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

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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 (HM Treasury, 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 (HM Treasury, 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 (HM 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 and 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 study is fit for purpose (Tillman et al., 1994). The tools above, summarised in Table 1, vary in terms of the life cycle stages they include, i.e. the production, construction, use, and end of life stages. The UK GBC (2017) 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 and 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 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 (HM Treasury, 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 (2017) 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 and Firth, 2013) measuring cradle-to-gate emissions, others (e.g. Monahan and 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,

Table 1
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

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 a 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 and Black, 2012), or different construction techniques (Du and 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. (2008) 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 and Heath, 2012)). This stands in contrast to the number of review articles for LCA studies on buildings (e.g. Abd Rashid and Yusoff, 2015; Anand and Amor, 2017; 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 for the 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−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).

$$Rolling\ resistance = A + Bv + Cv^2 \tag{1}$$

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 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).

$$Tunnel\ resistance = A + Bv + tfCv^2 \tag{2}$$

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 2.

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 (2018), 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

Table 2
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)

Table 3
Results for embodied emissions saving for four decision cases.

Decision case	Reference emissions (tCO$_2$e)	'With change' emissions (tCO$_2$e)	Reduction in embodied emissions (tCO$_2$e)
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 4
Results for embodied and use phase assessment for the tunnel decision with net change in emissions for each scenario highlighted in bold.

		Reference (larger) tunnel (tCO$_2$e)	Reduced diameter tunnel (tCO$_2$e)	Change in emissions (tCO$_2$e)
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**

emission factor would increase the potential burden shifting effect).

4. Results

Table 3 presents the results for embodied carbon emissions (calculated using the CIT Tool) measured in tonnes of carbon dioxide equivalent (tCO$_2$e) 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 4, 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$_2$e 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.

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 Fig. 1). 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
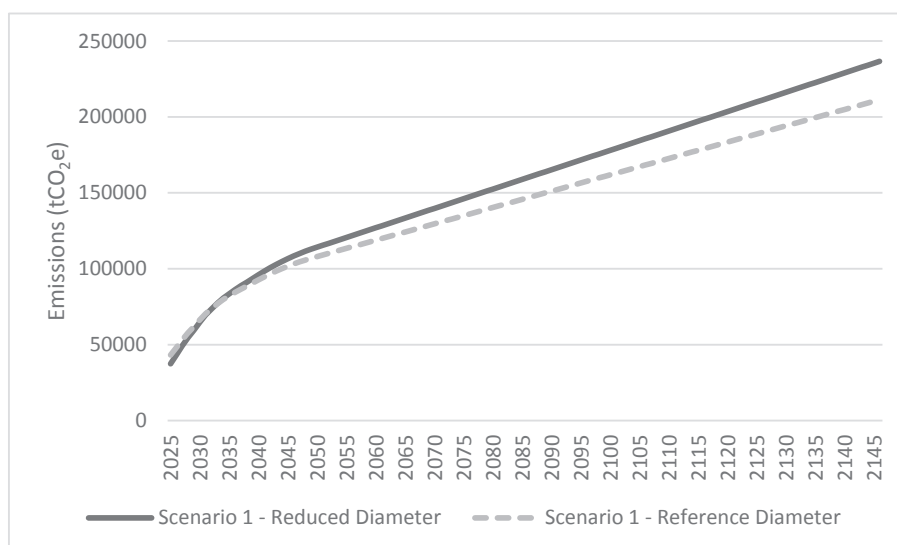
Fig. 1. Scenario 1 emissions (tCO2e) from 2025 to 2146.

changes to passenger habits, were not considered as although these may decrease the use phase emissions the initial burden shifting could not be overturned.

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). Fig. 2 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, would effectively identify cases with a risk of burden shifting. However, it is worth 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 and Weidema, 2004), while attributional LCA quantifies the impacts that occur within a normatively defined inventory boundary (UNEP and 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
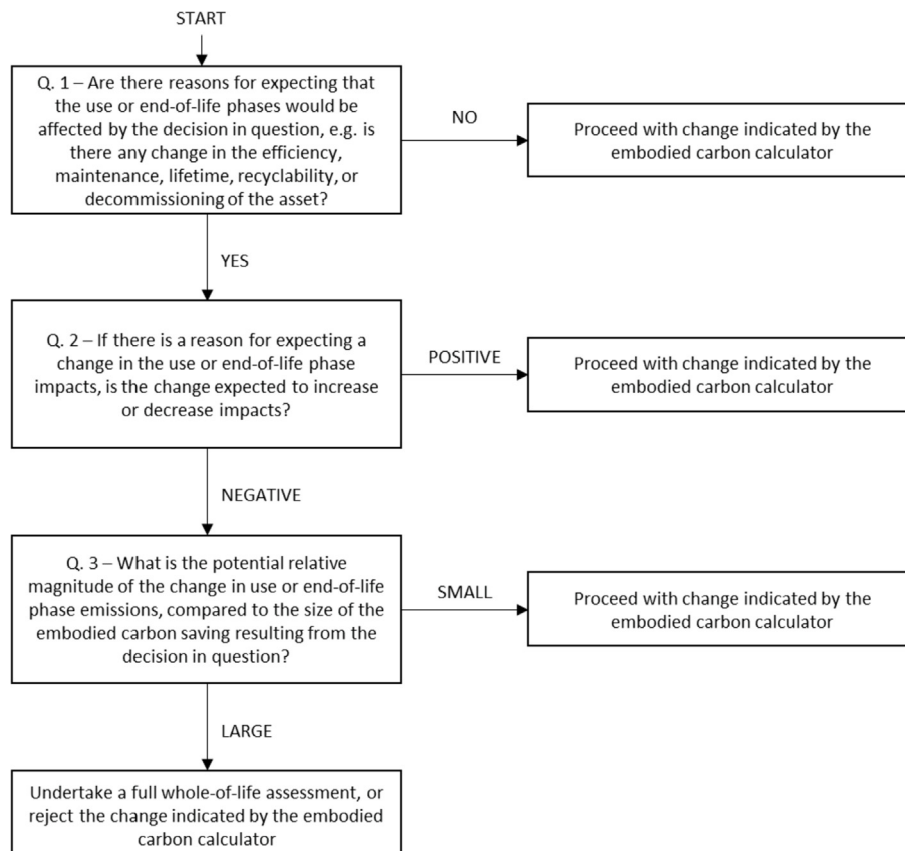

Fig. 2. Flowchart of suggested heuristic guidelines.

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.

Declarations of interest

None.

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