overarching linkages to the three approaches and outline some of the challenges faced which shaped how the research was undertaken.

Successfully reducing GHG emissions in the construction industry requires overcoming several technological and social challenges. As such it is important to take a multi-perspective approach to understand how best to achieve emission reductions. As this research draws on literature from different fields, it was important to use methodological approaches that were appropriate for each discipline. To ensure that the three papers in this portfolio were all aligned to the broader theme of overcoming challenges of reducing GHG emissions in the construction industry, a common research object (the CIT Tool) was used in each paper. This helped to provide a link between the papers and gave a rich understanding of the issues surrounding the use of the tool by exploring three different types of challenge. The use of the CIT Tool fitted into the methodology of each paper as follows:

The objective of Paper 1 was to understand if there was a risk of burden shifting where reducing emissions during one phase of a project led to increases in emissions elsewhere. To explore this risk, the CIT Tool was used to test four decision cases where design changes had been made to reduce embodied emissions during the construction of a project. Where there was a potential risk of burden shifting a full LCA was performed.

Paper 2 was designed to understand the challenges of integrating a carbon calculator such as the CIT Tool into an organisation within the construction industry, and what was required in order to overcome these challenges and successfully implement the tool and other carbon management practices within an organisation. To address this, two industry workshops were held, the first with environmental / sustainability professionals and the second with practitioners who would use the CIT Tool once completed. Following these workshops a series of semi-structured interviews were conducted to get specific insights into how the carbon calculator, and carbon management practices more generally, could be integrated within an organisation.

Finally, the aim of Paper 3 was to explore how a collaborative approach could help reduce GHG emissions throughout the infrastructure asset supply chain. Issues raised from the previous research had shown that suppliers may be unwilling to share the data required for the CIT Tool to be used. As such, it was important to understand why this would be an issue and what steps were required to address these issues. To do this, a review of academic literature and consultancy case studies was performed, where the objective of each study was to highlight how a focal company had engaged with their supply chain to reduce carbon emissions or improve energy efficiency. These case studies were supported by findings from engagement workshops with a contractor and their supply chain to understand the difficulties around reducing emissions on large construction projects.

6.2 Methodological Challenges

Over the course of the three years of this research project there have been several methodological challenges that have had to be overcome. Information on these challenges, and how they were overcome is provided below.

Perhaps the biggest challenge to overcome was the limited access to data. The original research design for Paper 1 was to use the CIT Tool on a live construction project to demonstrate how the tool could be used to reduce emissions during the design phase. However, it soon became apparent that there was insufficient data to perform an accurate analysis and that it would be months, if not years, before there would be a suitable level of data to do a comparative analysis. For this reason, the decision was made to perform the case study on a hypothetical railway tunnel. A quantity surveyor was briefed on the research proposal and shared designs for a hypothetical tunnel with details about the materials required and the expected emissions. From this it was possible to carry out the assessment as detailed in Paper 1.

Issues around access to data also emerged during the data collection stage of Paper 3. Early work on this paper had looked at how collaboration could help improve emissions efficiency in the infrastructure asset supply chain. By reviewing literature on this topic, a framework had been developed and a workshop was planned where a contractor and their supply chain could examine the framework and provide feedback on this. A date had been set for the workshop and invitations sent to suppliers but about a month before the workshop the contractor asked us to cancel the event as they believed they were already asking too much of their supply chain. Clark (2008) states that research fatigue can occur when individuals or a group become tired of engaging with research and demonstrate a reluctance to continue in the research process. As the contractor was keen to build strong relationships with their supply chain, they were worried that if they asked them to engage in too many projects, they would grow wary and be less cooperative going forward.

Without access to primary data, a different approach was required for Paper 3. As a result of this, the decision was made to develop a case study analysis of existing cases where focal organisations and their supply chains had successfully reduced emissions. From this, it was possible to see the challenges faced and how these were overcome. From these case studies, it was possible to show how collaboration could help overcome the challenges and the paper was able to propose a strategy on how supply chains could collaborate to help reduce emissions in the construction industry.

A change of approach was also required during Paper 2. Initially, the plan for the paper was to hold six industry engagement workshops throughout the course of the three year research project. However, after the first two workshops it was found that conversations kept coming back to the same issues and barriers, and discussions on practical solutions on how to overcome these issues were not substantial. Data saturation is defined by Fusch and Ness (2015) as the point at which there is enough information to replicate the study, and where the ability to obtain additional information has been attained. At this point in the research, it was decided by the candidate and the research team that data saturation had been reached and that no new barriers were likely to be discovered through additional workshops. As such, to progress with the research new methods were needed. In order to get a better idea of how to overcome the barriers gathered at the workshops, it was decided a better approach would be to conduct semi-structured interviews where the participants could be briefed beforehand and had time to come up with solutions that were directly related to their job role. This meant that the issues raised at the workshops could be discussed in more detail and the proposed solutions could be integrated into the paper's findings.

6.3 Summary

This section of the thesis starts in Section 6.1 by showing how a common research object, the CIT Tool, was used in the development of each of the three papers that makes up this portfolio. Following this, attention was turned to two main methodological challenges that were encountered through the three years of the PhD. The first challenge, access to data, was a common theme through each paper, which led to a change of methodological approach being needed for Papers 2 and 3. Section 6.2 summarises these challenges and states what was done to overcome these issues.

7 Summary to the Introduction

It has now proven that climate change is a manmade problem that if left unchecked could see global average temperatures rise significantly (IPCC, 2013). The construction industry has been heavily linked to climate change and the rise in GHG emissions, through the emissions embodied in materials used to construct assets, directly through the construction of assets, or indirectly through the operation, use and maintenance of assets once complete. For this reason it is crucial that if the UK, and other countries globally, are to achieve their carbon reduction targets, that the construction industry takes significant steps to measure and reduce GHG emissions.

The CITT Project was designed to deliver a step change in how the construction industry manages carbon through the development of an embodied carbon calculator (the CIT Tool). This tool quantifies emissions associated with the extraction of materials, transportation, and the build phase of large infrastructure projects. However, by only measuring and taking steps to reduce embodied carbon emissions, there is a risk that emissions elsewhere in the asset's lifecycle may rise as a consequence. As shown, there has been very few research papers that have explored the risk of burden shifting and the studies that do (e.g. Hacker et al., 2008b; Huberman & Pearlmutter, 2008; Monahan & J. C. C. Powell, 2011) focus on housing rather than infrastructure projects. As such, Paper 1 of this thesis tests the CIT Tool to see if there is evidence of burden shifting on a rail infrastructure project and highlights what can be done to avoid this risk.

It is not just the development of carbon calculators the construction industry need to address. As has been shown, the construction industry has long been criticised for its performance and has been described as one of the most diverse and unstable sectors within the UK economy (Dainty et al., 2001). Within organisations, resistance to change (Vennström & Erik Eriksson, 2010) and a work-winning strategy that encourages awarding work to the lowest bidder (Yuventi et al., 2013) has hindered the industry's adoption of new technologies and innovation. As such, as well as developing the CIT Tool, it is important to understand the barriers that prevent the adoption of the tool. Paper 2 seeks to understand these barriers and develops a framework for how to incorporate the use of the tool, and other carbon management practices within organisations in the industry.

For emission reductions to be successful, collaboration will be required between a large number of stakeholders in order to efficiently reduce emissions through the lifetime of the infrastructure asset. Latham (1994) and Egan (1998) were both concerned about the level of fragmentation in the industry, stating that collaboration and better working partnerships are needed if the construction industry to is improve productivity. However, two decades later, this is still a real issue in the industry, highlighted in the Farmer Review (2016). Paper 3 looks at the factors that lead to successful supply chain collaboration and proposes how these could be incorporated within the construction industry to improve carbon management practices aimed at reducing emissions.

With these challenges in mind, this thesis takes a multi-perspective approach to look at the challenges of developing and using carbon calculators in the construction industry. Each of the issues summarised above will be looked at in detail in the following chapters. The remainder of this thesis is structured as follows: Chapter 2 (Paper 1) presents the empirical findings from the burden shifting case studies; Chapter 3 (Paper 2) shows the barriers to the carbon calculation tool and how these can be addressed; Chapter 4 (Paper 3) provides detail on the factors required for successful supply chain collaboration; and finally, Chapter 5 provides a conclusion to the thesis.

Paper 1: The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector

Abstract

The infrastructure sector is associated with a large proportion of total greenhouse gas emissions, including the emissions from the production of materials and the construction of infrastructure assets, as well as use phase and end-of-life emissions. Largely due to the direct control the sector has over pre-use phase emissions, a number of carbon calculator tools for the sector focus exclusively on these sources. However, a recognised limitation with considering only parts of the whole life cycle is the risk of burden shifting, e.g. reducing material input emissions but increasing emissions in the use or end-of-life phases. Despite recognition of this problem in principle, there are very few empirical studies which explore the risk and impacts of burden shifting within the infrastructure sector, or construction sector more broadly. This paper addresses the gap in the existing literature by exploring the possibility of burden shifting occurring due to the use of an embodied carbon calculator. The analysis shows that burden shifting will occur for some actions aimed at reducing embodied carbon, but not others, e.g. in Decision Case 4, an initial saving of 5,810 tCO_2e during construction was offset by increased use phase emissions in as little as six years. In order to support the use of embodied carbon calculators we propose a number of heuristics to identify cases where burden shifting may occur, and therefore where a whole-of-life assessment is needed. We also suggest that the infrastructure sector is in a learning process in terms of carbon measurement, and that over time there should be a transition from embodied carbon calculators to whole-of-life assessment, and from whole-of-life attributional life cycle assessment to consequential carbon assessment methods.

1 Introduction

The infrastructure sector is associated with a large proportion of total economy-wide greenhouse gas emissions. In the United Kingdom (UK), emissions attributed to the built environment were 349 $MtCO_2e$ in 2014 (UK GBC, 2018), representing just over half of the UK’s current emissions (Mott MacDonald, 2013). These emissions include those from the construction of infrastructure assets, as well as the operational/use and end-of-life phases of the assets. Given the scale of emissions, policy-makers and the sector itself have identified the need to manage and reduce these emissions. For example, the UK Government published the Infrastructure Carbon Review in 2013 (Mott MacDonald, 2013), setting out a road map for reducing emissions from the sector. In turn, the sector has accepted the need to reduce emissions and has produced a carbon management standard, PAS 2080 (BSI, 2016), which specifically focuses on infrastructure. More recently, the Infrastructure and Projects Authority (2017) and the UK Government (2017) have released reports highlighting the importance of clean growth and the role of infrastructure in helping the UK meet its emission reduction targets. Similar reports have been developed in other parts of the world, for example the International Institute for Sustainable Development’s Low-Carbon Innovation for Sustainable Infrastructure report for the European Union (Wuennenberg & Casier, 2018), and in China’s most recent 5-year plan low carbon infrastructure is featured as a key area for climate change mitigation (CPC, 2015).

As the infrastructure sector embarks on developing carbon management practices it is necessary, as highlighted in PAS 2080, to measure and benchmark carbon emissions. One of the main quantification methods for informing carbon management practices and decision-making is life cycle assessment (LCA), which models the environmental impact of a product or asset throughout its life cycle (ISO, 2006). BS 15978 (BSI, 2011) for ‘Sustainability in Construction Works’ separates a building’s life cycle into four stages: the product stage (A 1-3) which includes raw material extraction, transportation and manufacturing; the construction stage (A 4-5) which finishes with the completion of the asset; the use stage (B 1-7) which includes operational energy, maintenance and repair; and finally the end-of-life stage (C 1-4) which includes decommissioning and disposal of materials.

LCA or ‘carbon footprinting’ tools are progressively being developed and adopted by the infrastructure sector, and examples include the UK Environment Agency’s Carbon Planning Tool (Environment Agency, 2016), Highways England’s Carbon Emissions Calculator (Highways England, 2016), the Rail Safety and Standards Board’s (RSSB)

Rail Carbon Tool (RSSB, 2015), and asPECT, a tool developed by a consortium from the UK highways sector (Wayman et al., 2012). Similar tools have been developed outside the UK, for example Athena's Eco Calculator for North America (Athena, 2018) and the Swedish Transport Agency's (STA) Klimatkalkyl tool (Trafikverket, 2016), whilst Mott Macdonald's Carbon Portal (Mott MacDonald, 2016) and Atkins' Carbon Critical Knowledgebase (Atkins, 2010) are designed for global use. The choice of system boundary is of great importance in making sure that the assessment is fit for purpose (Tillman et al., 1994). The tools above, summarised in Table 4, vary in terms of the life cycle stages they include, i.e. the production, construction, use, and end-of-life stages. The UK GBC (2017b) is flexible as to the boundary used in the preparation of an LCA, either cradle-to-completed construction which encapsulates A1 to A5 of BS 15978, or a cradle-to-grave assessment which takes a whole-of-life approach. One of the reasons why a cradle-to-completed construction approach may be adopted is that contractors or developers feel they have direct control over the materials used within an infrastructure asset, and how the asset is built, but have limited control over how an asset is used on completion. A further reason is that many datasets only include cradle-to-gate emissions (Sansom & Pope, 2012) making it challenging to model the use phase and end-of-life phases of infrastructure projects, whereas it is relatively straightforward to measure embodied emissions.

This situation, i.e. the use of tools which do not encompass a whole-of-life approach, is potentially problematic as it can give rise to the problem of 'burden shifting', which occurs when improvements in one part of the life cycle result in counter-acting or

Table 4. Non-exhaustive summary of available carbon calculators for infrastructure projects.

Developer	**Tool**	**Region**	**Life cycle stages measured**
Environment Agency	Carbon Planning Tool	UK	Cradle-to-grave
Highways England	Carbon Emissions Calculator	UK	Cradle-to-gate + construction
RSSB	Rail Carbon Tool	UK	Cradle-to-completed construction, use optional
UK highways sector	asPECT	UK	Cradle-to-grave, no use phase
Athena	Eco Calculator	North America	Cradle-to-gate / grave
STA	Klimatkalkyl Tool	Sweden	Cradle-to-gate, with operation and maintenance
Mott Macdonald	Carbon Portal	Worldwide	Cradle-to-grave
Atkins	Carbon Critical Knowledgebase	Worldwide	Cradle-to-completed construction, use optional

negative impacts elsewhere. Indeed, the avoidance of burden shifting is one of the foundational reasons for adopting a life cycle approach:

> The core reason for taking a life cycle perspective is that it allows identifying and preventing the burden shifting between life cycle stages or processes that happens if efforts for lowering environmental impacts in one process or life cycle stage unintentionally create (possibly larger) environmental impacts in other processes or life cycle stages (Bjorn et al., 2018, p.12).

1.1 Terminology

An important contextual issue to address before proceeding with the empirical study of burden shifting and 'embodied carbon' calculators, is to provide some clarity on the terminology used, as the term 'embodied' is used in different ways by different practitioners, standards, and scholars. On one hand, the Infrastructure Carbon Review (Mott MacDonald, 2013, p.7) states that 'embodied carbon refers to the emissions associated with the creation of an asset' but does not mention maintenance and end-of-life emissions. On the other hand, RICS (2012, p.3) state embodied emissions are 'emissions associated with energy consumption and chemical processes during the extraction, manufacture, transportation, assembly, replacement and deconstruction of construction materials or products'. Other industry reports, e.g. WRAP (2011) and the UK GBC (2017b) straddle the fence stating that embodied emissions are associated with the building of an asset but may also include maintenance, deconstruction and end-of-life if required.

Within the academic literature, similar ambiguity can be found in the definitions and interpretations of embodied emissions (Ibn-Mohammed et al., 2013). Moncaster and Song (2012, p.28) define embodied energy as that 'used during the manufacture of the building materials and components, in transporting these to site, and during the construction process itself' but add that it can also 'include the energy needed for refurbishment and replacement of components during the lifetime of the building and that used in the demolition, waste and reprocessing at the end-of-life stage'. Some (e.g. Dixit et al. (2010) and Goggins et al.(2010)) have further broken-down the term into 'initial' embodied emissions, during the build phase of the asset, and ‘recurring’ embodied emissions to do with maintenance and refurbishment of the asset during its lifetime. As such, there are a number of case studies regarding embodied emissions which have differing boundaries, with some (e.g. Iddon & Firth, 2013) measuring cradle-to-gate emissions, others (e.g. Monahan & J. C. Powell, 2011) cradle-to-site emissions, and others (e.g. Biswas, 2014) measuring cradle-to-grave emissions. For clarity, for the remainder of this paper we will refer to embodied emissions as cradle-to-completed construction emissions, with the use phase, maintenance and end-of-life accounted for separately.

On a further point of terminology, we use ‘construction’ to encompass both buildings and infrastructure, with ‘infrastructure’ referring to man-made structures and facilities that provide services for society (e.g. roads, sewerage, water and waste management systems, energy generation and distribution, communication systems etc.).

1.2 Aims and Objectives

Given the use of carbon calculators within the infrastructure sector which do not encompass a whole-of-life approach, and which therefore *in principle* give rise to the risk of burden shifting, an important research question is whether there are real-world situations in which burden shifting is likely to arise for infrastructure projects. This paper aims to explore the potential for burden shifting from the use of embodied carbon calculators in the infrastructure sector, and to develop measures to help mitigate that risk.

The remainder of the paper is structured as follows: Section 2 provides an overview of the LCA literature on infrastructure and construction more broadly, and the issue of burden shifting, and shows that there are surprisingly few studies in this area; Section 3 sets out the methodological approach used in the paper; Section 4 sets out the results from the cases explored; Section 5 discusses the implications of the results, and proposes a number of heuristics for identifying situations where burden shifting may occur; and Section 6 concludes and suggests areas for further research.

2 Literature Review

The intention of this review is to provide a brief overview of the literature on LCA and burden shifting, with a particular focus on infrastructure (and construction more broadly). Given the extent of literature on LCA in infrastructure there are surprisingly few research articles that explicitly discuss infrastructure and burden/problem shifting in a substantive and relevant sense. Of those that do, some investigate the potential of burden shifting between environmental impact categories (Del Borghi et al., 2013; Laurent et al., 2012), whilst others study the risk of burden shifting between different life cycle stages. For example, Zhang and Xu (2015) show that only measuring embodied carbon emissions on hydropower projects omits indirect emissions after construction, meaning the projects were not as efficient as first assumed.

Within the construction literature several articles have discussed how best to reduce embodied carbon emissions, whether through choice of materials (e.g. Purnell & Black, 2012), or different construction techniques (Du & Karoumi, 2013). Russell-Smith and Lepech (2015) develop a framework to aid the reduction of cradle-to-gate emissions but warn that the framework may miss important environmental issues by omitting use and end-of-life phases. Häfliger et al. (2017) modelled the variations in emissions from four structures when using different system boundaries, and found that two of the structures showed similar emissions if measuring cradle-to-gate or cradle-to-grave, whereas two structures increased emissions significantly when measuring whole-of-life emissions. This suggests that burden shifting is possible in some, but not all cases.

In terms of the findings from the studies on buildings and burden shifting, there appears to be a mixed picture as to whether or not burden shifting is likely to occur. Several authors (Stephan et al., 2012; Basbagill et al., 2013; Cabeza et al., 2014) highlight the potential risk of burden shifting through the choice of materials or location of the building, and the risk of burden shifting underpins Pomponi and Moncaster's (2016) criticism that half the studies they reference do not take a whole-of-life approach. However, of the few studies that do explicitly look at burden shifting, Hacker et al. (2008a) found that the choice of building materials did lead to burden shifting, while Monahan and Powell (2011) found little difference in operational emissions, implying no burden shifting effect. Huberman and Pearlmutter (2008) found increases in use phase emissions (caused by material substitution), but not enough to offset the reductions in embodied emissions over a 50-year period. These studies, which all relate to the construction of housing, therefore present a mixed picture in terms of the risk of burden shifting, and therefore support the motivation for the current research, i.e. to further extend the existing evidence on this issue.

To finish, we find it interesting that although the number of LCA studies related to infrastructure is likely to be larger than the number of studies for buildings, there appears to be an absence of any comprehensive review articles for infrastructure LCAs (although there are review articles for specific types of infrastructure, e.g. utility-scale wind power (Dolan & Heath, 2012)). This stands in contrast to the number of review articles for LCA studies on buildings (Abd Rashid & Yusoff, 2015; Anand & Amor, 2017; e.g. Buyle et al., 2016; Cabeza et al., 2014; Sharma et al., 2011). Although beyond the scope of the present paper, an area for future research would be a comprehensive literature review of LCA studies related to infrastructure.

3 Methodology

In order to explore the risk of burden shifting from the use of embodied carbon calculators we adopted a case study approach, and applied an embodied carbon calculator to a number of decision cases, which were intended to reduce the embodied emissions of a large infrastructure project in the UK. A case study research design specifically looking at a single project (Bryman, 2008) is sufficient for establishing the possibility of burden shifting effects, and for informing the choice of heuristics for identifying that risk, but will not support inferences about the *probability* of burden shifting.

The carbon calculator selected for the study was the Carbon Infrastructure Transformation (CIT) Tool, which applies emissions factors to quantity data for the materials used in infrastructure projects (i.e. a ‘bill of quantities’), and is representative of many of the embodied carbon calculators available in the market. The selected case study infrastructure project was a high-speed rail project, as data were available from an industry partner for a number of design decisions aimed at reducing embodied emissions (i.e. data from a bill of quantities, with and without specific design decisions). A high-speed rail project was also considered of interest as a number of high-profile infrastructure projects of this type are currently in development (e.g. HS2 in the UK, and HSR in California). The case study design decisions selected were:

Decision Case 1: Reducing the thickness of a diaphragm wall (d-wall). A 40 m deep d-wall was reduced from a thickness of 1200 mm to 1000 mm.

Decision Case 2: Replacing sections of d-walls with secant piling. On the retain cut, 80% of two 500 m long sections of d-walls were replaced with secant piling which use less material to produce and are quicker to erect.

Decision Case 3: Using an alternative method to excavate and build the outer shell of a ventilation shaft. Here four 1200 mm thick d-walls were replaced with a 300 mm sprayed wall circular shaft.

Decision Case 4: Reducing the diameter of the train tunnel. The single-tracked, 10 km tunnel diameter was reduced from 9.3 m to 8.2 m. This led to a reduction in the quantity of concrete, reinforcing bars, and earthworks.

The reduction in embodied emissions from each of the design decisions was calculated using the CIT Tool, in order to simulate the information a client, designer or contractor would have if using an embodied carbon calculator to inform their decision-making. We then explored whether any of the decisions were likely to give rise to burden shifting effects, i.e. whether there are likely to be counteracting increases in emissions elsewhere in the life cycle. For Decision Cases 1 and 2, the methodology in Inui et al. (2011) was followed, which assumes that the retaining structures are left in place at the end of their 120 year designed lifetime, and that no maintenance work is required during their service life. This was corroborated by the design team for the high-speed rail project, and it was concluded that there are unlikely to be burden shifting effects from Decision Cases 1 and 2. For Decision Case 3, the internal structure of the ventilation shaft is unchanged by the design decision, and as a result the emissions during operation, use, maintenance and end-of-life would be identical to the baseline scenario. For Decision Case 4 however, the change in tunnel diameter would be expected to influence the air resistance to trains travelling through the tunnel, and therefore increase energy consumption during the use phase. As a result of this, Decision Case 4 was taken forward for further analysis, to estimate the potential magnitude of the burden shifting effect. The details of this analysis are provided in the section below.

3.1 Decision Case 4 – Use Phase Calculations

The diameters of the baseline tunnel and the low-carbon design tunnel were 9.3 m and 8.2 m respectively, and both were 10 km, straight, single-track tunnels.

An Alstrom AVG high-speed train was selected to model the use phase energy consumption for the tunnels, as it has been described as the most economic high-speed train in terms of energy consumption and maintenance, and is therefore a likely model to be used in practice (Alstrom, 2017). To understand the effect the tunnel would have on resistance, the 'in field' rolling resistance of the train was calculated using the Davis equation for rolling resistance as a quadratic function of velocity (Hansen et al., 2017) (Equation 1), as used in a similar study by Bosquet et al. (2014). A is the train-specific constant resistance factor (kN), B is the train-specific linear resistance factor (kNh/km), C is the train-specific quadratic resistance factor (kNh^2/km^2) and v is the train's velocity. The train specific values for the Alstrom AVG were taken from Network Rail (2009) and Asplan Viak AS (2012).

$$Rolling\ resistance = A + Bv + Cv^2 \quad (1)$$

The next stage was to determine the increased resistance for the train travelling through the tunnel. This was derived using an adapted form of the Davis equation for measuring resistance in tunnels, as used by Novak (2006) (Equation 2), where tf is the tunnel factor which is the ratio (≥1) of tunnel drag to open-air drag. This is

Table 5. Summary of train and tunnel specific data

Train – Alstrom AVG	Value	Reference
Seating Capacity	650 persons	Network Rail (2009)
Maximum Speed	300 km/h	Network Rail (2009)
Length	250 m	Network Rail (2009)
Energy Consumption	0.033 kWh/seat-km	Network Rail (2009)
Energy Consumption per km	21.45 kWh/train km	Network Rail (2009)
Train-specific Constant Resistance Factor (A)	6.542605 kN	Asplan Viak AS (2012)
Train-specific Linear Resistance Factor (B)	0.0106356 kNh/km	Asplan Viak AS (2012)
Train-specific Quadratic Resistance Factor (C)	0.0004717 kNh^2/km^2	Asplan Viak AS (2012)

Tunnel	Value	Reference
Tunnel Factor (T_f) – Reduced Diameter Tunnel	2.38	Lukaszewicz and Andersson (2009)
Tunnel Factor (T_f) – Reference Tunnel	1.96	Lukaszewicz and Andersson (2009)

calculated using several factors, of which the blockage ratio of the train in the tunnel is the most important, but the train type, train length and tunnel length are also considered (Novak, 2006).

$$Tunnel\ resistance = A + Bv + tfCv^2 \quad (2)$$

Tunnel factors for tunnel diameters of 9.3 m and 8.2 m were taken from Lukaszewicz and Andersson (2009). Using these, the increased resistance for the two tunnels over the 'in field' rolling resistance, and the increased energy that would be required for trains to go through each tunnel, were calculated. The energy consumption was calculated to be 1.73 and 2.05 times higher for the baseline tunnel and the reduced diameter tunnel respectively, over the general 'in field' energy consumption. As such, the energy consumption increased to 37.14 kWh/km for the baseline tunnel and 44.01 kWh/km for the reduced diameter tunnel. A summary of the input data for calculating the train's energy consumption is provided in Table 5.

The carbon emissions for electric-powered trains depends on the grid emission factor, and to forecast UK grid emissions into the future the Department for Business, Energy and Industrial Strategy's (BEIS) long-run grid-average, generation-based, electricity emission factors were used. This is the same dataset used by the Department for Transport (DfT) in their forecasts, although the 1.5% uplift used by DfT only includes transmissions and distribution (T&D) losses, and does not include emissions associated with upstream life cycle stages. According to the 2017 conversion factors from BEIS (2017), the emissions from T&D losses and upstream activities is ~21%. As such, the BEIS long-run grid-average factors were adjusted upwards using this uplift factor.

Regarding the trains in the tunnel, there were three key variables: the number of trains passing through the tunnel each day; the train's speed through the tunnel; and the grid emission factor. Three scenarios were modelled in order to test the sensitivity of the potential burden shifting effect to different assumptions for the number and speed of trains, and the grid emission factor. Scenario 1, a central estimate, assumed 260 trains per day going through the tunnel and an average speed through the tunnel of 250 km/h, and the adjusted BEIS grid factors were used. Scenario 2 was a lower estimate with 230 trains per day, an average speed of 200 km/h, and a 10% increase to the emission factors. Scenario 3 was an upper estimate with 290 trains per day, an average speed of 300 km/h, and a 10% decrease to the emission factors. These three scenarios were modelled over a 120 year period, which is the expected lifetime of the tunnel.

Finally, a number of limitations and assumptions should be highlighted. First, the use of the rail line does not change over the time period. With time, high-speed rail could become more popular if it is cheaper and quicker than other forms of transport, but conversely new technology, such as Hyperloop (2018) could limit the use of high-speed rail. In the future the speed and capacity of the trains could be improved, which would have an impact on the projected emissions. Another assumption was that train efficiency does not change. If trains were to become much more efficient, the use phase emissions would be lower compared to embodied emissions (and the potential burden shifting effect would be reduced). Finally, it is assumed that the UK will meet its 2050 targets set out in the Climate Change Act of 2008, which is the basis for the BEIS forecast grid emission factors (and a higher average grid emission factor would increase the potential burden shifting effect).

4 Results

Table 6. Results for embodied emissions saving for four decision cases

Decision case	Reference emissions (tCO_2e)	'With change' emissions (tCO_2e)	Reduction in embodied emissions (tCO_2e)
1. Reducing thickness of D-wall	5,260	3,350	1,910
2. Replacing D-wall with secant piling	22,080	13,850	8,230
3. Alternative method of excavation	6,140	2,360	3,780
4. Reduction in diameter of tunnel	43,220	37,410	5,810

Table 6 presents the results for embodied carbon emissions (calculated using the CIT Tool) measured in tonnes of carbon dioxide equivalent (tCO_2e) for the four decision cases. As shown, all four cases show a reduction in embodied emissions, i.e. a design team or contractor using the CIT Tool would be justified in implementing the proposed reduction measures, based on the information provided. For Decision Cases 1-3, no changes in the use or end-of-life phases were identified, and therefore it is assumed that there is no burden shifting effect and the Tool correctly identifies the emission reduction opportunity. However, in Decision Case 4, use phase electricity consumption is expected to increase.

The results for the embodied and use phase emissions for Decision Case 4 are presented in Table 7, and show that choosing the smaller tunnel in order to reduce embodied emissions is expected to increase overall emissions. For example, in Scenario 1 emissions would increase by 25,260 tonnes CO_2e over the 120 year assumed life time. Scenarios 2 and 3 show a variation in the magnitude of the burden shifting effect, but in all cases there is a substantial overall increase in emissions, indicating that the effect is robust to different input assumptions.

Table 7. Results for embodied and use phase assessment for the tunnel decision

		Reference (larger) tunnel (tCO_2e)	Reduced diameter tunnel (tCO_2e)	Change in emissions (tCO_2e)
Scenario 1	Embodied	43,220	37,410	-5,810
	Use phase	168,120	199,190	+31,070
	Total	211,340	236,600	**+25,260**
Scenario 2	Embodied	43,220	37,410	-5,810
	Use phase	128,140	150,380	+22,240
	Total	171,360	187,790	**+16,430**
Scenario 3	Embodied	43,220	37,410	-5,810
	Use phase	212,140	252,840	+40,700
	Total	246,360	290,250	**+34,890**

In addition to the overall change in emissions it is also important to consider the temporal distribution of emissions, particularly with decisions that have impacts over a long period of time (Brander, 2017; Krezo et al., 2016). With the reduced diameter tunnel there is an initial reduction in emissions as 'up-front' embodied emissions are reduced by the decision to build a smaller tunnel, but then that emissions 'benefit' is eroded over time as the higher use phase emissions accumulate. From a decision-maker's perspective it is useful to understand that the carbon benefit from reduced embodied emissions is short-lived: for example, for Scenario 1, it would only take eight years of operation for the smaller tunnel to have higher total emissions (as shown in Figure 6). The switching point (from reduction to increase) in emissions would occur after thirteen years for Scenario 2 and six years for Scenario 3. As this switching point occurs so early in the operational phase of the tunnel, scenarios that depended on major changes that could happen in the future, for example, faster or more efficient trains, or changes to passenger habits, were not considered as although these may decrease the use phase emissions the initial burden shifting could not be overturned.

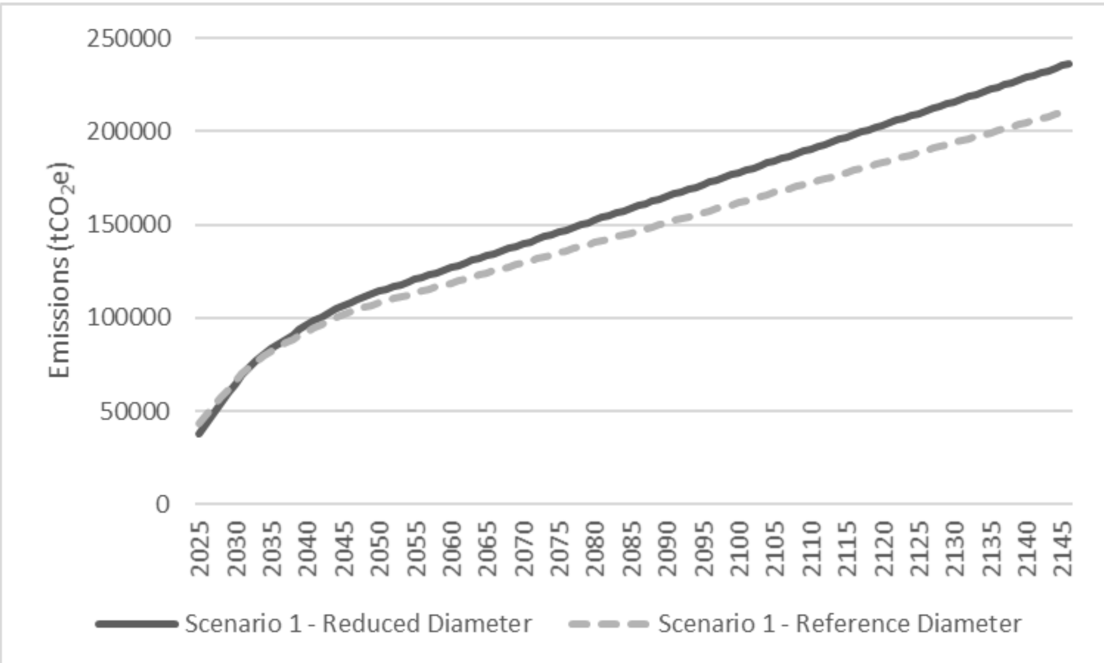


Figure 6. Scenario 1 emissions (tCO2e) from 2025 to 2146.

5 Discussion

5.1 Recommendations

The results show that embodied carbon calculators can successfully identify emission reduction opportunities in some, but not all, cases (which tallies with the mixed picture on burden shifting for buildings identified in the literature, e.g. Häfliger et al. (2017). A question then arises whether only whole-of-life assessments should be used, or whether there is an appropriate role for embodied carbon calculators? As mentioned in the Introduction, one apparent reason that a number of existing tools focus on embodied carbon is that it is often difficult to model the use and end-of-life phases, and imposing a requirement for whole-of-life assessment may be onerous and dis-incentivise the infrastructure sector from engaging in carbon management practices.

A possible solution to this problem is to combine the use of embodied carbon calculators with a set of heuristics or 'rules-of-thumb' for identifying when burden shifting effects are more likely to occur, and therefore when the use of an embodied carbon calculator would need to be supplemented with a whole-of-life approach. This heuristics approach has been suggested for other aspects of life cycle assessment, notably for situations when attributional LCA is likely to miss significant market-mediated effects, and therefore when a consequential LCA is required (Rajagopal, 2017). Figure 7 sets out an initial set of questions or heuristics that practitioners can use to identify the risk of burden shifting.

Applying these questions to the decision case of the rail tunnel, the answers would be: 1. Yes, there are reasons for expecting a change in use phase emissions; 2. The change is expected to lead to an increase in use phase emissions; 3. The magnitude of the change could be large compared to the size of the reduction in embodied emissions, and therefore warrants a whole-of-life assessment. This indicates that the use of an embodied carbon calculator, together with this simple set of heuristics, could effectively identify cases with a risk of burden shifting. However, it is worth

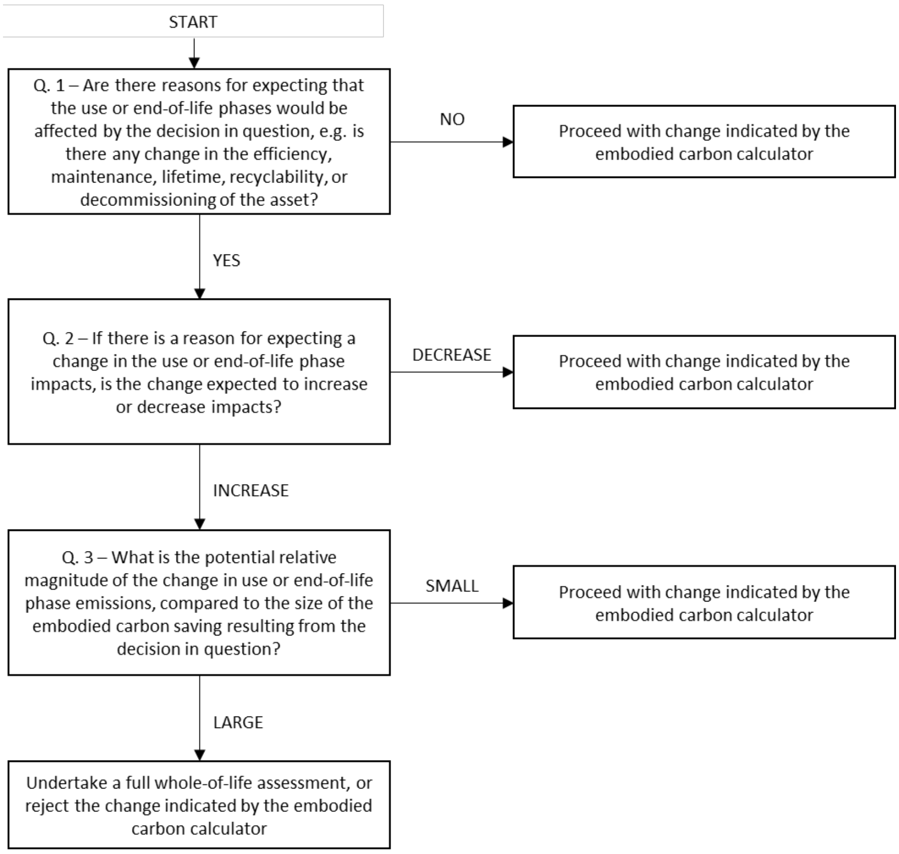


Figure 7. Flowchart of suggested heuristic guidelines.

noting that there is a remaining limitation with this approach, namely that using an embodied carbon calculator would still miss the identification of emission reduction opportunities in the later life cycle stages (even though negative burden shifting can be avoided). In the absence of information on the use and end-of-life phases of an infrastructure project, a design team or contractor will not be able to make informed decisions aimed at reducing emissions within these life cycle stages, and therefore for the project as a whole.

Broadening the discussion on burden shifting further, we offer the observation that concern with burden shifting, which is acknowledged as one of the underpinning motivations for a whole-of-life approach (Bjorn et al., 2018; ISO, 2006), is also effectively the underpinning motivation for using consequential rather than attributional LCA. Consequential LCA aims to quantify the total change in impacts caused by a decision (Ekvall & Weidema, 2004), while attributional LCA quantifies the impacts that occur within a normatively defined inventory boundary (UNEP & SETAC, 2011), with the boundary often defined in terms of the processes that are physically used within the life cycle of a product. A widely recognised limitation with attributional LCA is that it does not necessarily capture all the changes caused by a decision (Plevin et al., 2014), and therefore can result in burden shifting, i.e. impacts may be reduced within the normatively defined assessment boundary, but increase elsewhere. A notable example is bioenergy policy, which may reduce emissions from the processes directly used in the life cycle of fuels, but increase emissions elsewhere in the system through indirect land use change (Searchinger et al., 2008) or material displacement effects (Brander, 2017).

The hierarchy of sophistication from embodied emissions calculators to whole-of-life assessment, and from whole-of-life attributional LCA to consequential methods, maps onto evolution of capacity for carbon measurement within industry sectors. The infrastructure sector, and indeed many other sectors, are currently in a learning process with regards to carbon measurement and management. The use of embodied carbon calculators may be appropriate given the current level of capacity, but as skills and capacity develop there should be a transition to using whole-of-life methods, and from whole-of-life attributional methods to consequential methods, which aim to fully capture the changes caused by decisions. As a recommendation to software developers, this transition should be planned for within the structure of tools currently in development.

5.2 Implications for Practice and Theory

The major implication of this research for practice is to highlight that care is needed when using embodied carbon calculators. For example, the Carbon Trust (2014) suggest that low temperature asphalt could significantly reduce emissions, although the claim only takes account of emissions during road construction without determining changes in the use phase. Here we have shown that burden shifting is a real risk that practitioners must consider, and the heuristic guidelines developed indicate how the risk of burden shifting can be minimised. With the formulation of normative rules recognised as a form of theory development (Suddaby, 2014), the theoretical contribution of this paper is the formulation of these heuristics.

5.3 Limitations and Future Research

It should be noted that the present study has focused exclusively on greenhouse gas emissions, while a further form of burden shifting may occur between impact categories (Laurent et al., 2012), e.g. a decision may reduce greenhouse gas emissions but increase biodiversity loss etc. A further area for development is therefore the formulation of heuristics for addressing this form of burden shifting, or the inclusion of other impact categories within decision-support tools.

As alluded to by Häkkinen et al. (2015), planning must begin during the design stage of a project to achieve the best low-carbon solutions. As shown in our results, this planning must also give consideration to the use and end-of-life of the asset. However, accurately calculating emissions in these phases will be difficult as it relies on suppliers giving their emissions data during the planning phase of a project, which they may be reluctant to do before a contract of work is awarded. As such, future research should explore how collaboration can be achieved between clients, contractors and their supply chains so that collectively low-carbon designs can be implemented. As well as the technical issues associated with quantifying changes in emissions, we recognise that there are also social, organisational, and institutional barriers to the adoption of carbon management practices within the infrastructure sector. The interplay of carbon calculation tools, such as the CIT tool, with these barriers should also be the subject of future research. Finally, another opportunity for future research is to develop a comprehensive literature review of LCA studies related to infrastructure, as this literature appears to be dispersed across different journals and research communities, which suggests there may useful new insights from taking a holistic overview.

6 Conclusions

The infrastructure sector is developing and using embodied carbon calculators in order to manage emissions associated with infrastructure projects, but this gives rise to the possibility of burden shifting. Although the possibility of burden shifting is widely recognised in principle, there is very little empirical research on the issue, either generally or specifically in relation to infrastructure projects. In order to address this research gap, the current study explores the possibility of burden shifting for a number of decision cases related to a high-speed rail project in the UK, and finds that in some cases the use of an embodied carbon calculator correctly identifies emission reduction opportunities, but in other cases the use of such tools may result in burden shifting.

In order to address this problem we propose a number of simple heuristics, which can be employed alongside the use of embodied carbon calculators. We also suggest that over time (as skills and capacity for carbon measurement increase) there should be a transition from relatively simple embodied emissions calculators to whole-of-life assessment, and from whole-of-life attributional LCA to consequential methods, as such methods aim to capture all changes in emissions caused by a decision, and therefore fully address the problem of burden shifting.

Paper 2: Dirty works – enabling carbon management practices in the construction industry

Abstract

Pressure is growing on the construction industry to reduce carbon emissions. Whilst progress has been made in developing carbon calculation tools to quantify emissions, the uptake of these tools has been slow. We identify the reasons for the slow implementation of carbon management in the construction industry and propose a three step framework for implementing carbon management practices within an organisation to overcome those barriers. Using a case study approach we examine the barriers and drivers to the implementation of a carbon calculation tool. Our findings suggest that barriers can be internal or external to the organisation, but can also be shared between the organisation and the wider industry. To overcome those barriers firstly, there must be external motivation incentivising the organisation. Secondly, the organisation's leadership must take responsibility for setting the organisation's strategy around carbon management. Finally, carbon management must be integrated throughout each team within the organisation.

1 Introduction

Climate change is 'the greatest challenge of our time' (Fanelli, 2014, p. 15), and to prevent the Earth's average temperature exceeding the 1.5 ^{o}C target set in the Paris Agreement (UN, 2015), a significant reduction in greenhouse gas emissions is needed. An often overlooked sector for achieving such a reduction in carbon emissions is the construction industry. Directly or indirectly the construction and use of infrastructure assets accounts for over half of the United Kingdom's (UK's) total carbon emissions (Mott MacDonald, 2013) and should be reduced by 50% by 2025 (HM Government, 2013). Although growing attention has been paid to carbon management (CM), which we define as any practice or process that aids the management and of reduction carbon emissions, the actual implementation of such practices and consequent reduction of emissions in this industry has only taken place slowly (Xavier et al., 2017). It has been tentatively argued that this is due to the industry's resistance to change (Lines et al., 2015) and slow adaptation of new innovations (Robinson, 2018). Other scholars have stated that challenges stem from the perceived contradiction between investment in environmental concerns and profitability (Porter & van der Linde, 1995), the perception that environmental policies are viewed as a marketing gimmick (Le Breton & Aggeri, 2018), and the danger that if considered after the initial design stage meaningful impact is difficult to achieve (Williams & Dair, 2007). It is not well understood why the uptake of such practices has been slow and how best to implement new processes in this area.

Recently, there has been a call for researchers to develop a better understanding of the reasons for the slow transition of organisations to a low-carbon economy and help to identify pathways to a more rapid and transformative change (Wittneben et al., 2012). It is to this end that we aim to explore two research questions:

1) Why have organisations in the construction industry been slow to implement CM practices?

2) How can organisations in the construction industry improve the implementation of CM practices?

To answer these questions, we identify the barriers and drivers to accelerate the implementation of CM practices in the construction industry, and develop a conceptual framework suggesting the steps required to enable this change. We use a case study approach to examine the development and piloted implementation of a carbon calculation tool within a selected construction organisation through qualitative data collected over a three year period. In doing so, we fulfil the call of Paper 1 to explore the barriers preventing the implementation of carbon calculators in the construction industry. We also make reference to Giesekam et al. (2016) who state there have been few qualitative studies looking at low-carbon techniques within the construction industry so this paper goes some way to fulfilling that gap.

The remainder of this paper is structured as follows: Section 2 first discusses the construction industry and its challenges in implementing change and innovation before looking at the literature on barriers to sustainable change; Section 3 presents our methodology and discusses our data coding and analysis; in Section 4 we present our findings; in Section 5 we discuss how CM can be integrated within an organisation and propose a framework for steps required to implement CM practices; and finally we conclude in Section 6.

2 Theoretical Background

2.1 The Construction Industry, Change and Carbon Management

For CM practices to be incorporated within the construction industry, scholars agree that transformational change is required to allow innovative technologies to be implemented and successfully used (BSI, 2016). However, governments and private-sector organisations have long been concerned with how the construction industry deals with change (Fernie et al., 2006). As a result, the industry is often perceived to be lagging behind other industries in terms of implementing innovation, reacting to market tends, improving quality of products (Hoonakker et al., 2010), and is even showing lower levels of productivity (Yuventi et al., 2013). The lack of such timely innovation in this industry has been attributed to four main issues. First, the fragmented nature of supply chains often including a large number of stakeholders making collaboration difficult (Jacobsson & Linderoth, 2010; Yuventi et al., 2013). Second, an absence of accountability between different phases of a construction project (e.g. work-winning and project delivery) which limits efficiencies and makes it hard for teams to understand what is happening outside their area of expertise (Yuventi et al., 2013). Third, a procurement process which encourages a ‘race to the bottom’ with work often being awarded to the bidder offering the lowest price (Yuventi et al., 2013). Here, other considerations such as the sustainability of products or carbon emissions are often overlooked. Fourth, contractors using temporary project-based models so that new processes and knowledge accrued often fail to be transferred from one project to another (Miozzo & Dewick, 2002).

Regardless of the above indications on the reasons for an absence of innovation, research on CM specifically in the construction industry has only looked at specific technical issues, for example the choice of building materials (e.g. Giesekam et al., 2016), low- or zero-carbon building designs (e.g. Kershaw & Simm, 2014), or measurement practices (e.g. De Wolf et al., 2017). Research specifically on how CM processes are adopted within organisations is lacking, however, engaging with CM could be promising for the industry which becomes evident by looking more generally at sustainability related efforts. Tan et al. (2015) for example found that a high sustainability performance of contractors in the construction industry leads to higher revenue growth and provides opportunities to achieve competitive advantages over rival organisations. To develop this competitive advantage, organisations establish technical and technological capabilities and knowledge (Pinkse & Dommisse, 2009, Chang et al., 2016), and develop best practice case studies to showcase the positive achievements of such efforts (Chang et al., 2016). However, how individual construction organisations can meet the carbon reduction challenge is not well understood from these investigations.

Other scholars have developed frameworks for CM. Wahyuni and Ratnatunga (2015) create a general template for developing effective CM strategies proposing five steps for managing carbon: develop an understanding of emissions; identifying exposure and cost implications; developing a strategy; implementing the strategy; and monitoring progress. Bekaroo et al. (2019) look at how to reduce employees' personal emissions suggesting a circular 'plan-do-check-act' framework starting with setting objectives, learning, reducing, monitoring progress, measuring and then setting new objectives. Whilst both these frameworks are useful in proposing the steps required, they fail to shed light on the overarching factors that need to be in place for organisations to be able to successfully implement CM practices.

2.2 Barriers to Sustainable Change

In the absence of research on the introduction of carbon management specifically, research on change in the construction industry more generally shows that there are various barriers which are specific to the area where, and/or type of, change that is to be implemented e.g. within the construction process (e.g. Vennström and Eriksson, 2010), the implementation of new technologies (e.g. Porwal and Hewage, 2013), and to do with sustainability issues (Pinkse & Dommisse, 2009). Barriers identified are then often grouped together, for example, Vennström and Eriksson (2010) identified that barriers to change in the construction industry arise along three categories;

attitudinal, industrial and institutional. Attitudinal barriers focus on individuals and their views on change, industrial barriers arise from other organisations such as competitive pressures and industry practices, and institutional barriers are the ‘rules’ and refer to laws, standards and procurement processes which make it difficult for the industry to change.

The most recognised categorisation of barriers is the recognition that the observed barriers occur along internal or external boundaries of an organisation. In their review article on the barriers to sustainable development activities in organisations, Álvarez Jaramillo et al. (2019) classified over 170 barriers using this ‘established criteria’ (p. 522). Del Río González (2005) explains internal barriers are barriers that an organisation has direct control over, such as the organisation’s characteristics or strategies. Internal barriers include the organisation’s leadership (Arnold & Hockerts, 2011) or the organisation’s environmental capabilities (Kesidou & Demirel, 2012). External barriers are barriers that an organisation has little control over, such as policy directions, consumer preferences, or competitors’ decisions. External barriers include competitive pressures from rival organisations (Cai & Li, 2018) or lack of government support (Sajjad et al., 2015). Whilst comprehensive, the review study written by Álvarez Jaramillo et al. (2019) on the barriers to sustainability only refers to one case from the construction industry, from which only three of the 170 barriers are attributed to: acquiring financial capital, a lack of expertise, and the time of work shifts. However, it would be expected that there are many more reasons that sustainability activities are not implemented within the construction industry. To that end, we plan to use the categorisation of internal and external barriers used by Álvarez Jaramillo et al. (2019)to develop a better understanding of the barriers that exist within the construction industry.

3 Methods and Data

3.1 Procedures and Data Sources

A case study approach (Baxter & Jack, 2008) was used to answer our research questions. The case study followed the development and implementation of a carbon calculator, the Carbon Infrastructure Transformation (CIT) Tool, within a contractor organisation. The CIT Tool quantifies and reports emissions prior to the start of the build phase (see BS 15978 (BSI, 2011) and PAS 2080 (BSI, 2016)) and allows construction estimators, planners and designers to collaborate on carbon reduction practices to minimise carbon emissions and associated costs on large infrastructure projects. Thus, CM practices can be initiated before the construction phase begins, and can both reduce emissions and increase profitability. Given the exploratory nature of the research (Blumberg et al., 2011), a qualitative approach was used to gather data. The data collection can be divided into three phases:

The first phase of data collection for this case study gathered an industry-wide perspective of the challenges involved in integrating the CIT Tool and CM practices within the construction industry. To get the widest possible reach one workshop (Workshop 1) was organised with 23 participants working for 21 organisations across the construction industry: seven participants from contractor organisations, seven from client organisations, four from environmental consultancies, two from engineering consultancies, two from regulatory bodies, and one participant from a technical consultancy. The selected participants were associated with environmental or sustainability roles within their organisations to be able to have knowledge on current environmental practices within the industry and carbon-related tools and initiatives. Workshops were used as they allow for a particular subject to be explored in depth (Bryman, 2008), revealing various barriers and challenges faced when implementing CM practices within infrastructure organisations. During the workshop, participants were divided into four focus groups and took part in three breakout sessions. The first addressed barriers to the CIT Tool’s implementation, the second looked at how to overcome these barriers and enable change, and the third session asked what other CM practices they were aware of within the construction industry. Each of these sessions were recorded and transcribed. As well as this posters were used to allow participants to stick post-it notes of their barriers and solutions.

The second phase of data collection captured the practitioner’s (See Table 8) perspective (construction employee who would use the tool if implemented). This was done in two stages, firstly four semi-structured interviews (lasting on average 39 minutes) were carried out with practitioners from one contractor (Contractor A). These interviews were recorded and transcribed. Next, a second workshop (Workshop 2) was organised with 13 practitioners from two contractors (Contractor B and Contractor C) who have previously traillled the CIT Tool. During the workshop participants were split into two groups for two breakout sessions, again each was recorded and transcribed. The content of these workshops was designed to gain an understanding of how CM practices were perceived throughout the industry and within each selected organisation. The practitioners were also asked to discuss the preliminary findings from Workshop 1 on barriers and enablers to the tool's implementation and elaborate further on these. Posters and post-it notes were again used to capture the main thoughts of the participants.

The final phase of data collection explored the current operating practices and processes around CM. For this we focused on Contractor B. During this phase 10 semi-structured interviews (one group and nine individual interviews, averaging 45 minutes) were conducted to investigate the level of understanding within different teams and at different job levels (see Table 8). Whilst most of the discussion in the workshops had looked at the barriers preventing CM practices, the aim of these interviews was to understand the enabling factors required to overcome these barriers. During this time, one researcher – as an observer – also joined a number of working groups on CM, and conducted open interviews (recorded via field notes only) with a client (Client A) and supplier (Supplier A) of Contractor B.

Table 8. Job titles of interview participants

Contractor A (Interviews 1-4)	Contractor B (Interviews 5-14)
Trainee Quantity Surveyor	Group Head Supply Chain
Business Development Manager	Head of Supply Chain – Rail
Quantity Surveyor	Business Development Manager
Planner	Knowledge Manager – Group Work Winning
	Piping Designer – Water
Client A	Planning and Technology Manager
Head of Carbon Neutrality	Estimating Manager
	Business Improvement Director
Supplier A	Group Carbon Manager
Commercial Development Manager	Sustainable Engineering Manager
Sustainable Construction Manager	Finance Director

3.2 Data Coding and Analysis

We used an inductive approach to our data analysis drawing from Gioia et al.'s (2012) analysis guide. The first stage of our analysis was to examine the barriers to the tool's implementation within the construction industry. Posters created at the workshop and transcriptions of the group discussions from Workshop 1 were analysed in NVivo, a commonly used qualitative data analysis software, and from these barriers were grouped into first-order concepts.

Next we integrated data from the four semi-structured interviews with Contractor A and Workshop 2 to identify how this additional data supported or contradicted our initial first order concepts. This allowed us to integrate data from our multiple sources and multiple research tools to allow for 'data triangulation' and 'methodological triangulation' (see Denzin, 2009). Doing this allowed us to reopen the coding to strengthen our concepts and develop second-order themes. Once the second-order themes were agreed upon we suggested categories for the barriers that would describe and explain the findings from our data (see Table 9).

In total, we identified 126 barriers from the workshops and the four interviews with Contractor A. Barriers were grouped with other similar barriers which led to 26 first-order concepts and 10 second-order themes relating to barriers to the tool's implementation within an organisation. These barriers were then categorised in three groups: External Barriers, Internal Barriers and Shared Barriers (see Figure 8 for summary). At this point similar barriers started to reappear and data saturation was reached. As such, our focus shifted to understanding how to overcome these barriers by undertaking semi-structured interviews with Contractor B. Again NVivo was used to code the interview transcripts, mapping the enabling factors discussed to the barriers to gain an understanding of the best ways to integrate CM practices within an organisation.

Table 9. Data coding for barriers to implementation – indicative quotes taken from workshops.

Barriers to implementation *(code refers to workshop number, group and session (e.g. 1D1 means Workshop 1, Group D, Session 1)*	**Theme**	**Category**
Carbon not part of commercial process "I have a commercial background, a big user of the NEC form of contract. I've never seen carbon mentioned in a contract before." 1D1 **Sector / discipline fragmentation "**the tool will be treated great and it will work with the right will, but actually, in order to get the best of it, you've got to do something about how fragmented everything is". 1R2 **Work-winning / delivery disconnect** "There is a bridge between the great work that happens at work winning, and then what you guys do on the delivery side. That is where we are all pulled back and we all fall down." 2K1	Organisational Processes	Internal Barriers
Carbon as bolt-on process "Going from bolt-on to BAU" … "we need to move away from bolt-on processes to administrative processes". 1D1 **Integration with other teams** "where addressing carbon … it is everybody's role, the planners, the procurers, the designers." 1D1	Silo Mentality	
Leadership involvement "it's a big challenge, getting leadership involved because it's such a big issue, people don't have time for it". 1R1 **What is the management's appetite?** "it has to be the bid manager and the project director that have ownership of making sure there is visibility around the strategy and project delivery". 2K2 **Resources required to implement** "It needs a dedicated resource … it can't be a bolt-on, someone has to take it on." 2K1	Leadership	
Lack of regulation for measurement "potentially one of the barriers is the absence of any regulation". 1D1 Alignment to standards "you should set a KPI to align your environmental management with how you make money". 1M1 **Need for client leadership** "if you have a joined up approach across client groups then it will make the industry better at responding". 1D1	Targets and Requirements	External Barriers
No common carbon dataset "if the carbon library is something each company still has to go away and develop, that governance piece about how that is put together is always going to be a big issue". 1K1	Standard Carbon Library	
Competition with other tools "are you suggesting you want those people using those other tools to get rid of their tools and to use this tool"? 1R1 **Unique selling point** "is it just going to be another tool or does it have a unique selling point"? 1K1 **Compatible with BIM** "are they compatible with the BIM model, the data that's prescribed to get to that?" 2D1	Tool Integration	
Knowledge deficit "it isn't just knowledge in terms of 'this is how the tool works', it's 'why does this matter to me in my role'". 1D1 **Shortage of skills** "people don't have the knowledge. Before you can get to talk to them the just don't have the basic expertise, so changes and skill". 1R1 **Communication strategy** "the biggest barrier as a whole is communication … I don't see people communicating points of carbon". 2D1	Education	Shared Barriers
Industry buy in "that whole value chain indifference with the client, the designers, through the constructors and supply chain is quite key". 1K1 **Speed of procurement process** "but through talking to our clients, and those outside of the sustainability world, literally the procurement or commercial, or the planners will look me in the eyes and say 'is this going to delay my project'? 1M1 **Engaging the whole supply** chain "there needs to be a mutual benefit, has it got clients and the supply chain to come up with reductions"? 1D1	Collaboration	
People reluctant to share data "we've got one [a barrier] on whether people will want to share their data … we have that around confidentiality as well". 1M1 **Consistent method of collating data** "if you wanted to align different standards of measurement then you have to have a consistent approach for any client request". 1D1 **Extra work collating data** "we can't honestly ask the supply chain to give us this extra carbon data". 1R1	Data Acquisition	
Industry slow to roll out incentives "then we should look at SMEs, this fourth stage with the wider industry with loads of requirements" … "which is slow to change at the best of times". 1M1 **Does the industry want to change?** "you just hear the same and see the same faces and there isn't any real industry leadership, What is the drive in the industry?" 2D2. **What is in it for company/individual** "it's got to be very clear to each organisation, what's in it for them, why should they adopt the tool … it's about what's in it for me, why is this better"? 1M1	Resistance to Change	

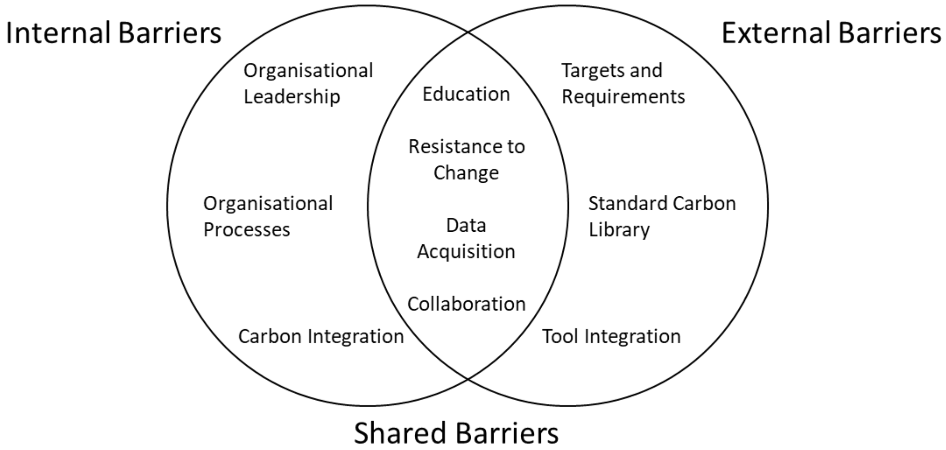


Figure 8. Summary of barriers to the implementation of carbon management within the construction industry

4 Findings

Through the initial workshops relating to CM implementation we identified barriers to successful, meaningful CM implementation. Our findings revealed three broad groups which we classify as ‘External Barriers’, ‘Internal Barriers’ and ‘Shared Barriers’. A lack of targets or requirements that establish what should be achieved through CM practices was seen as one of the biggest barriers to the implementation of CM practices within a construction organisation. Participants often pointed to a lack of regulation providing such targets stating that it was unlikely for their organisation to move towards implementing CM practices if they were not required to do so. Likewise, participants stated that CM tends to be overlooked if the client does not specifically asking for this in the procurement stage and/or incentivise low-carbon solutions. Other participants stated the need for standard datasets to be used throughout the industry to encourage collaboration and common working methods. Finally, another barrier participants pointed to was the fact that many similar tools exist in and beyond the construction industry therefore not knowing which one to use or how the one piloted in our study could provide unique findings or complement other tools. We call these barriers ‘External Barriers’ which are barriers outside of the direct control of a construction organisation. Secondly, we found diverse ‘Internal Barriers’ preventing CM processes within organisations. The participants discussed the lack of desire from their organisation’s senior leadership indicating that CM practices were not as important as business as usual. Participants also feel that CM is not fully integrated within organisational processes, and that there is a fragmentation of teams within the organisation with some engaging with CM and others not. We also found evidence of a number of barriers that are 'Shared', both within the organisation and the wider industry. Our participants at these two levels observe a resistance to change to the implementation of CM practices shown by the lack of drive from the industry and slow adoption within organisations. This, they link to an absence of sufficient training and knowledge to implement the practices in meaningful ways. In addition, the participants point to the absence of standardising processes around CM practices and state that currently there is little collaboration throughout the supply chain in order to enable CM practices.

After identifying these barriers, the participants guided us towards potential steps to enable CM in the construction industry. We thus proceeded to detail a framework with steps required to overcome these barriers to enable CM practices within an organisation. We suggest three steps in this framework: Firstly, external motivations for the organisation to start the implementation process. Secondly, the need for the organisation's leadership to take responsibility for implementing CM practices over the long term and within the entire organisation. Finally, CM needs to be integrated within each team across the organisation, from procurement to project delivery. We will discuss in detail the steps and the associated framework here.

4.1 Enabling CM Practices Within the Organisation

The data shows that the internal barriers can be best overcome through focusing on three aspects. First, construction organisations must be motivated or incentivised from external sources such as regulations, client incentives or industry pressure. Second, the organisation's leadership is required to incorporate CM practices as part of the organisation's vision and strategy. Third, CM must be integrated through each team within the organisation. Each of these enabling steps will now be explained using data gathered from the semi-structured interviews.

4.1.1 External Motivation: Supporting CM Practices from Outside the Organisation

The participants described in the interviews how construction organisations can be persuaded to adopt CM practices through external influences. Our analysis shows that complying with regulated targets and meeting the client's requirements are major drivers for incorporating CM processes within the organisation.

> Everything that we do in terms of the supply chain and the materials we get is driven by regulations within the industry and regulations that our clients have to abide by … obviously we will do what we are told to in terms of what is regulated for use to do. (Interview 6).

The quote shows how this participant sees a clear link between regulations and change. Thus, regulatory pressure is a significant driver to motivate change throughout the industry. The participants for example explain this link by referring to other technological advances such as BIM (Building Information Modelling) that have recently been introduced. The participants explain that BIM was only introduced by organisations after governmental requirements to do so. Regarding the implementation of the CIT Tool specifically the following participant explains:

> I think a tool like this, and thresholds for carbon reduction, need to be mandated, need to be driven from the government … if BIM wasn't mandated a couple of years back I think supply chains, contractors, consultancies just wouldn't have adopted it. (Interview 4).

Despite an increase in specifications that organisations can comply with, such as BS 15978 and PAS 2080, there is scarce regulation calling for organisations to manage and reduce their carbon emissions on infrastructure projects. If regulation is lacking in the area then the organisation will require other forms of incentives to change their processes. Another major driver for implementing change that the participants voiced is the interest of the client in CM practices. The participants feel that during the procurement process most bids are assessed on whether they are likely to be finished to the estimated cost and/or on time alone. Emission reductions are not considered in this assessment. The data shows that if emission reduction targets were part of this assessment then organisations would be encouraged to critically examine how they are addressing this. Especially if the clients are starting to request this as this participant observes:

> If you look at the leadership that is coming from the likes of Client A, Client B, Client C, Client D, a lot of the [carbon reduction] requirements are starting to be mandated as part of that leadership, their role is really important. Without them saying change is needed, change won't happen. (Interview 5).

However, there are still challenges as not all clients are mandating CM as part of their procurement process, which is a concern of the participants:

> It's a bit hit and miss at the moment, it is driven by what the client wants so on some jobs we do it and on some jobs we don't. (Interview 10).

Differences in client requirements/expectations on CM practices also make it difficult for organisations to follow standardised processes within their own organisation, and across teams and projects. Likewise, if a client has a CM tool or carbon library that they are implementing and their contractor is using a different CM tool/library then the reported emissions could vary despite the same approach being used. Instead, the participants state the need for a standardised approach throughout the industry to ensure consistency and avoid the risk of an organisation becoming isolated in their practices:

> It is a very slow changing industry and that is due to the nature of the works that we do. It can be risky so we can't go our own way, go off on one and do something completely different. (Interview 12).

Our analysis finds that organisations are concerned about changing business as usual if it is not industry-wide practice yet. They are unlikely to adopt CM practices without being incentivised to do so. Regulatory pressure and/or incentives however, from the government or the client to adopt CM practices were seen as crucial steps in enabling CB practices. Standardising the way CM is integrated throughout the industry would also encourage more organisations to consider adopting CM practices. The steps revealed here align with the barriers around targets, standardisation and resistance and help form the first part of our enabling framework entitled external motivations (see Figure 9).

4.1.2 Leadership's Role in CM Implementation

The data also shows how the role of a construction organisation's leadership team is important for the successful integration of CM practices. During an informal interview with a participant from Client A, the participant explained how their chief executive had stated the importance of reducing carbon emissions and the need to incorporate CM fully within their organisation. To achieve this the chief executive had identified a 'carbon champion' on their executive board who endorsed the work being done by interdisciplinary teams to reduce carbon emissions. This was particularly beneficial in incorporating CM into the organisation's long-term strategy and direction.

Although Contractor B had an environmental team and a carbon specialist embedded amongst their innovation team there was a feeling that for CM practices to be fully integrated throughout, the organisation's top leadership needed to lead from the front. This was explained by two of the participants from this organisation.

> Leadership should actually talk about it. I don't recall [the CEO] ever talking about carbon, yet, or anyone talking about it at the roadshow or anything like that. If it was given that bit of profile, people see it as more important if their leader is talking about it. They think oh, it must be important, I need to do something about it. If it doesn't get mentioned then obviously people assume it is not as important, simple as that. (Interview 11).

> Having buy-in from the leadership, not necessarily saying 'you shalt do this', but who are really pushing the agenda and they are the ones standing up and saying this is the fantastic work that we are doing and should be doing more of. (Interview 6).

A dedication towards CM practices from the organisation's leadership team can then encourage the organisation to define strategy, develop processes, provide training and encourage collaboration around CM. Speaking about how Client A defined their strategy around CM, one participant said:

> They were very much at the forefront of setting a whole strategy that was based around it. I think they did it quite cleverly in that they realised the importance of carbon generally, but they knew that was a key driver in allowing them to achieve other things that they wanted such as

> reducing their cost base … They set a whole strategy around it, and I think it caught the industry out a little bit, it was quite revolutionary at the time. (Interview 5).

Defining a strategy around CM can give other advantages such as cost savings and efficiencies. However, the data shows that once a strategy has been implemented, it is important to have standardised processes that can be followed across the entire organisation. These processes, the participants feel, must also be clearly communicated to ensure consistency amongst teams and across projects. When asked about the best way to develop standardised processes, one participant suggested starting with one individual from each team across a construction organisation showcase the benefits of incorporating CM practices:

> If you could find a link the whole way through, so find one estimator that's keen as mustard to engage with the plan, and you get it demonstrated on one project, then potentially they redo it again, then you can build that momentum. (Interview 12).

This approach would encourage case study exemplars to be created that could then be shared throughout the organisation to help with educating and training staff. This is important as the participants observe that there was an issue with disseminating best practice around CM with practitioners:

> We need a flow of information down to people at my level of the organisation … or if it is, I am not aware of anything. (Interview 8).

The development of training materials and examples of CM in practice would help staff recognise the benefits that can be realised through the implementation of CM practices and helps speed the delivery of processes within the organisation.

Finally, leadership on CM practices can encourage collaboration with other organisations to jointly commit to reducing carbon emissions. For a tool such as the CIT Tool to be successful the user will require data on carbon emissions from their supply chain. However, this could be a problem as one participant explains:

> We have had problems with some suppliers who were not very happy to give us the data, because they don't see the benefit from their side. (Interview 5).

Intellectual property was an important issue with participants from Supplier A who were concerned that if they shared their carbon emissions data with a contractor, the contractor could reverse engineer the method to use on future bids themselves without having to use the original supplier. However, developing collaborative relationships was challenging anyhow for Contractor B as explained in this quote:

> We are trying to do a lot of work on collaboration, we are trying to get far better at collaboration but we haven't got that sussed. (Interview 11).

An organisation's leadership has an important role in encouraging collaborative relationships by showing that they are committed to seeing emission reductions throughout their supply chain. One of the issues with collaboration around carbon emissions is that it is highly unlikely that costs and benefits will be shared equally. To deal with this collaborative frameworks need to be developed to help contractors and their supply chain work together to reduce carbon emissions, finding forms of incentives that benefit all. The steps revealed here align with the 'Internal Barriers' and form the second part of our enabling framework entitled 'Leadership' (see Figure 9).

4.1.3 Integrating Carbon Practices Throughout the Organisation

Finally, a clear integration of carbon practices within a construction organisation was identified by the participants. It is not just with external partners that collaboration is required, the participants feel. For CM practices to be successfully adopted within an organisation a collaborative approach is needed to integrate CM at the core of their organisation. The participants find that CM is currently seen as part of the environmental team's remit only, as this participant explains:

> In terms of where it [carbon] sits within [the organisation], it is one specific area of the environmental team rather than spread across the business. (Interview 6).

As such, opportunities for reducing carbon emissions are being missed throughout the organisation. There is also a view that carbon reduction is an afterthought or a 'tick box' exercise to make sure that work-winning bids were compliant when required. An environmental manager from the first workshop explains:

> I feel like a minister without a portfolio. No one really quite knows what my purpose is, yet they could learn stuff from what I do. (1D1).

Here, based on the data, the solution is that by integrating CM within each team then more significant carbon savings could be achieved. There was a sense that it was not just the carbon and environmental teams that were isolated from other teams. One participant states:

> If I'm honest, in the organisation, we struggle with a bit of a silo mentality, and people do things with the best intent within their own silo not aware of what else is going on in the business. (Interview 11).

To improve the efficiency of the organisation, measures must be taken to break down these 'silos' so that teams (e.g. designers, planners, estimators) can work together to integrate low-carbon designs within projects. Working together can also bring other benefits such as creating efficiencies on the design, reducing costs and saving time and other resources, however to realise these potential efficiencies collaboration is required. The following quote shows this:

> This only works if you have actual collaboration and communication between the different disciplines … you could have the most amazing tool in the world, but unfortunately, if there is not that cross-collaboration between sectors or between disciplines, your tool falls flat on its face. (Interview 12).

Breaking down the carbon 'silo' and integrating CM practices within each discipline whilst encouraging open communication between each team would help the organisation in developing a joined up approach to effectively reduce carbon emissions and drive change throughout the organisation.

Overall our analysis finds several factors required to enable CM practices within an organisation. Firstly there is a need for an external motivation to encourage and incentivise the organisation in implementing CM practices. Secondly, the organisation's leadership must take responsibility for seeing CM being integrated within the organisation's strategy and processes, provide training and encourage collaboration. Finally, CM must be fully integrated within each team and not just seen as a task for the organisation's environmental specialists. These steps recognise the barrier of carbon integration and form the final part of our enabling framework in Figure 9.

5 Discussion

We have discussed that while many organisations in the construction industry have tentatively incorporated CM practices, to date there has been little research seeking to understand how CM practices can be successfully integrated within organisations in this industry. We thus provided insights into CM-related barriers and associated steps by answering two research questions: why have organisations in the construction industry been slow to implement CM practices, and how can organisations in the construction industry improve the implementation of CM practices?

Our first contribution is towards the limited research of CM practices in the construction industry. Whilst other scholars have looked at specific issues related to CM practices (e.g. De Wolf et al., 2017; Giesekam et al., 2016; Kershaw and Simm, 2014), we have addressed the broader issue of how to integrate these practices within an organisation. Our findings suggest several barriers to overcome including a lack of regulation and incentivisation from clients, the need to develop common standards and processes that can engage the full supply chain, an organisation's leadership, the need for training and education, and overcoming resistance to change. By exploring these issues we were able to suggest steps for overcoming these barriers and enabling CM to be successfully adopted within the construction industry as described in more detail below.

Our second contribution is to add to the growing literature on barriers to environmental practices being adopted within organisations more generally. Several scholars used the 'established criteria' (Álvarez Jaramillo et al., 2018, p. 522) classifying barriers as either internal or external to the organisation. We too found examples of internal and external barriers to overcome. However, we found another level of complexity whereby barriers could be shared both within the organisation and the wider industry. For example, our findings support the views of Robinson (2018) and Lines et al. (2015) that the industry can be perceived as slow, or resistant to change. To overcome these perceptions, training is required to educate employees within the organisation, and also members of the wider industry on what the challenges are in emission reductions, why they should care and how their job role can make a positive difference. Another shared barrier is the need for collaboration. Within organisations there is a need for different disciplines to come together to consider emission reduction. Tools such as the CIT Tool will help with this so that designs can be optimised for carbon reductions before they are finalised. There is also a need to form collaborative partnerships amongst supply chain members. Studies suggest that up to three quarters of work carried out in the construction industry is performed by sub-contractors (Segerstedt & Olofsson, 2010), and developing shared goals around emission reduction will be vital for the industry to make serious cuts in carbon emissions.

Our third contribution, and perhaps most importantly, are three steps that an organisation can take to enable CM practices within their organisation. We summarise these steps in a framework showing the factors required for organisations to be able to successfully implement CM practices. As shown in Figure 9, we suggest three steps that are required to successfully implement CM practices, such as the integration of the CIT Tool. Firstly, there must be external motivations for the organisation to start the implementation process. Secondly, the organisation's leadership must take responsibility in driving change within the organisation. Finally, CM has to be fully integrated within each team in the organisation, from procurement to project delivery.

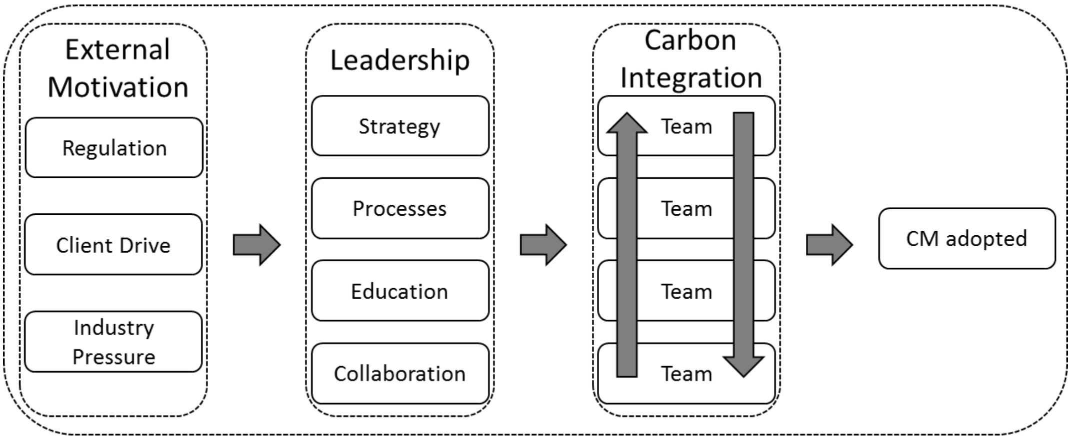


Figure 9. Framework of the steps required to successfully implement carbon management within a construction organisation

The first step required is external motivation for the organisation to consider the implementation of CM processes. Regulation is considered one of the most effective measures for motivating the construction industry on environmental issues, however often regulatory practices lag behind best practice or do not exist at all (Williams & Dair, 2007). The construction industry is heavily regulated in other areas, this means that for emission reduction to be considered seriously regulations must be developed too. Without strict regulation, client leadership in the form of procurement requirements became the main reason for an organisation to think of adopting of CM processes. Like Giesekam et al. (2016), we found that reducing cost on the project was still seen as the most important requirement for clients, and as a result contractors will not expend time and resources on reducing environmental impacts if these are not aligned to cost savings. Our framework also shows that expectations of CM practices also need to come from the client and the broader industry uptake. For example, recently a number of organisations have started becoming certified to PAS 2080. The more organisations that become certified against CM criteria, the more pressure there is on the organisation to follow to avoid the perception that they are not acting at a similar level.

Secondly, the executive leadership of the organisation must commit to the implementation of CM practices. Silence from the organisation's leadership can be taken can suggest that CM is not considered a high priority. In contrast, when the leadership engage with carbon reduction it is straightforward to incorporate CM part of their corporate strategy, develop processes for implementing change, educate their staff and open collaborative relationships with their suppliers. This supports the findings of Chen and Chang (2013) who found that transformational leadership has a positive influence on the implementation of green performance once implemented. However, as stated above there must first be a reason for the executive leadership to act, for example, in the Netherlands, the CO_2 Performance Ladder – a management tool to encourage organisations to reduce their emissions – was mandated on the construction industry as part of the procurement process. Rietbergen et al. (2017) found a large shift in positions from boards of directors before and after this was mandated for them. Beforehand they had shown little leadership in the area but later CM became a recurring topic in management meetings, which led to better performance on these issues from their organisations. As leadership start engaging more with CM, it will also become easier for each team to integrate CM practices.

The final step to successfully implement CM practices within an organisation is integrating carbon practices within each team. The environmental specialists we engaged with through the workshops and interviews often gave the impression that they were on the periphery of their organisations and that they were only called upon when a specific environmental task came up. As Yuventi et al. (2013) state, the lack of accountability between teams makes it difficult for others to appreciate tasks outside their silo. For CM practices to be adopted within the organisation it is important to overcome this issue so that each team engages with carbon reduction and it is not seen solely as the responsibility of the 'carbon specialist'. If each team is considering what they can do to reduce emissions it becomes easier to collaborate with other teams to develop the most efficient designs. Chang et al. (2016) found that developing demonstrable case studies is crucial for increasing the profile of sustainable construction. We propose starting with small case studies showing how CM practices such as the CIT Tool could be used to bring teams together, increase efficiency and reduce cost and carbon emissions. One of our findings was that a lack of standard processes acted as a barrier to change. These case studies can be used to develop consistent approaches that can be scaled up to be followed on larger projects.

Tan et al. (2015) conclude by stating that within the construction industry, integrating sustainable practices can increase an organisation's economic performance and competitiveness. Here we have shown the barriers to overcome and the steps required for an organisation within the construction industry to take to integrate CM practices which would bring these wider benefits.

5.1 Limitations and Future Research

A number of issues are worthy of further discussion and research. One limitation to this research is that despite engaging with the wider industry during the workshops, all interviewees worked in work-winning roles rather than project delivery. As a result, the processes discussed for promoting CM were specific to the strategy of the organisation. Future research should develop an understanding of the relationships between those in work-winning roles and those in project delivery to understand the difficulties of implementing CM practices during the construction phase of projects. Pinkse and Dommisse (2009) found that transferring knowledge between projects was difficult due to the large number of stakeholders involved and the uniqueness of each project. As such, future research should consider how CM practices are shared between projects so that best practice is ensured on future projects. Finally, another area worthy of future research would be to better understand the role of collaboration between organisations to improve CM practices on projects. This research points to the need for policy makers to emphasise the importance of multiple stakeholders in collaborating in CM issues to enable individual organisations to move forward. Achieving emission reductions in the most efficient way goes beyond one organisation and requires a high degree of collaboration between supply chain actors during the design, build and use of the asset. Therefore it is important to understand how organisations can work together to jointly reduce the environmental impact of a project.

6 Conclusion

With growing pressure to mitigate climate change, the construction industry has a significant role to reduce the amount of carbon emitted to the atmosphere. To achieve reductions in emissions, CM processes must be adopted within the construction industry, however such practices are still in their infancy. Our paper seeks firstly to understand the barriers that have slowed the implementation of CM practices within the industry, and secondly to reveal the steps required for an organisation to successfully adopt CM practices. Our research found several barriers that were hindering the implementation of carbon management processes within the industry, which we classified along internal and external barriers, a common practice used in the change literature. In addition to this grouping we also identified shared barriers. Our external barriers occur due to a lack of regulation, incentives or industry pressure to integrate CM practices. Over these barriers construction organisations have little control. Our internal barriers allow more direct control from a construction organisation. These barriers include their leadership's appetite for change, developing new processes and integrating CM throughout the organisation. The shared barriers are issues that arise on the intersection of organisation and the wider industry. These barriers need to be addressed both within the organisation and also the wider industry, such as overcoming resistance to change, improving training and education and developing collaborative partnerships.

Our research paper shows the importance that CM practices can play for the construction industry and associated organisations. Even though rarely implemented, the paper shows how stakeholders across the industry point towards the importance for their industry to advance its implementation. While currently one of the 'dirtiest' industry across the UK, the size of this industry with its potential to drastically reduce emissions if a coherent carbon methodology, leadership and regulation is established paired with aware stakeholders is promising and could mean a step change for UK's construction organisations, industry and policy makers.

Paper 3: Achieving infrastructure emission reductions through supply chain collaboration: challenges and opportunities

Abstract

Purpose: Achieving ambitious cuts in carbon emissions through the lifetime of an infrastructure asset will require collaboration between a large number of diverse stakeholders. This paper explores the challenges faced by the construction industry in reducing carbon emissions throughout the infrastructure supply chain and investigates how collaborative approaches could overcome these challenges.

Design/methodology/approach: Eight collaboration success factors were identified and tested on case studies from a variety of sectors and countries, to determine the key challenges faced by organisations seeking to reduce emissions through supply chain collaboration, and how these challenges were overcome. This was supplemented with insights from the construction sector, gathered through interviews and engagement workshops.

Findings: The case studies highlight several important factors required to reduce supply chain emissions. These include strong leadership to build trust and encourage the sharing of information, shared resources and incentive mechanisms designed to align stakeholder behaviour with the overall objective. Based on these factors, the paper develops recommendations for how stakeholders can more effectively collaborate on construction projects to reduce infrastructure emissions.

Practical implications: The findings of this paper can be applied by organisations seeking to collaborate with their supply chain to minimise emissions through the lifetime of an infrastructure asset.

Originality/value: The study provides new insight into the challenges and opportunities for collaboration to reduce emissions throughout the infrastructure supply chain. It shows how the construction industry can transition from the

traditional, transaction-based model towards a collaborative approach for achieving emission reductions.

1 Introduction

The need to improve collaboration in the United Kingdom (UK) construction industry has been identified as a priority since at least the early 1990s. The Latham (1994) and Egan (1998) Reports, commissioned by the UK Government in response to extensive job losses in the industry during the 1990-1991 economic recession, identified partnering and collaboration as keys to reform and improved productivity. Nevertheless, the industry has been relatively slow to respond to these recommendations. The latest Government-commissioned review of the industry's current and future state (The Farmer Review - Farmer, 2016) still points to a lack of collaboration as one of the critical symptoms of failure and poor performance in the industry. A recent study commissioned by the Home Builders Federation (Graver et al., 2016) likewise identifies increased supply chain collaboration as the key to unlocking the sector's growth potential.

A new and urgent imperative to collaborate across the construction industry has emerged in recent years, driven by the growing requirement to reduce the industry's impact on the environment, particularly with respect to climate change. Although direct greenhouse gas (GHG) emissions from the UK construction industry are relatively small (13.4 $MtCO_2e$ in 2017, or 2.4% of the UK's national GHG emissions on a production basis (ONS, 2019), this rises to 48 $MtCO_2e$ when embodied emissions in construction materials are included (UK GBC, 2018), and up to 515 $MtCO_2e$ when emissions from the operation and use of all UK infrastructure are included – 53% of the UK's national emissions on a consumption basis (Mott MacDonald, 2013). This has led the UK Government – through Construction 2025 (HM Government, 2013) – to call for a 50% reduction in emissions from the sector by 2025.

To help the industry reduce GHG emissions, carbon calculation tools – such as the CIT Tool – are being developed to highlight carbon hotspots on projects and help designers create low-carbon alternative solutions. However, as highlighted in Paper

2, a lack of collaboration between organisations is regarded as one of the potential barriers preventing the tool being integrated within the industry. As such, understanding how collaborative partnerships in the industry can be improved will be of critical importance if carbon calculators are to be used widely in the industry.

Beyond the use of carbon calculators, achieving ambitious cuts in emissions will require significantly enhanced collaboration across infrastructure asset supply chains, for the simple reason that emissions arise at different stages over the lifetime of an asset, including direct emissions from construction of the asset, emissions embodied in the materials used, emissions from operation and decommissioning of the asset and emissions associated with third party use of the asset. The proportions vary for different projects, but on average across the UK, around 30% of total infrastructure emissions are considered to be under the control of the asset owner (construction and operation emissions, including embodied emissions), while the remaining 70% can be influenced to some degree (end-user emissions) (Mott MacDonald, 2013). When client-industry and contractor-supply chain relationships are adversarial, there is little chance of effective control or influence being exercised over lifetime project emissions: as Benjaafar et al. (2013, p.99) observe, 'Multiple actors taking actions based on their own self-interests, and without coordination with others, are not likely to make decisions that minimise emissions for the entire supply chain'.

Given this imperative, it is notable that supply chain collaboration to reduce emissions in the construction industry remains an understudied topic. A recent review of the emerging literature on low carbon supply chain management (Das and Jharkharia, 2018) identified nine papers on supply chain collaboration, and a further 16 papers on supply chain coordination. None of these 25 papers focus on the construction sector. Addressing this gap, in this paper we investigate the necessary conditions for achieving infrastructure emission reductions, the role of supply chain collaboration in these conditions, and how similar collaboration has been achieved in other sectors, thus providing a basis for understanding how the unprecedented level of collaboration required to achieve steep cuts in infrastructure GHG emissions might be achieved.

The remainder of the paper is structured as follows: section 2 provides important context on the infrastructure supply chain and challenges associated with emission reductions; section 3 reviews the literature on low carbon supply chain management and collaboration success factors more generally; and section 4 describes our research methodology. Section 5 summarises the results of our analysis of case studies on the challenges and opportunities for supply chain collaboration, supported with evidence drawn specifically from the construction industry. Finally, section 6 concludes and discusses opportunities to overcome these challenges.

2 Achieving Infrastructure Emission Reductions: The Challenge

A variety of actors are involved in each stage in the life of an infrastructure asset, as shown in Figure 10. Typically, at the start of the construction process, a client will outline their desire for an asset and engage a consultant to design a proposal of the completed asset. Following this, the client will invite contractors to tender for the work to oversee the construction of the asset. The successful contractor will then arrange agreements with suppliers and sub-contractors to perform certain parts of the project. At the completion of the asset, it will be handed over to the owner (or if chosen, an operator) who has control over the operation and maintenance of the asset, whilst there will typically be multiple third party end users who use the asset. At the end of the asset's life, it will typically be the owner who is responsible for decommissioning.

As Figure 10 shows, for UK infrastructure in general, direct emissions from construction are less than the embodied emissions in construction materials, while both are dwarfed by emissions from use and operation of the asset. Emissions during decommissioning or disposal of the asset are seldom estimated, but likely in most cases to be less than construction phase emissions, and given the long lifetimes of assets, it is often simply assumed that the structure will be left in place (e.g. Inui et al., 2011). Although the emissions profiles of individual assets vary, similar relative contributions can be found across many different types of asset, from roads and ports

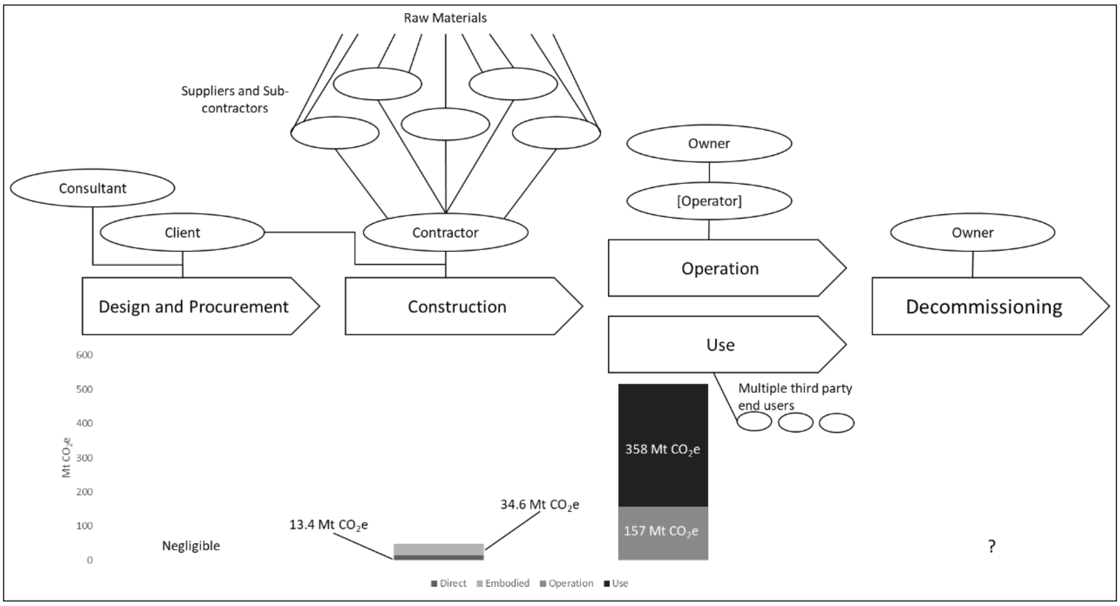


Figure 10. Stages in the life of an infrastructure asset and the parties involved, and the UK's annual emissions (on a consumption basis) at each stage. (Sources for emissions: Mott Macdonald, 2013; ONS, 2019; UK GBC, 2018).

to residential and commercial buildings. We therefore define infrastructure asset supply chain emissions as those arising over the whole lifetime of the asset, not just those from the construction phase. Emissions, and potential emission reductions, should ideally be measured using consequential methods (Brander & Ascui, 2015) that consider the system-wide changes in emissions actually resulting from implementation of an action, compared with a baseline scenario. Limiting consideration of emissions to any single phase, or not considering broader systemic effects, can lead to perverse outcomes. For example, Paper 1 highlighted the risk of burden shifting between phases in a case study of a railway tunnel, where design changes to reduce the tunnel diameter to minimise emissions in the construction phase led to an increase in use phase emissions, as each train required more energy to get through the tunnel due to increased resistance. An example of systemic consequential emissions could be an increase in emissions from people commuting longer distances, due to new rail infrastructure shortening travel times.

Achieving the 'right' or desired level of emission reductions is not simply a case of identifying the option with the lowest possible emissions in total across the asset supply chain, however. Consideration must also be given to a variety of other objectives and constraints, such as cost, standards, regulatory requirements and stakeholder expectations. Furthermore, because costs and other effects may accrue to different parties at different times over the asset life, the importance of these factors may be weighted differently by each party – as opposed to GHG emissions, which have essentially the same global impact regardless of where or when they are emitted. The 'right' strategy for emission reductions therefore also depends on the extent to which the needs and perspectives of stakeholders other than the decision-maker are taken into account.

For example, Sodagar and Fieldson (2008), reviewing the challenges facing the construction industry in meeting the required reductions in GHG emissions set by the UK Government, observe that environmental designs have financial, and often social, costs that must balance out to justify the construction of low-carbon structures. In some cases there may be 'win-win' solutions that meet multiple objectives: a phrase often used within the construction industry is 'reducing carbon reduces cost' (Mott Macdonald, 2013, p.3), based on the premise that building efficiently, e.g. re-using already excavated materials and using fewer virgin materials, and reducing transportation and energy demands, also tends to reduce costs. However, in their report looking at how to reduce GHG emissions on infrastructure projects through improved procurement requirements, Kadefors et al. (2019) argue that as such measures are cost efficient they would, or should, already have been undertaken during the design process. In other cases, measures taken to reduce emissions lead to an *increase* in cost: for example, a report on the costs and benefits of green buildings by Davis Langdon (2008) highlights that there may be a cost premium as high as 9 to 11% in achieving the highest standards. Although this may lead to lower energy consumption and costs for the owner and end users, it leads to higher costs up-front for the client and contractors. As costs and savings will not accrue equally, some level of incentive may be required for the client and contractor to consider the extra costs.

An example of the influence that other standards or regulatory requirements can have on the ability to reduce emissions can be seen in the case of eco-efficient cements. Cement is used in the production of concrete and is one of the most carbon-intensive building materials. To reduce the impact of concrete, eco-efficient cements have been developed. However, cements are subject to stringent national and international standards, which means that making modifications to adapt them for environmental purposes can be very difficult (Scrivener et al., 2018). High standards are set to ensure that quality and safety requirements are met, but these can act as a barrier to the development of more efficient cements.

The need to balance emission reductions against cost and other considerations, which may vary in importance for different stakeholders, means that decision-making will always be highly context-specific and subjective. Nevertheless, if both emissions and other factors are properly taken into account over the whole asset supply chain, and other systematic consequences are also considered, then decision-makers should be in a position to make better informed decisions, balancing the trade-offs between emission reductions, costs and technical specifications according to their priorities for each of these.

3 Low Carbon Supply Chain Management and Collaboration Success Factors

In recent years there has been a growing body of literature on the challenges and opportunities for sustainable (Pagell & Wu, 2009) or green (Srivastava, 2007) supply chain management. More recently, a sub-section of this literature has developed looking specifically at low carbon supply chain management, defined by Das and Jharkharia (2018, p.399) as a 'strategy that integrates CO_2 or CO_2 equivalent or GHG emissions either as a constraint or as an objective in supply chain design or planning'. Research in this area has investigated many issues including benchmarking emissions throughout the supply chain (e.g. Acquaye et al., 2014; Benjaafar et al., 2013; Dadhich et al., 2015), supplier selection (e.g. Shaw et al., 2012), legal drivers and commercial pressures (e.g. Hitchcock, 2012), and pricing strategies (e.g. Jaber et al., 2013; Toptal & Çetinkaya, 2017).

Within this body of research, some scholars have examined collaboration as a requirement for reducing emissions throughout supply chains, although none consider the construction sector. In their paper on collaborative strategies in supply chains, Carballo-Penela et al. (2018) found that by concentrating on specific actions, organisations were able to reduce emissions more effectively by collaborating than they would have been able to do working individually. Studies have looked at collaboration at different stages of a project, for example during design and planning stages (e.g. Trappey et al., 2012), or during shipping and transportation (e.g. Tinoco et al., 2017). Relatively few studies have investigated the success factors for successful collaborations to reduce supply chain emissions: Fawcett et al. (2008) highlight the need for trust and information sharing between organisations, Theißen et al. (2014) also suggest the need for trust and state that appropriate incentive structures are required, while Melander (2018) identifies goal alignment and knowledge sharing as being important for selecting the right partners to collaborate with. We therefore turn to the broader literature on collaboration for a guide, albeit noting the observation of Soosay and Hyland (2015) in their review of ten years of supply chain collaboration literature, that there is still a need for a greater understanding of the characteristics of successful supply chain collaboration.

Collaboration between organisations aims to jointly accomplish at least one shared goal that no single organisation could achieve acting by themselves (Wood & Gray, 1991; Bedwell et al., 2012). Since Thomson and Perry (2006) discussed the 'black box' of the collaboration process, an extensive literature has explored why some attempted collaborations succeed, whereas others fail, and what this implies for the factors required to build strong partnerships. Our review of this literature reveals eight critical success factors (also referred to as 'dimensions', 'themes', or 'activities') that frequently appear: trust; common aims; leadership; structure; administration; incentive mechanisms; information sharing; and shared resources. These factors are presented in Table 10, and summarised below.

Trust is essential to a team's performance (Patel et al., 2012) and should be established early in the project. Each party must have confidence that each other member will act in the best interests of the group and not just themselves. Mayer and Kentor (2016) identify trust as critical to a stakeholder's willingness to share information and resources. Building trust can enhance integration and cooperation between parties and reduce functional conflict (Anbanandam et al., 2011).

Table 10. Common factors in successful collaboration

	Trust	Common Aims	Leadership	Structure	Administration	Incentives	Information Sharing	Shared Resources
Anbanandam et al. (2011)	x		x		x	x	x	
Bedwell et al. (2012)				x				
Cao and Zhang (2011)		x				x	x	x
Fawcett et al. (2008)	x						x	
Huxham (2003)	x	x	x	x				
Matopoulos et al. (2007)	x			x	x	x	x	x
Mayer and Kentor (2016)	x	x	x	x	x			x
McNamara (2012)	x			x	x		x	x
Patel et al. (2012)	x	x			x	x		
Simatupang & Sridharan (2005)						x	x	x
Soosay et al. (2008)					x		x	x
Theißen et al. (2014)	x					x		
Thomson & Perry (2006)	x		x		x		x	

Huxham (2003, p.404) states that it is 'common wisdom' that a collaborative group must have common aims or a shared vision which encourage each party to commit to work to the greater good. Cao and Zhang (2011) suggest that true goal agreement is achieved when supply chain partners perceive that their own objectives are the same as the objectives of the rest of the supply chain.

Leadership is vital for the success of collaboration and developing the greater good (Sullivan et al., 2012). Strong leadership adds legitimacy to the collaborative process and aids the ability of a group to make joint decisions. Anbanandam et al. (2011) express the importance of leadership in building long-term relationships that work towards common objectives.

A stumbling block for many collaborative partnerships can be a lack of structure, resulting in stakeholders not being aware of what each member is doing (Huxham, 2003). Bedwell et al. (2012) state that structural characteristics of collaboration can include leadership, the division of work, communication amongst members and distribution of members. A clear structure, for example involving a clear division of work and definition of roles between the parties involved, facilitates the development of long-term relationships between different stakeholders.

Effective administration enables the implementation of decisions and management of collaboration. Related to this, Soosay et al. (2008) state the need for joint planning to align the processes and capacities of participants in the collaborative effort. A well-defined administrative structure can help the collaborative parties move from governance to action (Thomson & Perry, 2006).

Risk and reward sharing is important in the development of long-term collaborative partnerships (Anbanandam et al., 2011). Appropriate incentive mechanisms can compensate for differences in exposure to the costs, risks and benefits of collaboration. Aligning incentives can promote the achievement of common aims, and encourages parties to align their actions towards the mutual purpose of the collaboration (Simatupang & Sridharan, 2005).

Information sharing is the ability to view, and use, data from other parties that if not for collaboration would not have been shared, in the pursuit of achieving shared objectives. Sharing information can help mitigate risk and is often seen as a prerequisite for building trust (Anbanandam et al., 2011). Collaborative actions have been shown to be improved by frequent and open information sharing which helps to build a common knowledge (McNamara, 2012).

Finally, as well as sharing information, sharing other resources can enhance the competitive position of all parties involved, enabling the creation of something greater than a single party can create on their own (Mayer & Kenter, 2016). Soosay et al. (2008) provide examples of shared resources including the provision of training and sharing various management processes.

To conclude, we find there are eight factors that frequently appear in the collaboration literature describing how to build successful collaborations. These are trust, common aims, leadership, structure, administration, incentives mechanisms, information sharing and shared resources. We now test these collaboration success factors to see which have the biggest impact in enabling successful supply chain collaboration.

4 Methodology

To investigate the importance for low-carbon supply chain management of the eight generic collaboration success factors described above, we performed a meta-analysis of case studies on collaboration aimed at reducing GHG emissions throughout a supply chain. Cases were found using online search engines including Google, Google Scholar, and Web of Science using search terms such as 'supply chain collaboration', 'low carbon supply chains', 'sustainable supply chains', 'energy efficiency', 'emission reductions' and 'case study'. Using these criteria, 41 case studies were identified. These studies were analysed and studies where the primary focus of the collaboration was another form of green or environmental practice, such as sourcing sustainable materials or waste management, were eliminated. This left 31 studies specific to an organisation's efforts to collaborate around reducing GHG emissions or creating energy efficiency. Studies focussing on the latter were retained as energy consumption is usually highly correlated with emissions and because it can be divided into similar components across a supply chain (e.g. direct, embodied and operational energy consumption). Further analysis was performed and studies that did not provide sufficient information were excluded. Examples of these were studies which stated that collaboration had taken place to reduce emissions, without directly stating what had happened, the steps undertaken and the final outcome. At this stage a further 15 studies were excluded, leaving a total of 16 studies that were used and described below.

The cases examined came from several countries and many industry sectors, thus providing a broad understanding of approaches that had worked to reduce emissions. A well acknowledged method of analysing reports and other textual data is content analysis (Duriau et al., 2007). A thematic content analysis (Anderson, 2007) was performed on these studies to find common themes which could be used to describe the challenges faced when collaborating, challenges with reducing environmental impact, and the different approaches used to overcome these challenges. The case studies were analysed in nVivo and each collaboration success factor was categorised as a 'node'. Following this the studies were analysed and any text relevant to the eight success factors was coded. Where the exact phrases varied from the eight factors, the researchers made assumptions to get the best match. For example, one study stated that the company 'asked suppliers to report high quality primary data', this was coded as 'information sharing'. The case studies varied dramatically in length. Industry case studies tended to be shorter (the shortest study was approximately 150 words) whilst academic studies tended to be longer and provide more detail.

To complement the findings of the case studies, data were gathered from numerous interactions with a wide range of stakeholders in the construction industry over the course of a three-year research project involving both of the authors. This data will be referred to as the 'construction industry dataset'. In particular, one of the authors, acting as a participant observer, attended two supply chain workshops hosted by a contractor aiming to encourage suppliers and sub-contractors to engage with emission reductions on major construction projects. During these workshops data was gathered using an audience interaction tool (Sli.do) which gave polling data from pre-set questions set by the contractor, and recorded questions and comments from the participants throughout the sessions. The output from the interaction tool was recorded in nVivo which was then used to create categories and sort the relevant data.

Following on from these workshops, four semi-structured interviews (Bryman, 2008), averaging approximately 45 minutes each, were performed with the contractor, two with members of the supply chain team, as well as an estimator and a designer. One of the authors was also present for follow-up meetings with two suppliers and a client of the contractor. As these meetings discussed commercially sensitive subjects they were not recorded or transcribed, but detailed notes were taken by the researcher and in each case the participants gave their consent for the typed notes to be used for research purposes. The interview transcripts and meeting notes were again coded in nVivo and categorised as with the case studies. The information gathered from the construction industry dataset was used to confirm the findings from the initial case study data, to emphasise the factors required for successful collaboration and to highlight the challenges that are faced collaborating through the infrastructure supply chain.

5 Cases of Collaborative Solutions for Supply Chain Emission Reductions

The case studies (see Table 11 for summary) were examined to understand how organisations were collaborating to implement emission reductions strategies through their supply chains. The studies examined organisations ranging in size from large global entities such as Walmart (see Plambeck, 2012) to much smaller organisations like Muntons, a malt manufacturer based in the UK (see Koh et al., 2013). The organisations studied were based in different countries within North America, Europe and Asia, and covered a wide range of sectors including retail, utilities, food, car manufacturing and IT. In each study, the principal aim was to understand how efficiencies could be made to improve carbon emission and energy performance throughout the supply chain, although each study looked at this challenge in a different way. For example, some organisations had limited knowledge of their suppliers and wanted to have a better understanding of their suppliers' emissions, whilst other organisations wanted to find the most appropriate methods to engage with their suppliers and go beyond simply reporting emissions.

The case studies highlight many of the factors required for successful collaboration, as demonstrated in Table 12. Of the 16 case studies, nine highlight issues related to information sharing and seven to incentive mechanisms, and four each to leadership and trust. The remainder of this section discusses these factors, with particular

Table 11. Collaboration success factors and where they were identified in the case studies

Case Study	Trust	Common Aims	Leadership	Structure	Administration	Incentives	Information Sharing	Shared Resources
1		✓				✓		
2	✓						✓	
3			✓			✓		
4			✓					
5							✓	
6			✓			✓		
7	✓						✓	
8						✓		
9							✓	✓
10							✓	
11	✓						✓	
12			✓					
13							✓	
14	✓					✓	✓	✓
15		✓				✓		
16						✓	✓	

attention to information sharing and incentives, due to the frequency with which these were mentioned. As Hassini et al. (2012) warn about the compatibility of systems developed for one industry working in another, we draw from our Construction Industry Dataset to see if the factors raised in the case studies are relevant to reducing emissions through the infrastructure supply chain.

Table 12. Summary of case studies cited in this paper. ('-' represents information not stated)

Case Study	Reference / Focal Company	Sector	Country	Company Size	Issue raised by case and how collaboration helped supply chain efficiencies and emission reductions
1	Ballot & Fontane (2010) Company X	Food / Logistics	France	-	Study showed that by sharing logistics, two companies could reduce their freight carbon emissions. However, due to the greater cost involved in this the option was not taken.
2	Hassini et al. (2012) Company Y	Utilities	Canada	Large	Found that a lack of trust over data confidentiality made suppliers wary of sharing data. Designed indicators to highlight levels of trust to work on improving issues and build trust with suppliers.
3	Gopalakrishnan et al. (2012) BAe Systems	Defence	UK	Large	Wanted to manage their supply chain emissions and keep their supply chain accountable. Designed a code of conduct for suppliers to sign up to stating how they would continue to reduce emissions on an annual basis.
4	PWC (2012) Best Buy	Retail	USA	Large	Found that due to position in the market and being able to influence downstream users, upstream suppliers were expecting Best Buy to take a leadership role in collaborating to reduce emissions.
5	Carbon Trust & BSR (2017) BMW	Motor	Germany	Large	To get a better understanding of the emissions of their products, engaged with suppliers to sign up to CDP to get a better understanding of their system-wide emissions with the ability to then collaborate at building efficiencies.
6	Carbon Trust & BSR (2017) Braskem	Chemicals	Brazil	Large	Wanted to raise their supplier’s awareness of the need to reduce emissions. To do this they hosted workshops and provided training to their suppliers who could then develop plans to cut emissions.
7	Carbon Trust (2019) Carlsberg	Beverages	UK	Large	Wanted to reduce direct and indirect emissions associated with their products. Worked with an NGO to target key suppliers and then worked collaboratively to reduce emissions.
8	PWC (2012) Canadian Tires	Retail	Canada	Large	There was a need to reduce emissions and waste from packaging. Worked with supply chain to reduce waste, resulting in cost and carbon savings on the finished products.
9	Carbon Trust & BSR (2017) Cisco	ICT	USA	Large	Wanted to know the best way to reduce emissions in their supplier’s manufacturing plants. They shared resources by installing thousands of sensors throughout the plants to pin-point emission hotspots and worked together to reduce emissions.

10	Lee (2011) Hyundai	Motor	S. Korea	Large	Had limited knowledge on the source of emissions of their products. Engaged with supply chain to map where emissions came from on each product and collaborated with supply chain partners to reduce emissions.
11	CDP (2018) Kellogg	Food	USA	Large	Were not sure how best to measure emissions from all their suppliers. Engaged with NGOs to provide support which led to a greater level of trust from suppliers willing to cooperate.
12	EPA (2010) Kimberly-Clark	Personal Care	USA	Large	Realising that reducing their emissions required their supply chain to act as well, they took a leadership role, engaging and encouraging their supply chain to sign up to CDP to measure and monitor their impact and worked together to reduce their emissions.
13	Koh et al. (2013) Muntons PLC	Food	UK	Small	Had no data from suppliers on the source of their emissions. Started using a data platform and engaged with suppliers to give data. Were then able to work collaboratively to reduce carbon hotspots.
14	EPA (2010) Pepsi Co	Food / Beverages	USA	Large	Wanted information on their supplier's emissions. Offered a specialist team of people to help suppliers reduce their emissions once the data had been gathered.
15	Carbon Trust (2006) Walkers	Food	UK	Large	Misaligned incentives meant opportunities to reduce energy consumption were missed. Redesigned contract so that both them and their suppliers could save money on same quantity of material supplied.
16	Plambeck (2012) Walmart	Retail	USA	Large	They wanted to improve energy efficiency but were not willing to pay a higher price for efficient products. They incentivised their suppliers through longer contracts for higher quality products.

5.1 Information Gathering and Sharing

In several cases the focal organisations were keen to reduce their environmental impact, but to do so required information from their suppliers that was not initially available. For example, Muntons (see Koh et al., 2013), was keen to reduce its GHG emissions but needed to understand the carbon hot-spots along their supply chain in order to do so. Kellogg (see CDP, 2018) wanted to identify the sources of emissions throughout their supply chain, but only had information from first-tier suppliers and lacked information about organisations further up the supply chain. Other challenges organisations found were that not all suppliers shared information, for example about one third of BMW's supply chain had not submitted data on their emissions (Carbon Trust & BSR, 2017). As well as a lack of information, uncertainty in the information or a lack of knowledge on how to use the information can be a problem.

As an example, one of the biggest challenges faced by Hyundai (see Lee, 2011) was determining what emissions came from which supplier, how the emissions could be measured and how they as an organisation could manage them.

In their report on how to manage GHG emissions in the supply chain, the EPA (2010) list several cases where organisations successfully engaged with their suppliers to gather information on emissions and potential emission reductions. In the majority of these cases the focal organisation asked suppliers to fill out a survey or questionnaire on their emissions, hoping that would kick-start the suppliers into considering emission reductions. However, administering a survey or questionnaire becomes difficult for organisations with extensive or complex supply chains. With a vast supplier list, to ensure consistency of the information from their suppliers, BMW (see Carbon Trust & BSR, 2017) asked their suppliers to sign up to the Carbon Disclosure Project (CDP), which encouraged their suppliers to set annual targets and made it easier to monitor progress. BMW employed modes of persuasion and mandate to promote supplier collaboration, developing pilot projects with key suppliers who engaged, and imposing targets on their highest emitting suppliers who were yet to sign up.

The use of IT can be beneficial in developing a shared understanding of emission sources throughout the supply chain. For example, Koh et al. (2013) developed an analysis tool to map carbon hot-spots along the supply chain, which enabled Muntons and their suppliers to identify areas requiring attention. This collaboration led to the creation of a centralised barley drying and storage unit which cut 1,700 vehicle movements and reduced emissions by 650 tCO_2e per year. When Cisco (see Carbon Trust & BSR, 2017) wanted to understand the emissions of their supply chain in Malaysia, they used their own resources to install thousands of sensors around their manufacturing partner’s plant. The use of the data gathered from the sensors enabled the organisations to work together to create efficiencies which led to emission reductions and cost savings. The use of tools like this helps minimise the time required to collect the data, which in turn helps address supplier concerns about the cost of gathering the data.

To overcome the issues of uncertainty regarding their emissions, Lee (2011) shows how Hyundai adopted the WRI/WBCSD GHG Protocol (2004), which helped them set scopes and boundaries for their emissions. They asked their ten top suppliers to follow the same protocol and were able to use the information they provided to create a carbon process map, which allowed them to accurately calculate the emissions of their products.

From the construction industry dataset, the need for accurate data on the embodied emissions associated with each material was seen as one of the key challenges when designing low carbon infrastructure projects. Emphasising the importance of this, one of the contractor’s estimators suggested developing

> a central library [of carbon emission factors], so that you only need to look in one place ... you’d ideally need to get your suppliers to get on board and list their materials.

However, concerns were raised about the increased time and resources required to collect accurate emissions information, with one participant stating:

> I can't see what I get from this. I can see my company putting in a lot of effort and I'm not sure what I get back?

To overcome this, the contractor offered to share a carbon calculation tool which included a library of carbon emission factors with their suppliers. By providing the tool, and training on how to use it, the contractor hoped to build the necessary trust for their suppliers to share their data.

5.2 Incentive Mechanisms

In their paper exploring the operational implications of integrating carbon emissions into supply chain optimisation models, Benjaafar et al. (2013) observed that although collaboration can reduce both costs and emissions for the supply chain as a whole, costs and emissions could still increase for some suppliers, thus necessitating new arrangements to compensate these firms. This was highlighted in the case study of a French food manufacturing supply chain by Ballot and Fontane (2010), who discovered that despite finding that emissions could be reduced by up to 25% by sharing warehouses and distribution centres with other organisations, significant differences between the cost efficiency and emission efficiency for each partner led to this opportunity to reduce emissions not being taken. Traditionally, collaboration in the supply chain has tended to create economic benefits mainly for the focal organisation. It is therefore important to develop mechanisms that enable the focal company to share these financial gains with their suppliers (Gunasekaran et al., 2015).

In addition to new incentive mechanisms being required, existing incentives may need to be withdrawn or reformed if they are misaligned with the objective of reducing emissions across the supply chain. For example, Walkers Crisps (see Carbon Trust, 2006) found that by purchasing potatoes based on their weight, suppliers had been incentivised to increase moisture content by storing their potatoes in artificially humidified warehouses, which used large amounts of energy. Walkers then also had to use around 10% more energy in the frying process to drive this moisture out. In this case, the contract between Walkers and their suppliers was changed to base the price on dry weight. As a result, both parties were able to reduce their energy demand and costs. Similar savings to both energy and cost were found by Canadian Tires (see PWC, 2012) whilst working with their supply chain to improve efficiencies.

In order to avoid incentive misalignment, incentives have to be created to meet the specific challenges that arise from each partnership, realising that each stakeholder will have different motivations for collaborating. For example, Scholtens and Kleinsmann (2011) found that some sub-contractors were extrinsically motivated to engage in emission reductions, driven by regulatory compliance and costs, whilst others were intrinsically motivated, driven by environmental awareness and relationship building. Incentive mechanisms can take many forms including financial incentives, coercion and co-option. Our review of the case studies revealed several examples of different incentive mechanisms and how they have been used to engage supply chains to reduce their GHG emissions and increase energy efficiency.

One option is for the focal organisation to pay a price premium to their suppliers for providing environmentally superior products. Kogg (2003) describes how this may be required for some smaller companies who do not have coercive power over their supply chain. In contrast to this case, Walmart, a multi-national wholesaler, was able to use its size and purchasing power to pressure suppliers into improving the energy efficiency of their products. Plambeck (2012) explains how Walmart refused to pay a price premium, instead offering longer contracts to those who could show they had improved the efficiency of their products. This meant that Walmart did not have to spend more money on higher quality products, while the suppliers could use the certainty of a longer contract to invest more resources into product development. Another form of coercion can be pressuring suppliers to sign up to standards. For example BAe Systems (see Gopalakrishnan et al., 2012) demanded that their suppliers agreed to a code of conduct which meant that they had to report their emissions and show what they were doing to reduce these, in order to win future work.

Alternatively, an organisation may choose to enter into a cost sharing agreement with their suppliers. Zeng et al. (2019) examine the difference between purchase price incentives and cost sharing incentives on a construction megaproject. Although they found that both mechanisms were of benefit to supplier development, they found that cost sharing between the collaborating stakeholders had a greater effect on quality than purchase price incentives. Benjaafar et al. (2013) explored how a supply chain performed under an emission sharing cap. They found that collaboration led to greater and more cost-effective emission reductions under a shared emission cap, as opposed to each supplier being limited by individual caps.

Penalties are an alternative to incentives. In a study of over 300 firms from a wide variety of sectors, Porteous et al. (2015) found that fewer than 10% of organisations offered price premiums for improving social and environmental performance, whilst the majority of organisations incentivised through training or increased business. They also analysed the effectiveness of three types of penalties (fines, reduced business and termination of contract) on suppliers who failed to meet efficiency targets. They found the most common penalty was a warning followed by reduced business. Nevertheless, they found that fewer than 30% of organisations actually terminated the contracts of those who failed to meet the standards.

Finally, it should be noted that there are other non-financial methods to incentivise the supply chain to engage and collaborate around supply chain emission reductions. For example, Braskem (see Carbon Trust & BSR, 2017) delivered training workshops to their suppliers, while Pepsi Co. (see EPA, 2010) gave their suppliers access to a full-time 'resource conservation specialist' who could help them develop build their capacity to reduce emissions and create efficiencies in their own organisations.

We find evidence to support this from the construction industry dataset too. During our engagement it became apparent that suppliers were seeking incentives to reduce emissions, for example, one workshop participant asked:

> If [your organisation] gets financial reward at a project from a client for carbon savings, will you pass or share that on to the supplier who offered the carbon saving?

This emphasises the need to develop the right features and attributes for incentive mechanisms to encourage suppliers to engage. During a follow up interview with the contractor's supply chain manager they agreed the need to incentivise the supply chain suggesting this starts during the selection of suppliers:

> In our selection criteria, you [the supplier] are going to be incentivised to promote carbon reduction, and then your delivery of those objectives through the project life cycle will be measured, and your ability to win repeat work will be determined on the ability of you to achieve those measures.

The incentive suggested here was the possibility of winning future work, however, this may not be the best mechanism to improve collaboration. There is a need for greater understanding on appropriate incentive mechanisms for the industry and how these would work for all stakeholders on a project. As highlighted previously, incentives could be financial, for example cost-sharing where each member of the project shares the costs and rewards of emission reductions, coercion where the focal company demands the supply chain to cooperate in reducing emissions, or co-optation where suppliers agree to meet voluntary standards. Future research should aim to understand which methods would be most applicable to the infrastructure supply chain in order to successfully reduce carbon emissions.

5.3 Leadership

Having an organisation that is willing to take on a leadership role helps in developing collaborative partnerships. Large multinationals such as Kimberly-Clark (see EPA, 2010) and Best Buy (see PWC, 2012) found there was an expectation from their stakeholders that they would take on a leadership role in reducing emissions across their supply chains. For supply chains that do not include a large multinational, as Kogg (2003) explains, this might mean that smaller organisations may have to take the initiative and lead the collaboration efforts.

There are several other ways in which leadership can be displayed. Before getting their suppliers to sign up to their code of conduct, BAe Systems themselves had to meet this standard. This started with their board of directors developing a mission to become a global leader in dealing with environmental challenges, and then equipping their own employees with training about how they could reduce their direct and indirect emissions. Another way of showing leadership is by providing training to the supply chain. Braskem (see Carbon Trust & BSR, 2017) found there was a lack of knowledge among suppliers on how to report and reduce emissions, so they delivered workshops to their suppliers to train and equip them on how to measure and manage emissions.

We found similar leadership being demonstrated from our construction industry dataset, where the contractor hosted engagement workshops, asking suppliers and sub-contractors to share emissions data with the aim of collaborating to create accurate carbon baselines. During these workshops, training was provided and the suppliers were encouraged to approach the contractor should they require help in understanding how to measure their emissions.

5.4 Trust

Trust is undoubtedly important in building strong collaborative partnerships, and a lack of trust is a common barrier to information sharing between parties (Danloup et al., 2015). In their case study of a Canadian utility company, Hassini et al. (2012) found that trust was one of the most important factors in building collaborative relationships, and that a lack of trust could lead to a fear of confidential data being compromised. Other case studies show how trust can be built to encourage collaboration, for example Pepsi Co. (see EPA, 2010) improved their relationship with suppliers by first sharing their own emissions data to gain the trust of their suppliers before asking their suppliers to share data with them.

Another way the focal company can build trust with their suppliers is to bring in a third party to show they are committed to emission reductions. Kellogg (see CDP, 2018) teamed up with an NGO and found that having an external, trusted organisation to partner with helped provide legitimacy to their desire for emission reductions, and help build trust with suppliers who were encouraged to engage and share data. Similarly, Carlsberg (see Carbon Trust, 2019) collaborated with the Carbon Trust to identify and engage with key suppliers to work in collaboration to drive down emissions that were outside Carlsberg's direct control.

We find evidence from our construction industry dataset to support this. Although the lead contractor tried to show leadership by bringing the supply chain together and offering to share resources, they quickly found difficulties engaging with all parties. One of the major concerns raised by suppliers was around trust. One supplier was very sceptical about sharing data with the contractor, and at a follow-up meeting stated that the concern was that their data could be used to estimate a cost breakdown which would lead to the supplier losing their intellectual property and unique selling point. This supplier stated that they would rather collaborate directly with the client, as they felt that the client, rather than the lead contractor, could be trusted.

5.5 Absence of Other Factors

Before moving on to the opportunities for how to reduce infrastructure supply chain emissions, it is worth a brief discussion on the other collaboration factors that were not discussed, and the reasons that they may not have come up in the case studies. Only two of the case studies examined highlighted 'common aims' and 'shared resources' as factors required for successful collaboration, and none of the 16 studies mentioned 'structure' or 'administration'. Does this mean that these factors are less important to collaboration? One reason for the lack of reference to these 'invisible factors' could be word limitations in the studies. Companies creating case studies will want to keep the word count concise and emphasise the key findings. It may be that talking about the structure of the partnerships, or administrative processes, is not as universally or immediately interesting to readers, being more mundane. However, they may be just as equally important. As such, we would recommend that future research seeks to understand the importance of structure and administration on the collaboration process relative to the other collaboration success factors.

6 Opportunities for Collaboration to Reduce Infrastructure Emissions

The construction industry has been described as one of the most diverse and unstable sectors within the UK economy (Dainty et al., 2001), frequently suffering from cost overruns, programme delays and poor productivity (Briscoe et al., 2004). The need to improve supply chain collaboration has frequently been identified as necessary to resolve these problems, given that suppliers and sub-contractors are typically responsible for at least three-quarters of the work on a construction project (Segerstedt & Olofsson, 2010). This need is arguably even greater when it comes to the unprecedented level of collaboration required to achieve significant emission reductions across the life of an infrastructure asset.

Based on the assessment of 16 case studies, we suggest several factors are required to develop successful collaborative partnerships. We find that information sharing and incentives are the main mechanisms that need to be in place to encourage parties to collaborate and reduce emissions through the supply chain. However, to support these mechanisms, leadership and trust are required to bring and keep parties together.

From the construction industry dataset we identified several challenges limiting the ability to build collaborative partnerships. Despite the efforts of the lead contractor to reach out and engage with their supply chain, there was a lack of trust which hindered the contractor's ability to act as a leader in the collaborative partnership. The need for accurate and consistent data on embodied emissions of different materials was also seen as a key challenge, followed by the time and resources required to gather, share and act on such information. The solution developed by the lead contractor – a shared carbon calculation tool – has the potential for wider adoption across the industry, and sharing the tool, as well as information within it, was found to be positive for building trust between parties. Nevertheless, it should be noted that at present, this tool only covers direct and embodied emissions, and not operational, use or wider consequential emissions from infrastructure assets. Further work is therefore required to develop more comprehensive tools which can provide the necessary guidance to aid decision-making. Finally, we observed a lack of appropriate incentives in our construction sector case study, which tended to undermine trust, as suppliers believed that the lead contractor would not share the benefits of collaboration with them. Future research should therefore consider how to structure incentives to encourage collaboration to drive down emissions throughout the infrastructure supply chain.

To overcome these challenges, we propose moving away from the traditional, linear construction model that the industry has used for years, to a client-centric framework (see figure 11). We suggest that it is the client, rather than the lead contractor, who should take a leadership role in supply chain collaboration, bringing all major parties together during the planning phase of the project. As Pero et al. (2017) state, it is important that collaborative efforts begin during this early stage, in order for each stakeholder to identify areas where emissions can be reduced prior to beginning construction. This is in contrast to the traditional design-bid-build model which discourages collaboration and encourages competitive pricing and limited quality.

As the case studies show, a strong, trusted coordinating entity is needed who is willing and able to provide incentives to encourage collaboration. As Skitmore and Smyth (2009) observe, it is the client that has control over the programme of investment and who is best placed to create incentives and encourage collaboration. Due to the nature of the industry, we suggest that the client is the only stakeholder

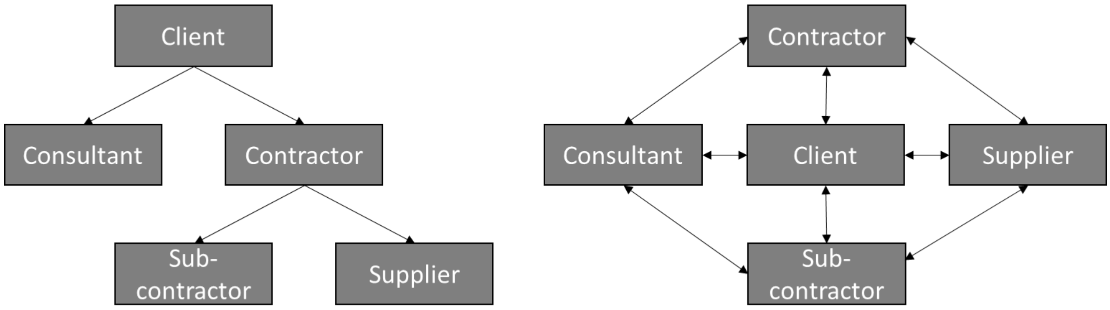


Figure 11. The traditional construction model (left) and proposed client-centric collaboration framework (right).

who is capable of providing the necessary leadership, although we note that there may still be significant shortcomings with a client-centric approach if the client is not the intended long-term owner of the asset. This suggests a role for government in providing the necessary regulatory incentives to motivate all clients to concern themselves with reducing emissions throughout the entire infrastructure asset supply chain. Current regulation in the UK is disjointed, with key initiatives such as the 2013 Infrastructure Carbon Review (Mott MacDonald, 2013), PAS 2080 – Carbon Management in Infrastructure (BSI, 2016) and Delivering Low Carbon Infrastructure (UK GBC, 2017a) restricted to direct, embodied and operational emissions from infrastructure, and thus excluding end-user emissions; whereas until recently various building standards target the latter but exclude the former (Doran, 2019).

Another fundamental limitation of a client-centric approach is that even if it is successful in driving collaboration to reduce emissions associated with a given infrastructure asset, the lessons learned are not necessarily transferable to other projects involving other groupings of stakeholders. The project-driven nature of the construction industry has long been identified as a barrier to long-term relationships (Fulford & Standing, 2014), and traditional procurement methods in the construction industry discourage collaboration (Osipova & Eriksson, 2011). The construction industry should consider new business models such as Project 13 (ICE, 2018a) which take the industry away from traditional transactional arrangements on a project-by-project basis, towards an enterprise approach more similar to a manufacturing supply chain. Project 13 defines an enterprise as 'an integrated organisation, aligned and commercially incentivised to deliver better outcomes for customers from infrastructure investment' (ICE, 2018b, p.4). This will involve bringing together organisations with the capabilities and behaviours to deliver new assets successfully. It is hoped that this model can lead to longer-term relationships between the different stakeholders in the infrastructure supply chain, improved efficiency and increased value. Future research should explore how these models could be implemented in the industry.

In conclusion, there is a need for the construction industry to improve collaboration and develop stronger partnerships to reduce carbon emissions across infrastructure asset supply chains. We identified eight generic factors associated with successful collaboration and looked for these in case studies aimed at reducing emissions through supply chains in a variety of sectors. Information sharing and incentives stood out as essential mechanisms to drive emission reductions across supply chains, but leadership and trust were fundamental enabling factors. The construction sector faces challenges with all four of these, although the development of a shared carbon calculator tool for estimating direct and embodied emissions has significant potential, both as an information-sharing mechanism and as a means of building trust between stakeholders. We propose a client-centric approach to improve collaboration in future, while recognising a role for government to provide additional regulatory incentives, and a role for the industry as a whole to collaborate in order to achieve longer-lasting relationships akin to those in the manufacturing sector.

Conclusion

Last year, the UK Government put into law the requirement of the UK to be 'net-zero' by 2050 (BEIS, 2019). This was soon followed by the Scottish Government stating this legal requirement by 2045 (Scottish Government, 2019). These laws will require businesses to seriously rethink their current business practices and develop new strategies and business models to significantly reduce their GHG emissions. The dilemma for the construction industry is that the best course of action to significantly reduce emissions would be to minimise the building of new assets. However, given other needs, such as a growing population and the need for faster and more reliable transport networks, the industry will have to develop smart solutions whilst addressing the need for significant cuts in carbon emissions.

In this thesis I have sought to address these issues by taking a multi-perspective approach to understand the challenges of developing and integrating a carbon calculation tool within the construction industry in order to measure and reduce carbon emissions. This has been done first by questioning the suitability of an embodied carbon calculator to successfully develop solutions to reduce emissions through the lifetime of an asset. In doing this, Paper 1 (Chapter 2) answers Research Question 1:

> Are there real-world situations in which burden shifting is likely to arise from the use of embodied carbon calculators for infrastructure projects?

Second, the thesis provides insight into the requirements for successfully integrating carbon calculation tools and other carbon management practices within organisations in the construction industry. This is addressed in Paper 2 (Chapter 3) answering Research Questions 2 and 3:

> Why have organisations in the construction industry been slow to implement carbon management practices?

And,

> How can organisations in the construction industry improve the implementation of carbon management practices?

Finally, for the carbon calculator to be successful and emissions to be reduced throughout the lifetime of an asset, collaboration is required throughout the infrastructure supply chain. Paper 3 (Chapter 4), addresses this issue by answering Research Question 4:

> What factors are required for successful collaboration through the infrastructure supply chain?

In answering these questions, this thesis provides practical recommendations to improve the performance of carbon calculators in the construction industry, aid organisations in developing strategies to implement carbon management practices, and summarises the key factors for improving collaboration across the infrastructure supply chain.

The remainder of this concluding chapter is structured as follows: Section 1 summarises the outcomes of this thesis, highlighting the major findings and implications of each of the three papers which make up this portfolio of papers; Section 2 discusses a number of limitations of this research; Section 3 provides some self-reflection on the PhD process; Section 4 presents a number of ideas for future research; and finally, Section 5 offers some brief concluding remarks.

1 Summary of Findings

1.1 The Risk of Burden Shifting

In Chapter 2 I examined the risk of burden shifting using an embodied carbon calculator, where design changes aimed at reducing embodied carbon lead to a net increase in emissions when the operation, use and maintenance of the asset are accounted for. This contributes to the literature on LCA in construction and addresses a gap in the literature as very few empirical studies have examined if there are real-world cases of burden shifting.

Through the analysis of four decision cases, this chapter reveals that although the risk of burden shifting does not appear all the time, in some cases design changes to reduce embodied emissions can lead to an increase in emissions during other life cycle stages. This has important implications for practitioners as it indicates a current shortcoming of the industry in terms of carbon measurement, and highlights the need for a whole-of-life assessment approach.

To overcome these challenges, the chapter develops a set of heuristic guidelines which can be followed to allow the user of the carbon calculator to avoid the risk of burden shifting. The chapter concludes by recommending that over time, as skills in carbon measurement increase, the construction industry transitions towards calculators that can provide whole-of-life assessments.

1.2 Barriers and Enablers to Carbon Management in Construction

In Chapter 3 I examined the barriers preventing the use of a carbon calculator (the CIT Tool) and carbon management practices being implemented within the construction industry, and sought to understand how these barriers could be overcome to enable carbon management practices within organisations. This was done by examining data gathered from two workshops and 14 semi-structured interviews.

This chapter reveals barriers to the adoption of the CIT Tool, and carbon management practices more generally, which within organisations could be classified in three groups: External Barriers were those that the organisation had little control over; Internal barriers could be classified as barriers the organisation had direct control over, meaning they would be simpler to overcome; Finally, Shared Barriers were those that needed addressed both within organisations and the wider industry.

To overcome these barriers, the chapter proposes a three-step framework. Firstly, there is a need for external motivations from the industry to encourage the organisation to take up carbon management practices. This could be in the shape of incentives from clients, or governments regulating the use of carbon management practices. Secondly, the leadership within the organisation must take responsibility for incorporating carbon management practices, helping to improve internal processes, providing training and engaging with other organisations to work together on reducing emissions. Finally, carbon management must be fully integrated within each individual's job role. By following this framework, this chapter concludes that the construction industry can take a significant step towards drastically reducing emissions in the sector.

1.3 Supply Chain Collaboration

In Chapter 4 I examined the factors required for successful supply chain collaboration aimed at reducing carbon emissions through the infrastructure supply chain. This was done by testing eight collaboration success factors through a meta-analysis of case studies which had been designed to explore collaboration and emission reductions in other sectors.

This chapter revealed that information sharing and incentive structures were the most important mechanisms required for successful collaboration, and that these were supported by building competencies in other factors such as leadership and trust. This chapter also shows the challenges faced by the construction industry in achieving these success factors, and highlights that the construction industry fails to build successful collaborations due to other overarching issues such as the project driven nature of the industry.

To overcome the challenges of collaboration, the chapter recommends moving away from the traditional linear relationships where a supplier would have little say on the design, to a client-centric framework where each stakeholder on the project works together to address issues of emission reductions prior to the start of construction. This has important implications for the construction industry as it means that new business models, such as the enterprise approach described in Project 13 (ICE, 2018a), will need to be developed to encourage greater collaboration. The results of these new business models could go beyond emission savings and could help the industry make improvements on costs, efficiency and delivery speed – other key challenges faced by the industry.

2 Overall Contributions

This PhD thesis makes several important contributions. Those that are specific to the main chapters of the thesis, the CIT Tool and carbon management practices in the construction industry are already discussed in the relevant chapters, so this section aims to look more broadly at the contribution of the thesis as a whole. In section 4.3 of the Introduction chapter, I show that there is currently little overlap between the disciplines discussed in each of the main chapters of this thesis. However, as is evident throughout the thesis there are several challenges associated with developing carbon calculators and integrating them within the construction industry. As such, this thesis makes an important contribution by showing that the challenge of reducing carbon emissions in the construction industry cannot be solved simply by focussing on one area of literature, and that a multi-perspective approach is required. This thesis takes an important first step at uniting these areas of literature and addressing the challenges of developing carbon calculation tools.

More broadly, this research supports some of the findings related to implementing Environmental Management Systems (EMS) within organisations. Several of the barriers to implementing EMS map with the internal and external barriers found in Paper 2, for example in their evaluation of implementing EMS in the Hong Kong construction industry, Tse (2001) finds that a lack of government pressure and a lack of client support were slowing the adoption EMS. A point that can be added to the literature on EMS is the need to break down the environmental / sustainable 'silos' that develop within organisations. ISO 14001 (BSI, 2015) for EMS follows a 'plan-do-check-act' framework to improve environmental performance within an organisation. One issue shown was that with frameworks like this, it is often the Environment or Sustainability Manager that is responsible for preparing this plan. In Paper 2 I show the challenges that these managers have in braking down the 'silo' and integrating carbon management throughout each team in the organisation. This highlights the need to integrate environment and sustainability issues throughout organisations, rather than just within one team, in order to achieve the maximum benefits.

It is also worth alluding to some of the other benefits this research brings to the construction industry. In recent years there has been a large drive to improve health and safety within the industry, specifically relating to wellbeing. Milner et al. (2014) highlight that there is an elevated risk of suicide among construction workers related to the demographic characteristics of a largely male workforce, particularly in unskilled roles. The framework developed in Paper 2 for integrating carbon management practices could be reframed to address at the issue of wellbeing, and show how this could be further promoted throughout the industry. For example, there has been growing media attention to the rise in mental health issues in men, and this could act as an external motivation. One of the issues in Paper 2 was the lack of communication from senior leadership on carbon management which sent a message to the rest of the organisation that it was not an important goal for the organisation. During one of the interviews collecting data for Paper 2, one of the participants stated as an example that the CEO always started each talk or speech to the staff mentioning wellbeing or health and safety. This encouraged others to consider how this could be improved. Finally, it would not just be the job of the Health and Safety team to make sure each individual was cared for. Throughout the organisation, and on live projects, each team has to integrated safety and wellbeing throughout their teams to ensure a safe workspace. This relates to the third part of the framework as integrating throughout teams.

Overall, this thesis highlights the need for a multi-perspective approach to reducing carbon emissions in the construction industry. Peter Drucker is credited with the well-known cliché, ‘what gets measured, gets managed’. To successfully reduce GHG emissions, the CIT Tool can be used to help measure emissions and create low carbon solutions. However, as shown, the development of carbon calculation tools themselves is not enough to drive change. Other challenges, both within organisations and through the wider industry also need to be addressed.

3 Limitations with the Research

The papers within this portfolio each contain discussion on their specific limitations, and also suggest areas of future research to overcome these limitations. Rather than replicating that discussion here, the remainder of this section addresses some broader, overarching limitations of the thesis as a whole and what may have been done differently to overcome these issues.

This thesis has taken a multi-perspective approach to look at the implementation of a carbon calculator in the construction industry, looking at challenges related to what the calculator measures, how to integrate the tool in organisations, and how to engage supply chains achieve emission reductions. Although this approach has provided research that is highly relevant to each of these areas, one limitation of the thesis could be that stronger contributions could have been made if the thesis had focussed solely on one of these research areas. This would have allowed me to spend the three years reading within one area of literature, rather than dividing my time researching three different areas. This would have made it easier to follow the direction of literature, as an example, it has been difficult to keep up-to-date with the literature on LCA in the construction industry since Paper 1 was published, as time has been spent working on the other two papers. Similarly, looking at just one topic could have meant attending the same conferences each year, building relationships and finding a network of people who know about the area of research who could have offered advice.

However, it is also worth pointing out some of the advantages of looking at different perspectives. Climate change is a multi-disciplinary problem, spanning sectors and borders. A carbon calculator itself will not reduce carbon emissions, it can highlight where savings can be made, but these changes then need to be implemented. Using a multi-perspective approach has allowed for contributions to be made in thesis to show how the uptake of carbon calculators in the industry can be improved, and how stakeholders can collaborate to ensure designs keep carbon emissions to a minimum. Had this research only looked at the challenges involved in the tool's development, these contributions would have been missed.

4 Reflections on the PhD

In this section I provide some brief reflections on the PhD process. This section is not meant as a negative outburst, but to give insight into some of the thoughts I have had over the three years of study. I will briefly touch on three areas, doing a PhD as part of a larger research project, the expectations of PhD students, and the difference in pace between industry and academia.

4.1 Project Driven PhDs

Within the Business School, I am not aware of any other PhD student who is currently working on a PhD that is part of a specific research project. Although this is more common practice in other schools, for example the School of Engineering or School of GeoSciences, it seems this is less common in the Business School. There have been advantages to this type of PhD arrangement, for example, having a set project meant that in my first year I had a clear objectives so that I was able to commit to the research rather than spending most of my first year updating my research proposal. The level of supervision was also very good this way, being able to work with co-authors who had knowledge of each of the three research areas. However, there were also disadvantages. Having pre-determined work packages on the project meant that I had to work on the deliverables set by the project, giving less flexibility in my approach. This was particularly challenging when I started my second paper as I had no prior experience of qualitative research. As the workshops had already been arranged, I quickly had to learn how to lead focus groups, collate the data and analyse the outputs. Overall, I think this approach worked very well. Being able to use a portfolio of papers approach to the thesis made it straightforward to create a paper from each of the work packages, and having a project timetable has been helpful in knowing at what stage I should be at throughout my studies.

4.2 Expectations of the PhD

Another challenge to overcome was the expectations around theoretical contributions and publications. Throughout the first year of the PhD programme it was driven into students that they need to make a strong theoretical contribution and aim to get published in top ranked journals. This is demonstrated by the financial rewards available to students from the Business School for being published in three and four-star journals. This was a message contradicted at both of the conferences I attended. During the PhD colloquiums at both conferences the PhD students were told that it was unlikely that the work from their thesis would make significant theoretical contributions and that targeting four-start journals was something that should be attempted later in the career with more experience.

A close friend, two years ahead of me in the PhD programme, submitted the first paper of their PhD to a four-star journal. Despite two rounds of revisions, the paper was finally rejected, meaning that at the end of their funded period they had no publications and had to find a job to earn money whilst they finished their PhD. This put stress on the rest of their studies and they reflected afterwards that it would have been better to have submitted to a lower ranked journal in order to get it published and make better progress with other papers. Taking this feedback on board, and knowing that like my friend, I had to finish my PhD in the time I had funding for, I targeted journals specific to the fields I was researching. Although the journals I have selected are not four-star journals, they have been selected as they are well respected in the areas of my research and are highly cited, which will enable my research to be widely read.

4.3 Relative Pace of Industry

A final area of reflection is the difference in pace between academia and industry. At the start of the PhD process in 2017 there were very few carbon calculators being used in the construction industry, and those in use were fairly basic. As an example, during a mapping exercise of tools on the market, performed early in the PhD process (May 2017), I noted of OneClick LCA that it was a 'simple tool' allowing users to get an LCA report. Now OneClick LCA is an industry leading tool which offers great services and global coverage. The advantage that the CIT Tool would have had over OneClick LCA is that it was intended to be open-access, and it would have given users the option of a free service rather than a subscription. This would mean that although the CIT Tool has less functionality, the user could chose a free tool that met their needs. However, recently a collaboration between Skanska and Microsoft has led to the development of EC3, which, when launched will be an open-source embodied carbon calculator. A recent demonstration of this tool shows superior functionality to the CIT Tool, and although the EC3 tool only works in North America, later this year when they develop functionality for Europe, it will be hard for the CIT Tool to compete. The level of investment in these tools has far outweighed the funding on the CITT Project, meaning they have been able to develop functionality beyond the scope of the CITT project.

It is not just tools that have advanced. At the start of this project, at industry conferences and workshops, people gave examples of the work their organisations were doing to reduce carbon emissions. In some instances organisations were showing how they had managed to reduce carbon by 10% on a project, and I remember being amazed by one presentation where savings of up to 20% were achieved. In a short space of time, the industry has started to move in the right direction, shown recently by Skanska signing up to be net-zero by 2045 (Skanska, 2019). Likewise, there are now four organisations who have become compliant with PAS 2080, the standard for carbon management in the infrastructure sector (Anglian Water (client), Mott MacDonald (consultant), Skanska (contractor) and Aggregate Industries (supplier)).

Is this to say that the research of this PhD is no longer valid, or that academic research generally is too slow to be meaningful? I would argue no. Although tools like OneClick LCA and EC3 now have more functionality than the CIT Tool and are better positioned for widespread adoption in the industry, the research of Paper 1 (Chapter 2) demonstrates there is a need for whole-of-life assessments of infrastructure assets in order to successfully reduce emissions through the asset's lifetime. This shows that despite the speed at which tools are developing, there is still a need to consider how to improve embodied carbon calculators to take account of the operation, use and end-of-life stages of a project.

Although tools are developing rapidly, other social, institutional and market drivers still lag behind. As highlighted in Paper 2 (Chapter 3), there are several barriers that must be overcome to enable successful carbon management within organisations. Likewise, as discussed in Paper 3 (Chapter 4), there is still a need to develop appropriate incentive mechanisms to encourage organisations to work together to reduce carbon emissions. Although examples of four organisations who have become PAS 2080 certified are highlighted, this is still a very small fraction of the organisations within the construction industry. This research provides recommendations that will support other organisations to follow these early adopters.

5 Areas of Future Research

Through the course of this PhD, a number of interesting research questions have arisen which are related to this thesis. The following section describes four ideas for future research that are worthy of attention.

5.1 Prescriptive Analytics for Decision Support

In Paper 1, an LCA methodology was used to determine the risk of burden shifting if the diameter of a railway tunnel was reduced in size. This paper found that embodied emissions could be reduced by building a smaller tunnel but that whole-of-life emissions would rise due to an increase in the energy consumed by each train going through the smaller tunnel. In calculating the emissions associated with the construction of each railway tunnel, one specific carbon emission factor was used for each material. However, embodied carbon emissions are subject to considerable uncertainty (Kang et al., 2015) and as such, using one carbon factor for concrete, steel and earthworks may affect the results of the assessment.

One method of representing uncertainty is the use of declarative statistics, described by Rossi et al. (2017) as a high level modelling framework that can be used to represent confidence regions for problems. Using this framework, Prof. Rossi and I developed a decision-support model to measure uncertainty for the case study from Paper 1. This study, explained in more detail in Appendix 1, showed that over 30 years of the railway tunnel being in service, average emissions were 5% lower by using the larger tunnel and uncertainty associated with lifetime emissions reduced by 44%.

This research could be taken further by using prescriptive analytics to build various decision-support models to investigate the trade-offs in emissions at different stages of a construction project. This would lead to the development of an optimisation tool that would be able to select the best option for emission reduction depending on the structure of the problem. Possible examples would be the choice of the optimal tunnel diameter for a given level of traffic; or the choice between two suppliers: one close to the construction site but featuring a higher emitting product, and one further away but with a more efficient product. The approach would explore optimal trade-offs and lead to effective solutions to these choice problems.

This would have profound benefits for decision makers during the design phase of construction project as they would quickly be able to determine the most effective solution for reducing emissions without the need to manually investigate a potentially very large space of possible options and associated impacts.

5.2 Drivers of Eco-innovation in the Construction Industry

In the introductory chapter to this thesis, eco-innovation was listed as one possible theoretical lens that could have been used for Paper 2. Although the decision was taken at the time not to use this approach, a possible area of future research would be to test a conceptual model for the drivers of eco-innovation with empirical evidence from the construction industry.

The OECD (2008, p.19) definition of eco-innovation refers to the 'development of products (good and services), processes, marketing methods, organisational structures and institutional arrangements'. The development of the CIT Tool and the organisational process and structures that need to be implemented to accommodate the tool within an organisation could be regarded as a form of eco-innovation. This could be used as a case study to show how eco-innovation could be adopted within the construction industry.

Based on a literature review focussing on the drivers for the adoption of eco-innovations, Bossle et al. (2016) develop a conceptual framework, shown in Figure 11, and develop five propositions to be tested by further empirical research. These propositions are:

- Proposition 1: Factors external to the company, that is (a) regulatory requests, (b) market demand, (c) cooperation and (d) redevelopment of industrial technology, can boost the adoption of eco-innovation by individual companies (p. 867).
- Proposition 2: Internal factors: (a) efficiency, (b) environmental capability, (c) environmental managerial concern, (d) human resources and (e) environmental strategy can boost companies' adoption of eco-innovation (p. 869).
- Proposition 3: Factors such as (a) company size, (b) sector, (c), and the presence of government support towards of eco-innovation can moderate the adoption of eco-innovation in companies (p. 869).
- Proposition 4: External factors can (positively) induce the improvement of internal skills within the company, developing internal factors to boost the adoption of eco-innovation (p. 869).
- Proposition 5: The adoption of eco-innovation has a positive effect on company performance (p. 869).

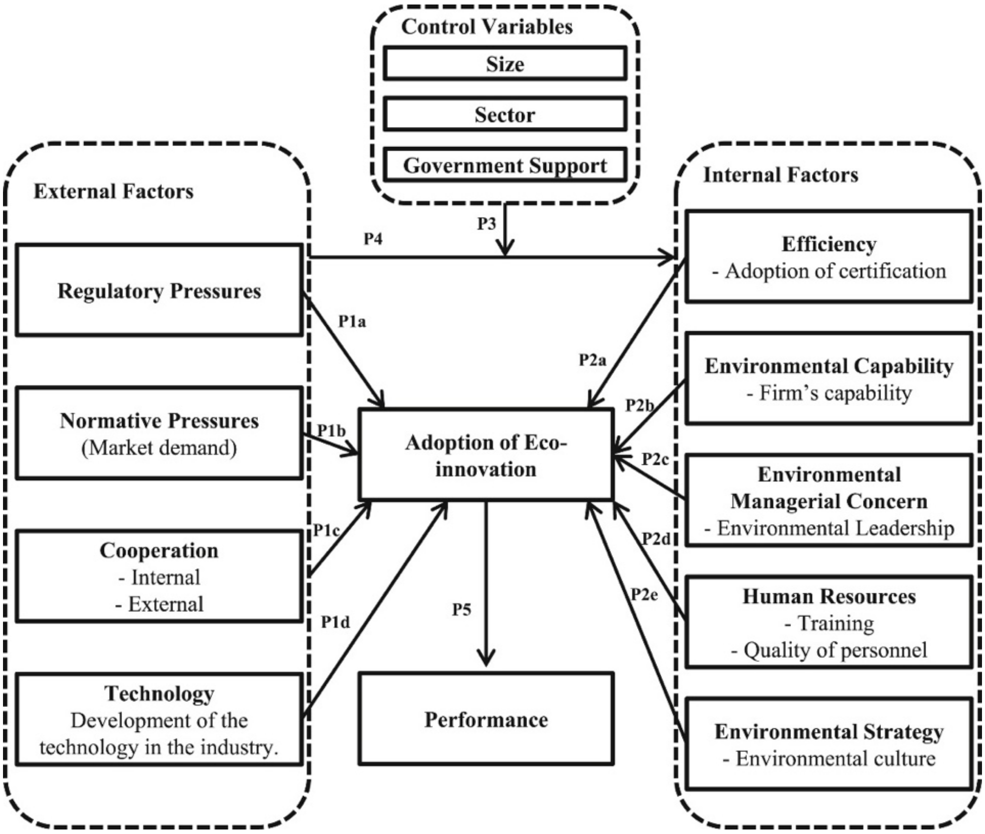


Figure 12. Conceptual model of the drivers for the adoption of eco-innovation derived by Bossle et al. (2016).

Bossle et al. (2016) state that as models like theirs are created, there is a need to test them with empirical evidence, a point reiterated by Xavier et al. (2017) in their systematic review of eco-innovation models. To that end, one research angle would be to provide empirical evidence to validate or query Bossle's model. This could be done by recoding the workshop and interview transcripts collated for Paper 2 to test the strength of each of the five propositions raised in the paper by Bossle et al. (2016).

5.3 Incentive Mechanisms

The case studies in Paper 3 showed the importance of having well designed incentive mechanisms to encourage supply chain members to collaborate with the aim of reducing emissions throughout the infrastructure supply chain. In their editorial opening for a special issue of Transportation Research Part E, Gunasekaran et al. (2015) challenged researchers to answer three open questions regarding green supply chain collaboration and incentive mechanisms:

1) How focal companies should collaborate to become greener?
2) How focal companies should design incentive structures for green initiatives?
3) How should the focal company appropriately reward members in the supply chain?

Gunasekaran et al. (2015) conclude that the majority of papers they considered, and the 11 they selected for the special issue, focus on the first question stating that future research should consider the remaining two issues. Likewise, Paper 3 falls into the first category. As such, an area of future research would be to consider how incentive structures can be designed to encourage emission reductions through the infrastructure supply chain.

As discussed in Paper 3, carbon emissions arise in several phases of the construction project and it is highly unlikely that the costs and benefits of reducing emissions will accrue equitably across all stakeholders involved in the project. Future research could investigate the effectiveness of different incentive mechanisms, for example cost-sharing where each member of the project shares the costs and rewards of emission reductions, coercion where the focal company demands the supply chain to cooperate in reducing emissions, or co-optation where suppliers agree to meet voluntary standards.

This could be investigated by analysing past case studies to see the effectiveness of different incentive mechanisms, and then assessing the feasibility of each of the mechanisms working to reduce emissions on large infrastructure projects. This research could build on the collaborative success factors discussed in Paper 3 and would show the construction industry the most effective mechanisms to drive reductions in carbon emissions through the infrastructure supply chain.

5.4 Transition towards an Enterprise Approach

As described in Paper 3, the construction industry has long been criticised for its failure to make efficiencies, improve performance and meet its client's needs. More than 20 years have passed since the Egan Report (1998) called for change throughout the industry, stating the need for stronger partnerships to improve the high levels of fragmentation in the industry. However, today organisations still use traditional contract-based procurement strategies, where work is often awarded to the lowest bidder at the expense of limiting quality and innovation.

Recently there has been an industry-led initiative to improve the way infrastructure projects are delivered and managed, named Project 13 (ICE, 2018a). Project 13 seeks to move the industry away from the traditional transactional arrangements to an 'enterprise model' where the 'owner' leads the enterprise and actively participates in the delivery of the asset. This allows suppliers and advisors to have a direct relationship with the owner, rather than going through a framework contractor. This could be a much more effective method of bringing together stakeholders with the right skills to deliver the right outcomes for customers, whilst also improving efficiency and productivity (ICE, 2018a).

One challenge with such an ambitious shift in practice is managing the transition to the new enterprise approach, as organisations will have to make significant changes to their current business models. At present, relationships are built on a project-by-project basis where the business model is designed on getting the best value for one specific project. The shift to an enterprise approach will require business models to reflect longer timescales where relationships are managed over longer periods and span multiple projects. Consideration must also be given to how to align commercial performance with the delivery of the outcomes for the customer, and how risks and rewards will be shared amongst the enterprise stakeholders.

One research angle would be to test how effective the enterprise model developed in Project 13 is compared to the traditional approach. This could be done by comparing case studies of similar projects using the traditional model and the new enterprise business model to assess if the new model improves performance. This would provide organisations with a framework for how best to make the transition to the new enterprise model.

Although carbon reduction is not the main driver for the change to an enterprise approach, it is still considered a desired outcome. This model could be well suited to providing a system-wide carbon assessment as it brings together multiple stakeholders during the design phase of the project, meaning each stakeholder could share their approaches to reducing emissions. Research could also consider how carbon is managed in the enterprise model and if there would be greater emission reductions using this model rather than the traditional project models.

6 Concluding Remarks

To finish, I provide a brief summary of the contributions of this thesis. Paper 1 finds empirical evidence to show the risk of burden shifting when only embodied carbon emissions are measured. The paper then develops a set of heuristic guidelines to ensure that embodied carbon calculators are appropriately used whilst tools which take a whole-of-life approach are developed. Paper 2 contributes to knowledge by addressing several gaps in the academic literature. Firstly answering the call of Wittneben et al. (2012) to develop a better understanding of the requirements needed for transformative change in organisations when it comes to low-carbon approaches. Paper 2 also adds to the limited research on carbon management practices in the construction industry, and by using a qualitative approach, addresses

Giesekam et al.'s (2016) concern about the lack of qualitative research that occurs in the construction industry. This paper also proposes a conceptual framework to enable carbon management practices to be incorporated within an organisation. Paper 3 brings together eight collaboration success factors from the literature on collaboration theory and tests these using case studies from the low-carbon supply chain management literature. In doing so, this paper contributes to literature by highlighting the most important factors for successful supply chain emission reductions. Overall, this thesis has highlighted the importance of taking a multi-perspective approach to reduce GHG emissions and enable carbon management practices.

There is an urgent need for the construction industry to reduce carbon emissions. The portfolio of papers in this thesis highlights the importance of reducing emissions not only in the design and construction of an asset, but making sure that consideration is given to how the emissions associated with the operation and use of the asset can be reduced. This thesis has shown that there are several challenges to successfully measuring and managing carbon in the construction industry, including the scope of emissions measured, how to successfully integrate carbon calculators within organisations, and how to engage supply chains to work together to reduce emissions through the supply chain. This thesis provides practical recommendations for stakeholders in the construction industry, highlighting how best to advance carbon management practices in this sector and enable steps to be taken on the road to a low-carbon future.

Appendix 1

The following is taken from the output for Work Package 5 of the CITT Project.

Decision analytics for infrastructure project design under uncertainty – a case study

Roberto Rossi and David Jackson

Embodied carbon is the overall CO_2 emitted in the construction phase of an asset life cycle (e.g. CO_2 emitted by earthwork, concrete pouring, and steel structure of a bridge). Operational carbon are CO_2 emissions associated with asset operations (e.g. emissions of vehicles crossing the bridge every day over the bridge lifetime).

We consider the problem of determining the optimal trade-off between embodied and operational carbon emitted in relation to a major infrastructure asset, more specifically a railway tunnel (Jackson & Brander, 2019). Jackson and Brander (2019) showed that approximately 91% of total embodied carbon emissions associated with the construction of a railway tunnel come from concrete, steel rebar and earthworks. By utilising emission factors from existing libraries and by modelling two possible scenarios (tunnel diameter of 8.8m and 9.9m), they were able to estimate average embodied carbon emissions for each scenario.

However, it is recognised in the literature that carbon emissions are subject to uncertainty (Kang et al., 2015). For instance, concrete emissions in kg per m^3 can be expressed as a lognormal random variable with parameters mu=5.43 and sigma2=1.22. As it is possible to observe in Figure 1, the variability of these emissions is substantial.

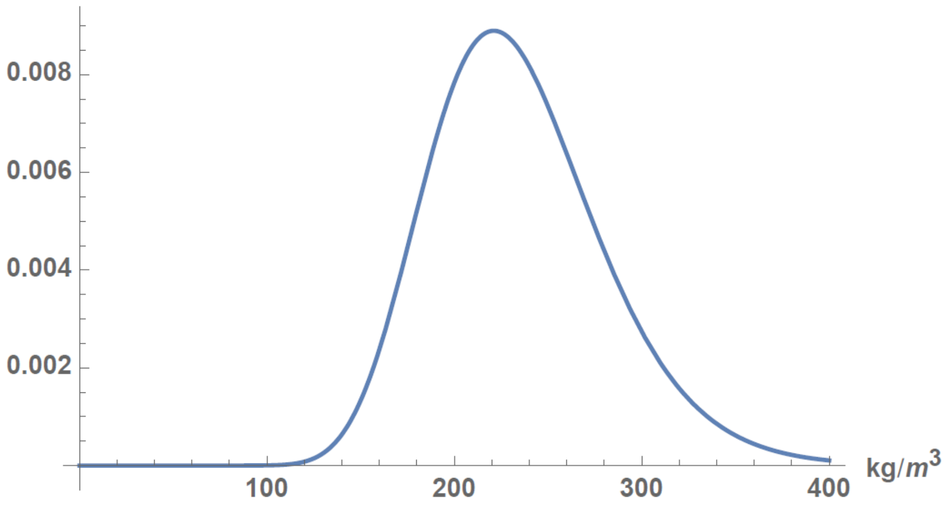


Figure 1: lognormal emissions (kg/m3) associated with concrete production (Kang et al., 2015)

Ignoring uncertainty associated with concrete and steel production, or earthworks may lead to considerable underestimation of embodied as well as operational carbon emissions for an asset. For instance, in the case of the (smaller) tunnel with diameter of 8.8m, a Monte Carlo analysis reveals substantial fluctuations about the average emissions reported by Jackson and Brander (2019), see Figures 2 and 3.

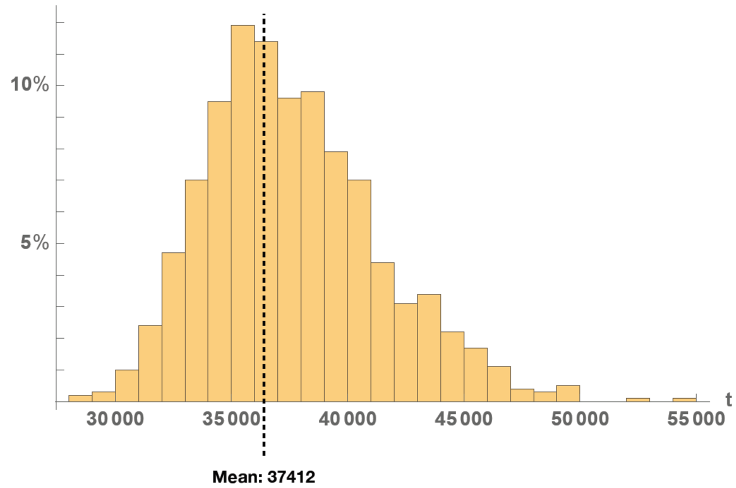


Figure 2: concrete emissions for the "small tunnel" scenario

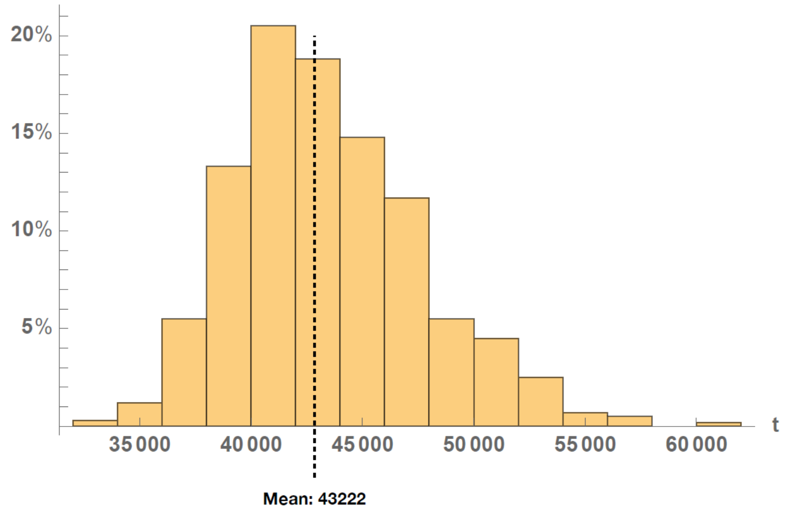


Figure 3: concrete emissions for the "large tunnel" scenario

A similar analysis can be carried out in relation to operational carbon emissions. Trains are propelled by electricity, to model emissions associated with electricity production, we built upon the analysis in (Jackson and Brander, 2019), which is based on the Department for Business, Energy & Industrial Strategy (BEIS) CO2 emission forecast from 2026 onwards (kg/kWh), see Figure 4.

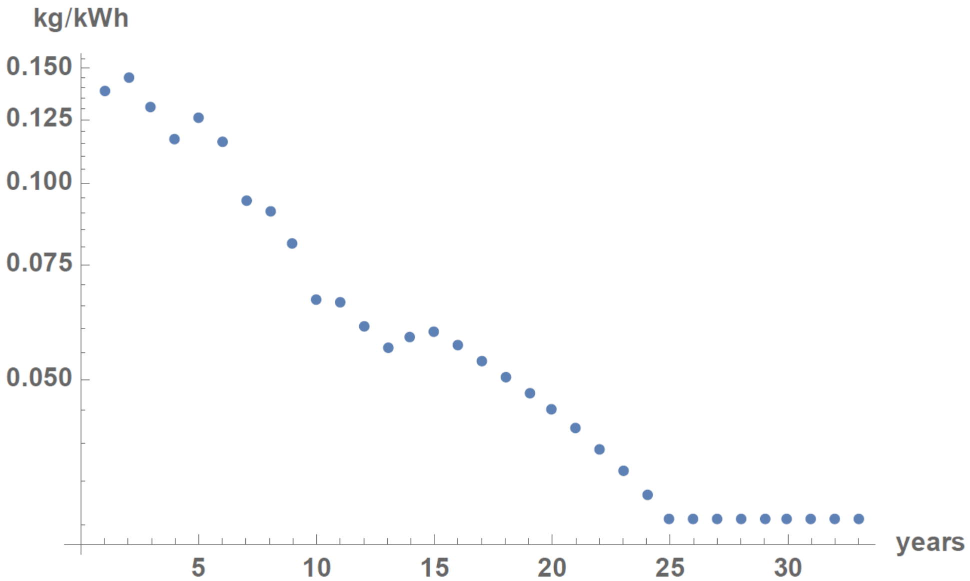
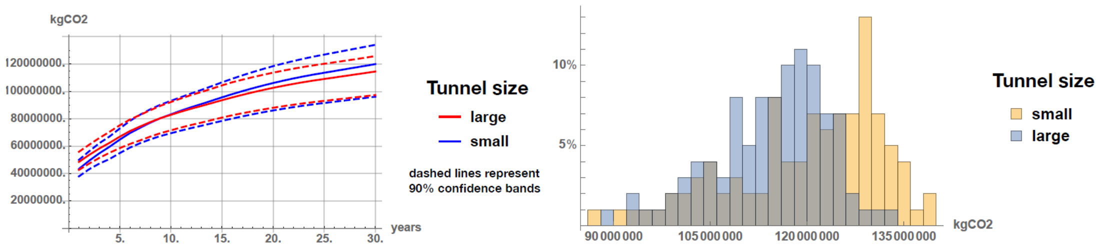


Figure 4: Department for Business, Energy & Industrial Strategy (BEIS) CO2 emission forecast from 2026 onwards (kg/kWh)

In the case of operational carbon emissions, random variables to be factored in our analysis may include the number of trains passing through the tunnel every day of its life cycle, the speed of these trains etc.

More specifically, we extended the trade-off analysis in (Jackson and Brander, 2019) between embodied and operational carbon emissions by considering lognormal distributed concrete emissions – instead of a constant average emission factor; and train speed in tunnel uniformly distributed between 50km/h and 300km/h – instead of constant average speed of 250km/h. The resulting analysis revealed that a larger tunnel leads not only to 5% average emission reduction over 30 years of service, but also to 44% reduction in uncertainty (i.e. variance) associated with lifetime emissions, see Figure 5.



Overall emissions during asset lifetime

Overall emissions after 30 years of service

Figure 5: integrated (embodied + operational) analysis

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