Building Research & Information

ISSN: 0961-3218 (Print) 1466-4321 (Online) Journal homepage: http://www.tandfonline.com/loi/rbri20

Construction sector views on low carbon building materials

Jannik Giesekam, John R. Barrett & Peter Taylor

To cite this article: Jannik Giesekam, John R. Barrett & Peter Taylor (2016) Construction sector views on low carbon building materials, Building Research & Information, 44:4, 423-444, DOI: 10.1080/09613218.2016.1086872

To link to this article: http://dx.doi.org/10.1080/09613218.2016.1086872

BRI Building Research & Information 2016
Vol. 44, No. 4, 423–444, http://dx.doi.org/10.1080/09613218.2016.1086872

Routledge Taylor & Francis Group

RESEARCH PAPER

Construction sector views on low carbon building materials

Jannik Giesekam[1], John R. Barrett[2] and Peter Taylor[3]

[1]Energy Research Institute, University of Leeds, Leeds LS2 9JT, UK
E-mail: pmjjg@leeds.ac.uk

[2]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

[3]Centre for Integrated Energy Research, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

As is the case in a number of countries, the UK construction industry faces the challenge of expanding production whilst making ambitious greenhouse gas emission reductions. Embodied carbon constitutes a growing proportion of whole-life carbon emissions and accounts for a significant share of total UK emissions. A key mitigation strategy is increasing the use of alternative materials with lower embodied carbon. The economic, technical, practical and cultural barriers to the uptake of these alternatives are explored through a survey of construction professionals and interviews with industry leaders. Perceptions of high cost, ineffective allocation of responsibility, industry culture, and the poor availability of product and building-level carbon data and benchmarks constitute significant barriers. Opportunities to overcome these barriers include earlier engagement of professionals along the supply chain, effective use of whole-life costing, and changes to contract and tender documents. A mounting business case exists for addressing embodied carbon, but has yet to be effectively disseminated. In the meantime, the moral convictions of individual clients and practitioners have driven early progress. However, this research underscores the need for new regulatory drivers to complement changing attitudes if embodied carbon is to be established as a mainstream construction industry concern.

Keywords: alternative materials, CO_2 reduction, construction sector, embodied carbon, greenhouse gas emissions, market acceptance, professional knowledge

Introduction

The construction sector is the largest global consumer of materials, and buildings are the sector with the largest single energy use worldwide (Krausmann et al., 2009; De Ia Rue du Can & Price, 2008). Consequently, buildings are also responsible for 19% of global greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change (IPCC), 2014). Recent studies have suggested that buildings offer the greatest abatement opportunities for reducing GHG emissions in the short-term (IPCC, 2014; McKinsey & Co., 2009). Policy-makers have responded to this through the introduction of regulation requiring improvements in building fabric and performance, such as the European Union (EU) Energy Performance of Buildings Directive. These regulations have principally focused on the operational GHG emissions associated with energy use in activities such as space heating, cooling and lighting. However, these regulatory drivers have not extended to the embodied carbon[1] associated with the initial production of structures (Figure 1).

A recent review of building life cycle assessments demonstrated that embodied carbon can account for anywhere between 2% and 80% of whole-life carbon emissions (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013). The precise proportion depends upon a number of characteristics including building use, location, material palette, and assumptions about the service life and future energy supply. The proportion tends to be higher in certain structure types, such as industrial warehousing, where embodied emissions can contribute up to 90%

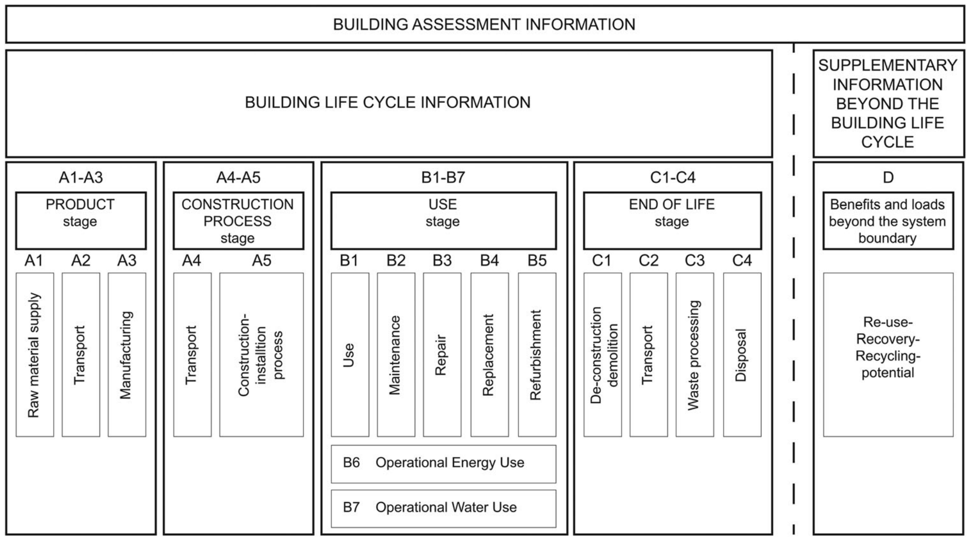

Figure 1 Life cycle stages from BS EN 15978:2011 Sustainability of construction works – assessment of environmental performance of buildings – calculation method

of the total (Sturgis & Roberts, 2010). The share of life cycle emissions attributable to embodied carbon is expected to increase further with reductions in operational emissions owing to improved operational performance and reductions in the carbon intensity of the electricity supply (Ibn-Mohammed et al., 2013). Meanwhile, absolute increases in embodied carbon can be expected with an anticipated growth in building activity and higher performance buildings typically requiring greater material use.

The importance of embodied emissions further increases when taking account of the temporal allocation of emissions. As cumulative emissions, not annual emissions, are the critical component in preventing unacceptable levels of climate change (Matthews, Solomon, & Pierrehumbert, 2012), some researchers have increasingly argued that a greater weighting should be attached to current rather than future emissions savings in economic analyses and policy-making (Rhys, 2011). When the temporal allocation of emissions is considered in building assessments, research by Heinonen, Säynäjoki, and Junnila (2011) demonstrated that the swift release of emissions, or a 'carbon spike', associated with construction phase emissions can dominate life cycle emissions in the time horizon relevant to adopted climate mitigation goals. This conclusion led the same authors subsequently to question the merits of building new developments as a means of climate change mitigation (Säynäjoki, Heinonen, & Junnila, 2012). In many cases, however, new development is unavoidable and, in such instances, a greater focus on embodied carbon mitigation is essential.

Prior to the economic downturn this embodied carbon amounted to an estimated 63 $MtCO_2e$ for UK structures built in 2007 (Giesekam, Barrett, Taylor, & Owen, 2014), representing 6% of the UK's carbon footprint. In 2013, the Green Construction Board Low Carbon Routemap for the Built Environment set out the need for a 39% reduction in embodied carbon by 2050 against a 2010 baseline, in addition to drastic reductions in operational emissions (Green Construction Board, 2013). In 2014 the UK Green Building Council (UKGBC) hosted the first industry Embodied Carbon Week, featuring numerous events and over 900 participants from 300 organizations (UKGBC, 2014a). The popularity of this series of events reflected the status of embodied carbon as a rapidly growing priority within the UK industry. Over recent years, aided by improved data access, the industry has significantly expanded skills and guidance in embodied carbon assessment (Clark, 2013; Royal Institution of Chartered Surveyors (RICS), 2012; UKGBC, 2014b, 2015; WRAP, 2011). The first commercial company to address this issue, Prologis, measured and offset 110% of the embodied carbon associated with the development of a distribution centre in Pineham in 2007; and standardized this approach across all UK projects from 2009 (Prologis, 2015). Their example has been followed by other large clients (such as British Land, Land Securities and The Crown Estate) who now require an assessment of embodied carbon on all high-value projects. The business case has been strengthened with a range of companies demonstrating cost savings through embodied carbon management (WRAP, 2014b). In response to this growing interest, a group of leading UK practitioners campaigned for inclusion of embodied carbon as an Allowable Solution under the previously proposed Zero Carbon building regulations (Battle et al., 2014). Regulations in the Netherlands and Germany already require whole-life carbon assessment on many projects, and embodied carbon is likely to feature in future EU harmonized sustainability assessments (European Commission, 2014). Several UK local authorities already require a basic assessment of embodied carbon be included in planning applications. Whole-life carbon assessment has also been awarded additional credits in sustainability assessment schemes such as Building Research Establishment Environmental Assessment Method (BREEAM), Green Star, Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB) and Leadership in Energy and Environmental Design (LEED). At the time of writing, the public WRAP Embodied Carbon Database, launched in 2014, featured assessments for some 231 projects and is set to expand substantially (WRAP & UKGBC, 2014). Clearly it is only a matter of time before embodied carbon assessment and mitigation becomes a routine consideration on many large construction projects.

Over half the embodied carbon in construction is associated with the consumption of materials (Giesekam et al., 2014). Consequently, a variety of embodied carbon mitigation strategies focus on minimizing the use of materials with carbon-intensive supply chains. These include strategies that seek to minimize extraneous material usage through 'lightweighting', structural optimization or site waste reduction; strategies that focus upon maximizing the useful life of materials by extending the life of existing structures and designing new structures to be adaptable and easy to deconstruct (allowing reuse of materials and components); or substitution of materials and construction products for alternatives with lower carbon supply chains. A variety of alternative materials are available, including materials derived from naturally occurring substances; materials that incorporate wastes or recycled content; materials that have been repurposed or sourced for reuse from other sites; and construction products that have been optimized through novel production techniques. However, there remain many barriers to adoption of these alternative materials amongst construction professionals. Yet, minimal qualitative work has been done on assessing these barriers (Watson, Walker, Wylie, & Way, 2012) and so the present paper aims to fill this important gap. The following sections review previous relevant work and then present results from a survey of 47 construction professionals and detailed interviews with seven industry leaders, exploring barriers to the use of these low carbon materials in greater depth.

The paper is organized as follows. The following section presents insights from previous work. The third section sets out the study boundaries and objectives. The fourth section outlines the study methodology. Results of the survey and interviews are presented and discussed in the fifth section. The limitations of the study are then discussed alongside suggestions for further research. The final section concludes with recommendations for the industry, professional institutions and government.

Review of previous work

Numerous past studies have addressed barriers to particular forms of 'green building' or 'sustainable building'. Some of these studies take broad definitions of sustainability, incorporating economic and social factors (*e.g.* Williams & Dair, 2007), whilst others have focused specifically on the environmental aspects of sustainability. However, these studies have tended to consider only operational emissions (*e.g.* Kershaw & Simm, 2013), the adoption of energy-efficient technologies (*e.g.* Pinkse & Dommisse, 2009), or the achievement of regulatory targets, such as zero carbon homes (*e.g.* Osmani & O'Reilly, 2009), that exclude the embodied emissions of materials used in construction. Few, if any, have focused specifically upon the barriers to alternative material choice as a means of mitigating embodied carbon emissions. The following review therefore draws upon literature from two streams. The first stream features studies that offer insight into the cultural and institutional barriers preventing sustainable innovation within the construction industry. The second stream contains detailed studies that address the adoption of specific alternative materials (*e.g.* straw bale).

Barriers to innovation in the construction industry

Construction is a highly fragmented, risk-averse, supplier-driven industry. Most construction firms employ small workforces and are limited in their research and development (R&D) capabilities and absorptive capacity (Arora, Foley, Youtie, Shapira, & Wiek, 2014). Few firms have the capacity to assess comprehensively all aspects of a novel material and often the ability to exploit new technologies is dependent on specific human capital. The nature of the industry necessitates moving between temporary projects, often of a unique character with a changing roster of stakeholders. Consequently, learning is done on a project-to-project basis with professionals developing perceptions and skills from their individual experiences. This unsystematic process of building up knowledge leads to a reluctance to use unfamiliar technologies and materials (Osmani & O'Reilly, 2009; Pinkse & Dommisse, 2009). This results in sluggish incremental change and the slow diffusion of innovations. This process of knowledge development is further hampered by poor knowledge exchange from academia to industry (Moncaster et al., 2010).

A litigious industry environment consolidates this aversion to innovation and necessitates a high quantity of pre-implementation evidence for new construction products to establish legitimacy and achieve acceptance (Arora et al., 2014). Construction professionals typically rely on case studies to evaluate novel products, placing a heavy burden on 'others' to innovate first. This aversion to innovation is reinforced by 'clearly delineated relationships based on contractual obligations' which 'constrain inter-firm relations and information sharing', 'reinforce hierarchies and power asymmetries' (Arora et al., 2014, pp. 239–241). The traditionally separated building process involving many parties often diminishes the ability of any individual to make holistic project decisions. Similarly, individual stakeholders often feel unable to enforce sustainable solutions 'down the line' (Williams & Dair, 2007). The need to overturn conventional partisan relationships and embrace a systemic approach to construction has been noted for some time (Egan, 1998; Royal Academy of Engineering, 2010). Despite this, contractual structures still regularly inhibit effective integration of design teams and the supply chain. Unfortunately, it is only through greater communication and early engagement of the full supply chain that the knowledge of all stakeholders can be fully leveraged. Without this early engagement project decisions are often made too late for cost effective or practical implementation (Kershaw & Simm, 2013).

Often this reluctance to innovate is compounded by outdated regulatory requirements, which lag behind the development of technologies and encourage firms to stick with conventional materials (Arora et al., 2014; Persson & Grönkvist, 2014). Clear and timely legislation is essential, as where regulatory obligations do not exist sustainability objectives are often ignored (Williams & Dair, 2007). Indeed, regulation is often cited as the most effective means of motivating the construction industry to address environmental issues, and the opportunity to gain competitive advantage through preparation for anticipated regulation is a significant driver for many companies (Osmani & O'Reilly, 2009).

Despite recent market changes, the prevailing financial climate has limited demand for innovative low carbon buildings (Persson & Grönkvist, 2014; Wang, Toppinen, & Juslin, 2014), with clients typically prioritizing project cost, timescales, functionality and aesthetics (Gold & Rubik, 2009). Thus, there is a clear dilemma. The embodied carbon emissions associated with the use of construction materials must reduce. This necessitates the wide-scale adoption of alternative materials, in a sector with a longstanding and justifiable aversion to innovation. The first steps of this transition must occur in the absence of strong regulatory, financial or client drivers. In this vacuum, the driving spirit and commitment of individuals remains the dominant source of progress within the industry (Persson & Grönkvist, 2014).

Barriers to the adoption of alternative materials in the construction industry

Zhang and Canning (2011) assert that a number of factors prevent the selection of innovative materials. Namely, the lack of short-to-medium-term commercial benefits; the lack of effective marketing and dissemination of information on new materials to practising engineers; and a lack of supportive material performance data and full-scale demonstration projects. The authors argue that this can be combated through the addition of design guidance alongside effective marketing and stakeholder engagement.

Even in cases where sufficient information and demonstration projects are available material choices are typically governed by other priorities. An international study of design teams conducted in 2012 by Arup for the World Business Council for Sustainable Development (WBCSD) demonstrated that although a large number of factors influence material choice, cost was the overarching priority and material sustainability criteria were often less influential than the personal knowledge and past experiences of the project team (Arup & WBCSD, 2012).

Whilst much research has focused on demonstrating the performance of alternative materials, authors have repeatedly noted a dearth of qualitative studies assessing the cultural, behavioural or perceptual barriers to adoption within design teams (Watson et al., 2012; Wong, Owczarek, Murison, Kefalianos, & Spinozzi, 2013). Where these aspects have been the subject of research, most studies have focused on the adoption of particular materials (*e.g.* timber; Bayne & Taylor, 2006; BRE, 2004; Connor, Kozak, Gaston, & Fell, 2004; Hemström, Mahapatra, & Gustavsson, 2011; Roos, Woxblom, & McCluskey, 2010; Wang et al., 2014) or on the recycling or reuse of narrow groups of materials (*e.g.* aggregates; Holton, 2003; Knoeri, Binder, & Althaus, 2011; Misra, Rao, & Jha, 2007; Tam, 2011). A past review of this body of literature by Giesekam et al. (2014) yielded an array of common barriers summarized in Table 1.

The suitability and sustainability of a particular material is highly dependent on site- and project-specific factors. The lowest embodied carbon solution will vary across structures types and from project to project. The end goal of policy-makers and advocates of low carbon construction must be to promote the most appropriate option for each particular project. Therefore, simultaneous promotion of a wide variety of material options is essential. This requires skills development and legislation that is sensitive to, and supportive of, this multitude of options. Therefore, whilst it is crucial for studies to assess the barriers to adoption of particular materials, it is also essential to

Table 1 Common barriers to the uptake of building materials with lower embodied carbon

Institutional and habitual	Economic	Technical and performance related	Knowledge and perceptions
Institutional culture and established practice promotes preferred material palette	High cost of new products	Lack of established standards, design guides and tools, and standardized details	Lack of awareness and practical knowledge of alternatives amongst practitioners
Focused training and recruitment results in departmental lock in to familiar materials	Market externalizes cost of embedded emissions	Lack of material performance data	Lack of client knowledge of alternatives
Time constraints prevent consideration of alternatives and favour familiar designs	Uncertainty premium placed on novel products	Lack of full-scale demonstration projects	Negative perceptions amongst practitioners
Lack of established advocacy groups for alternatives	High transaction costs of additional professional training and research	Policy and regulatory limitations and restrictions	Negative perceptions held by clients
Lack of effective marketing from material producers	Money sunk in existing materials (in terms of training, establishing relations with supply chains etc.)	Lack of confidence in contractor ability and availability of skilled labour prevents inclusion in design	Insufficient fit with the culture of the clients or end users
Lack of user–producer relationships	Lower design:fee ratio because of increased detailing	Shortage of specialist skills prevents installation	Perceived unreliability or risk of new alternatives
Habitual specification and historic practice of individual practitioners	Insufficient comparative information on costs	Insufficiently developed supply chains	Perceived concerns about material sourcing prevent selection
Material selection viewed as outwith influence of individual practitioner	Unwillingness to accept associated financial risk	Local availability of materials and technologies	Policy uncertainty
High level of design inconvenience	Access to finance for small and medium-sized enterprises (SMEs)	Difficulty obtaining insurance for novel and reused materials	Simply regarded as low priority and other considerations take precedence
Lack of supply chain coordination	Project financing incompatible with time constraints		
	Anticipated increase in lead times		
	Small industries producing alternatives cannot compete against established industries' economies of scale		

Source: Adapted from Giesekam et al. (2014)

identify the common leverage points and interventions that support multiple solutions.

This approach was adopted by Watson et al. (2012) when conducting an online questionnaire and series of subsequent interviews assessing the barriers to entry for non-conventional building materials. Watson et al. surveyed 62 UK construction professionals on their opinions and views of alternative materials, how often these materials are used and what influences their use. Results demonstrated that awareness of many alternative materials such as rammed earth, cross-laminated timber and straw bale infill was high, but use remained low. Over half the respondents had not considered using non-conventional materials. The principal barriers identified in that study were high costs, lack of technical knowledge and lack of client knowledge.

This study seeks to explore these common barriers and leverage points further through a survey and interviews with leading construction professionals.

Study objectives and boundaries

The principal objective of this study was to understand the economic, technical, practical and cultural barriers preventing construction professionals from selecting a variety of materials commonly identified as being lower in embodied carbon. It also sought to understand the role for regulation, professional institutions and advocacy groups in overcoming these barriers.

Despite the recent growth in understanding, embodied carbon remains a niche topic within the construction industry. It will doubtless be many years before embodied carbon estimation and mitigation is commonplace across all sectors and organizations. Therefore, this study did not seek to recruit participants that would constitute a representative sample of the UK construction industry at large. Instead, it targeted individuals with extensive experience using low carbon materials. The views and experiences of these early adopters will ultimately shape the industry's future approach to embodied carbon mitigation. Therefore, understanding their motivations and experiences is informative in developing regulatory strategies and guidance for the broader industry.

Construction industry supply chains are typically lengthy and complex, involving a variety of professions. Many of these actors have fundamentally different motivations and priorities. In this study, an attempt was made to limit participants to professionals involved in the design, specification and construction process. The survey and interviews were not targeted at developers, end-users or material manufacturers. Further specific studies that focus on the perspectives of these groups would be a welcome contribution.

Methods

The research adopted a qualitative mixed-method approach combining a survey and series of semi-structured interviews. This approach is commonly used across a range of disciplines and was selected to provide the desired combination of breadth and depth (Tashakkori & Teddlie, 2003). A sequential explanatory design was selected, whereby a survey would gather initial quantitative and qualitative data on the barriers to adoption, followed by interviews exploring the identified barriers in greater depth. An online questionnaire was hosted using Qualtrics and made available from 3 April to 23 May 2014. An open online questionnaire was deemed the most appropriate format as it provided the means for practitioners easily to share the survey and maximize the number and range of responses. Links to the survey were distributed through a number of major industry mailing lists, established contacts, LinkedIn groups and to a targeted set of individuals with extensive experience. Flyers with a survey link were also distributed at events during the UKGBC Embodied Carbon Week.

The survey featured 17 core questions (Table 2) with additional piped questions depending upon the participant's response. The core questions focused on gathering demographic data; establishing the perceived influence and responsibility of respective professions on material selection and embodied carbon reduction; gathering respondents' experiences with a range of 24 example low carbon materials; and exploring perceived barriers and drivers to the adoption of low carbon materials. The 24 example materials were selected to provide a range of both novel and traditional products. This included materials developed from natural sources; materials incorporating waste streams or recycled content and products optimized through novel production techniques. The materials were selected from a long list developed through a literature review, with preference given to materials included in prior qualitative studies to allow for comparison of results. This included Brettstapel; cross-laminated timber (CLT); structural insulated panels; straw bale (either load bearing, infill or modular); rammed earth; unfired brick; cob; adobe; hemp (including hemp-lime composites); limecrete; cardboard (tubes or panels); ethylene tetrafluoroethylene (ETFE); inorganic fibre reinforced polymers; geopolymer concrete; concrete containing agricultural wastes (*e.g.* rice husks, vegetable fibres or nut shells); concrete containing consumer wastes (*e.g.* plastics, glass or tyres); concrete containing construction and demolition wastes; concrete containing industrial wastes (*e.g.* steel slag, sewage sludge ash, silica fume); precast hollowcore floor slabs; optimized rollout reinforcement meshes (*e.g.* BAMTEC or ROLLMAT); recycled aggregates;

Table 2 Survey questions

1. What is your job title?
2. What is the typical project role of your employer?
3. In which country do you normally work?
4. For how many years have you worked in construction?
5. Approximately how many staff does your company directly employ?
6. How much influence do you have over the selection of materials and construction products on a typical project?
7. Who do you believe has the greatest influence over material and construction product selection on a typical project?
8. Please rank who you believe should ultimately be responsible for minimizing the embodied carbon emissions on a project.
9. What is your knowledge of the following materials and construction products?
10. How often have you used each of these materials?
11. How would you rate your experience of using each of these materials?
12. Thinking about the projects on which you used these materials. Why did you choose to use each material?
13. Would you use these materials again? / Why would you not consider using these materials again?
14. You stated that you are aware of but have not used the following materials on a project. Why have you chosen not to use these materials?
15. Thinking more generally about alternative materials in construction, how important do you believe the following factors are in preventing their use?
16. How important do you believe the following developments could be in encouraging greater use of alternative materials and construction products?
17. Is there anything else you would like to add about any of the topics discussed?

recycled plastic lumber; reclaimed steel; and reclaimed timber. This does not constitute a comprehensive list of all low carbon materials available in the construction marketplace. Such a list would be too lengthy for inclusion in a short survey.

Respondents were initially asked to describe their knowledge and experience of each of the 24 materials by selecting from three options: 'used on project(s)'; 'aware of but not used'; or 'little or no knowledge of'. Questions 10–14 were then filtered to gather respondents' experiences with each of the materials they had used, and reasons for not selecting materials they had not used. Following the questions about specific materials, respondents were asked to consider more general barriers and drivers to alternative materials. In all instances where respondents were asked to choose from a prescribed list the opportunity to add other options and provide comments was made available. A full list of questions and possible responses can be found in the supporting information.

Prior to distribution the survey was tested and refined based on responses from a pilot group of architects and engineers. Further sit-in testing was done to ensure full understanding of the questions. All survey participants were asked if they were willing to take part in a follow up interview exploring the topic in greater depth.

Survey participants demonstrating particular experience were selected for a series of in-depth interviews. Additional interviewees representing specific professions or industry bodies were also sought to provide an appropriate breadth of expertise. The interviews were semi-structured and typically of one hour in length. All interviews were conducted face to face and recorded for transcription. A common set of questions and prompts were prepared, tested and refined through a test interview. These common questions were designed to build upon responses from the survey. Additional questions specific to the experiences of each interviewee were also prepared to maximize the quality of responses. All interviewees were offered anonymity, which some declined. A full list of interviewees can be seen in Table 3.

Table 3 Study interviewees

Position	Type of organization
Sustainability Manager	Multinational contractor
Senior Engineer	Large multidisciplinary consultancy
Architectural Technologist	Specialist architectural practice
Director of Sustainability	Professional institution
Assistant Head of Sustainability	Large client
Sustainability and LCA Expert	Research technology organization
Founder	Sustainable Business Partnership and Chair of Embodied Carbon Task Force

Results

This section presents results from the survey and interviews. Owing to the sequential explanatory design of the study, whereby the survey results informed the interview questions, the core survey results are presented first, followed by a more detailed discussion around the emerging interview themes. This is followed by a brief discussion of study limitations and suggestions for further research.

Survey results

Survey results should be read with caveats on the limitations of the working sample and constrained scope of research, as outlined in the preceding sections. A summary of key survey results is below. Full tables of results can be found in Appendices A and B in the supplemental data online.

Demographics

The survey received 32 full responses and 15 partial responses that provided answers to the majority of the questions. An overview of the respondent demographics can be seen in Figure 2. The majority of respondents were architects, engineers and sustainability consultants. A small number of responses were received from contractors and project managers. 'Other' professionals were involved with research, development, trade associations or construction product manufacture and supply. A total of 77% of respondents worked primarily in the UK; the remainder worked in other developed countries.

Influence and responsibility of respective professions

Survey respondents were initially asked about their own influence on material and construction product selection. Most respondents felt they had at least some influence, with architects the most likely to report a strong or primary influence (Figure 3). Respondents were then asked to consider the influence of the respective professions. Respondents generally reported that the architect, client, civil/structural engineer and contractor had the greatest influence over material and construction product selection (Figure 4). Whilst some minor variation in these results exists when broken down by the respondents' profession, the architect, client, civil/structural engineer and contractor consistently remain the principal influences. These results are consistent with

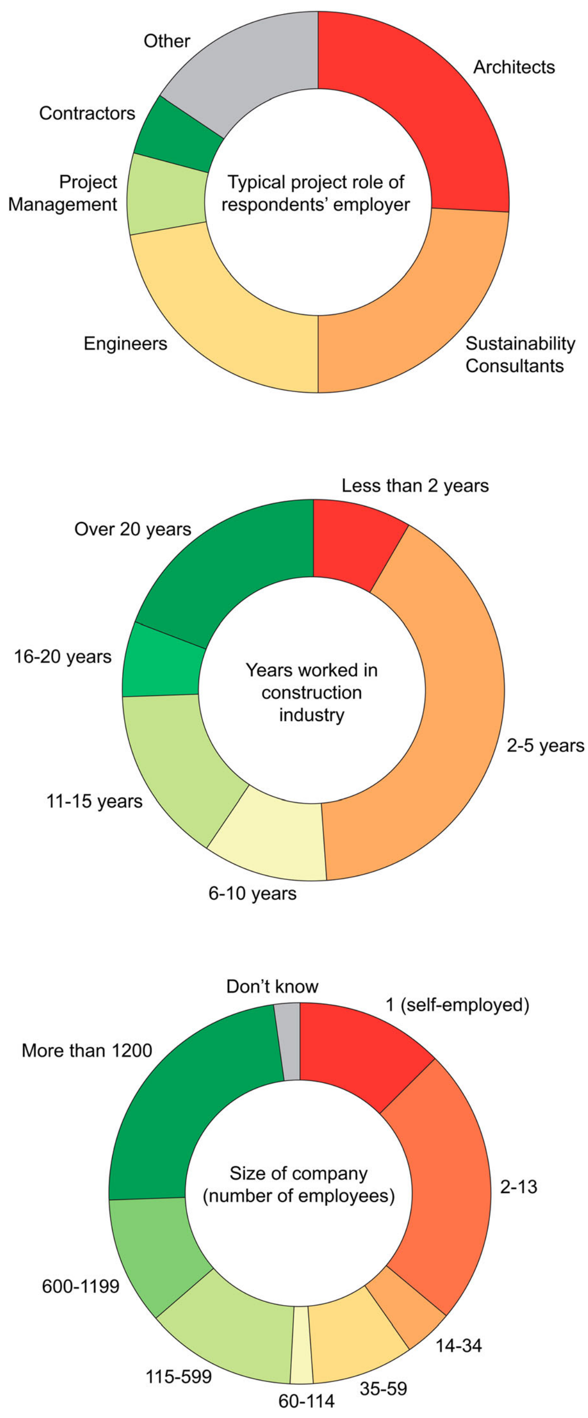

Figure 2 Survey respondent demographics

those from Watson et al. (2012) and the Arup study (Arup & WBCSD, 2012).

Respondents were then asked to consider the professions that should be most responsible for ensuring embodied carbon reduction on a project. Responses across all professions indicate that the architect should be the professional most responsible for minimizing the embodied carbon emissions on a project (Figure 5). Civil/structural engineers, the client and sustainability consultants also have a key role to play, and were consistently ranked higher than the remaining professions. It is clear when comparing Figures 4 and 5 that the professions identified as having the greatest influence over material and construction product selection are also those that respondents believe should bear the greatest responsibility for minimizing embodied carbon emissions.

Knowledge of alternative materials

Respondents exhibited a broad range of awareness and experience with the materials included in the survey (Figure 6). Each material had been used by between three and 22 respondents on at least one project. The most commonly 'used on projects' were CLT, recycled aggregates, precast hollowcore floor slabs, reclaimed timber, reclaimed steel and concrete containing industrial wastes. Straw bale, unfired brick, adobe and limecrete were the most commonly 'aware of but not used'. Brettstapel, optimized rollout reinforcement meshes and geopolymer concrete reported the highest rates of 'little of no knowledge of'. This is unsurprising as these are relatively novel products. When results were broken down by respondents' professions, sustainability consultants reported the highest proportion of 'used on project(s)' across a range of materials, and also the lowest rates of 'little or no knowledge of'. This may suggest that they possess a broader knowledge and experience working with a range of low carbon materials. This is in spite of the participating sustainability consultants, on average, having fewer years of industry experience than respondents from other professions. Amongst all respondents, reclaimed materials and alternative concretes were more likely to be routinely considered for use on a project than natural or unconventional materials.

Experiences with alternative materials

Survey respondents were asked to reflect on their experiences with materials they had used; many provided detailed comments. Across all materials, 65% of reported experiences were somewhat or mostly positive. No respondents reported a mostly negative experience and only 7% of experiences were somewhat negative. A total of 90% of professionals that had only used a material on one project would use the material again. This high rate of positive experiences may reflect a sample bias inherent in the self-selection process for survey participants. Those with positive experiences of alternative materials are perhaps more likely to participate in such a survey. Alternately, it could simply reflect generally positive experiences amongst those practitioners that have adopted alternative materials. Those who reported negative experiences with

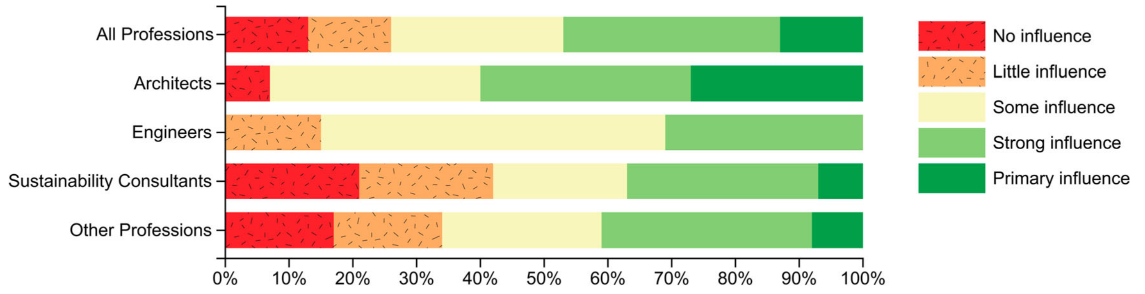

Figure 3 Perceived influence of respondents on material and product selection (response to survey question: How much influence do you have over the selection of materials and construction products on a typical project?)

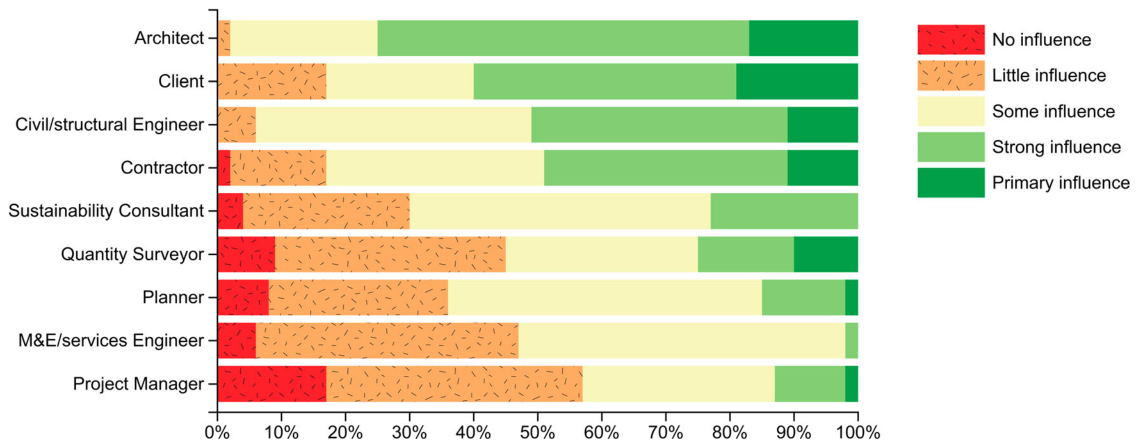

Figure 4 Influence of professions on material and construction product selection (response to survey question: Who do you believe has the greatest influence over material and construction product selection on a typical project?)

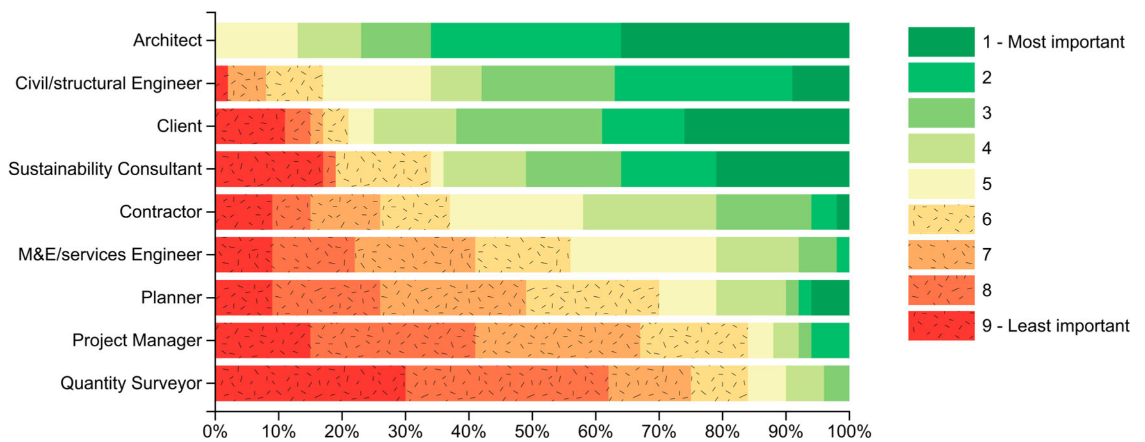

Figure 5 Professions believed to be most responsible for embodied carbon reduction (response to survey question: Please rank who you believe should ultimately be responsible for minimizing the embodied carbon emissions on a project.)

materials, or stated that they would not consider using a material again, generally expressed concerns about high costs, inadequate performance, inconsistent quality, lengthy construction times or difficulty sourcing product at scale.

Barriers

Participants were questioned on the barriers preventing their use of the specific example materials (Figure 7) and also on the barriers to alternative materials in construction in general terms (Figure 8).

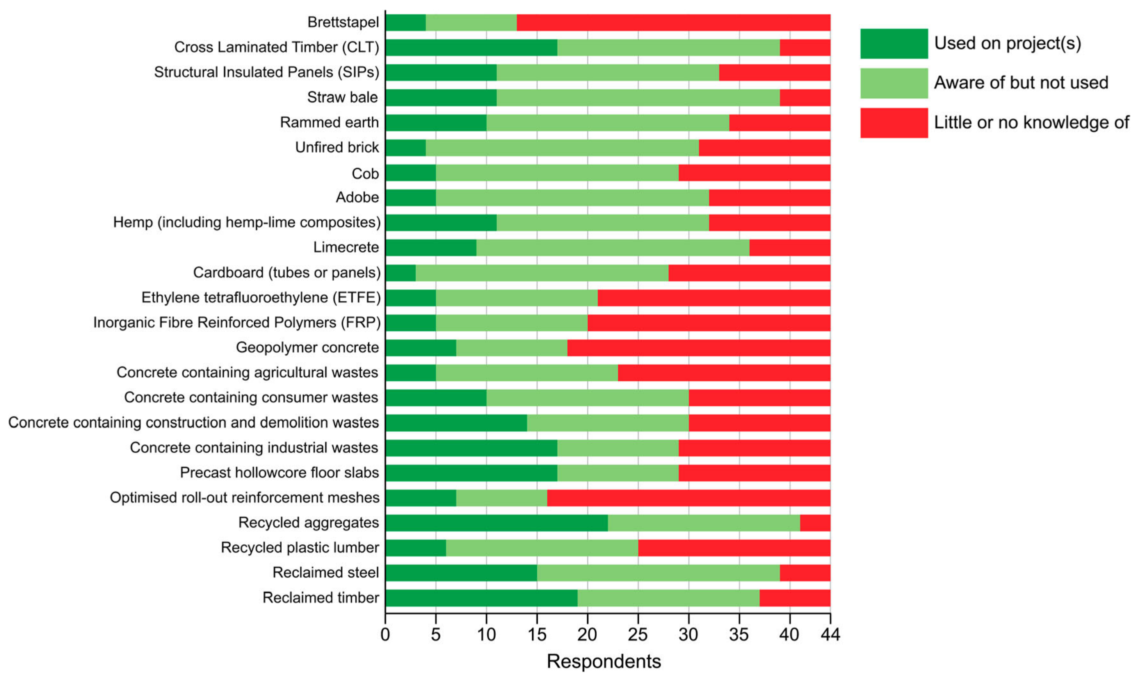

Figure 6 Knowledge of example materials (response to survey question: What is your knowledge of the following materials and construction products?)

Lack of design knowledge and skills was repeatedly identified as a major barrier and numerous respondents commented that they would like to know more about a number of the example materials. Few reported 'negative experiences of colleagues' as a barrier, and no respondents reported a mostly negative experience using any of the example materials. However, many cited 'negative perceptions' as a strong barrier. This may suggest that perceptions rather than experiences currently prevent selection of alternative materials.

When discussed in general terms, high costs were deemed the greatest barrier to low carbon materials.

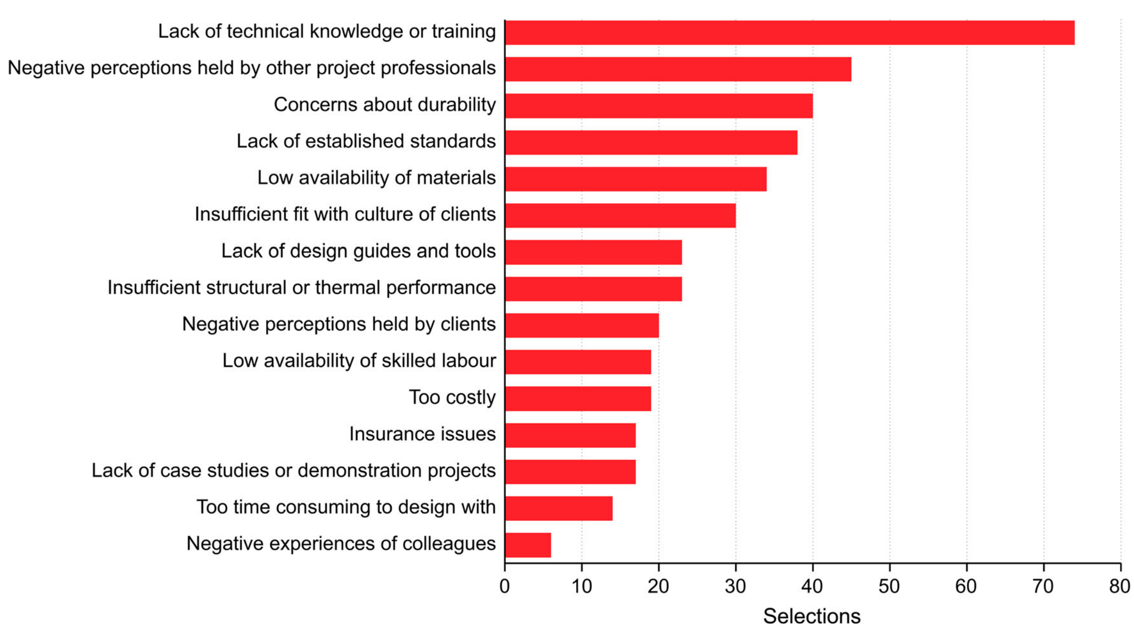

Figure 7 Barriers to use of the example materials (aggregated responses to survey question: You stated that you are aware of but have not used the following materials on a project. Why have you chosen not to use these materials?)

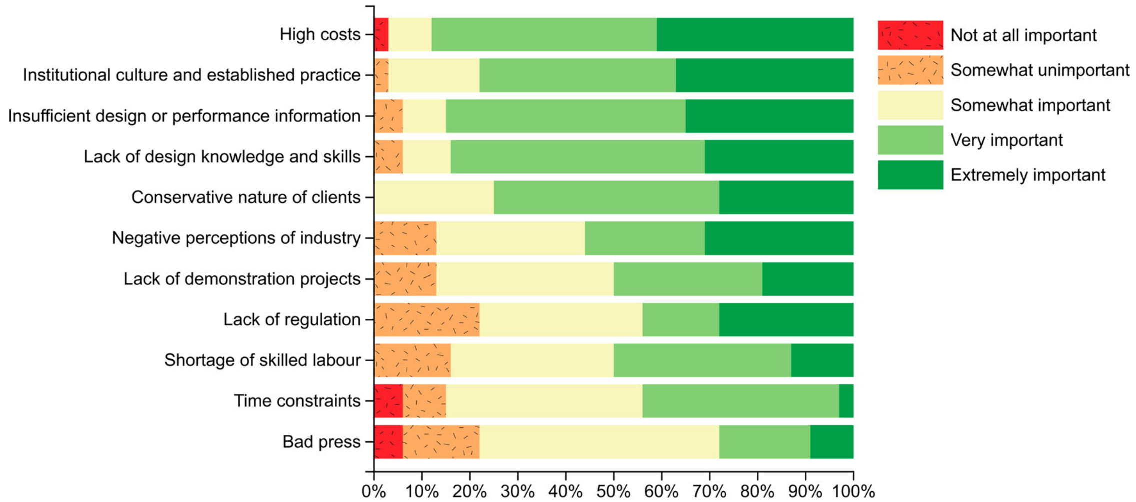

Figure 8 General barriers to use of alternative materials (response to survey question: Thinking more generally about alternative materials in construction, how important do you believe the following factors are in preventing their use?)

This is unsurprising, as clearly stated by a responding UK architect: 'on most construction projects, cost is still the major driver'. However, when specifically questioned on the 24 example materials, few respondents selected cost as a barrier preventing use. This suggests that the *perception* of high cost may be an important barrier in itself. This is a common barrier to sustainable building in general, and one that recent industry studies have sought to challenge (Abdul & Quartermaine, 2014).

Institutional culture and the conservative nature of clients were also identified as key barriers, alongside concerns about durability, lack of established standards and low availability of materials. In contrast, time constraints, lack of demonstration projects and availability of skilled labour were infrequently cited. 'Negative perceptions held by clients' and 'negative perceptions held by other project professionals' were more commonly selected for natural materials such as straw bale, rammed earth, cob and adobe. Meanwhile 'low availability of materials' was the most commonly selected barrier for reclaimed materials.

Drivers

When respondents were asked specifically about their reasons for selecting the example materials, the most commonly reported reasons were 'felt morally

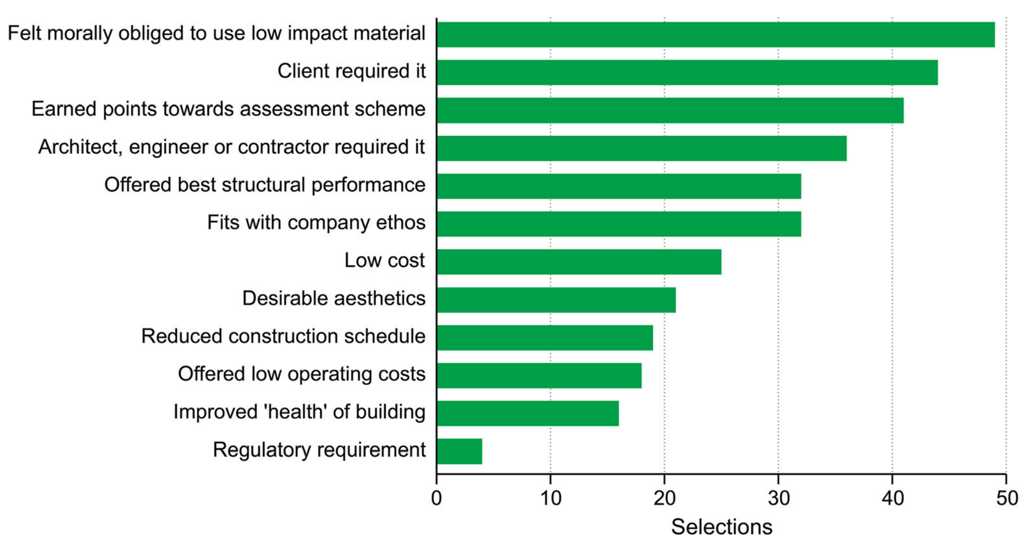

Figure 9 Current drivers of use of the example materials (aggregated response to survey question: Thinking about the projects on which you used these materials. Why did you choose to use each material?)

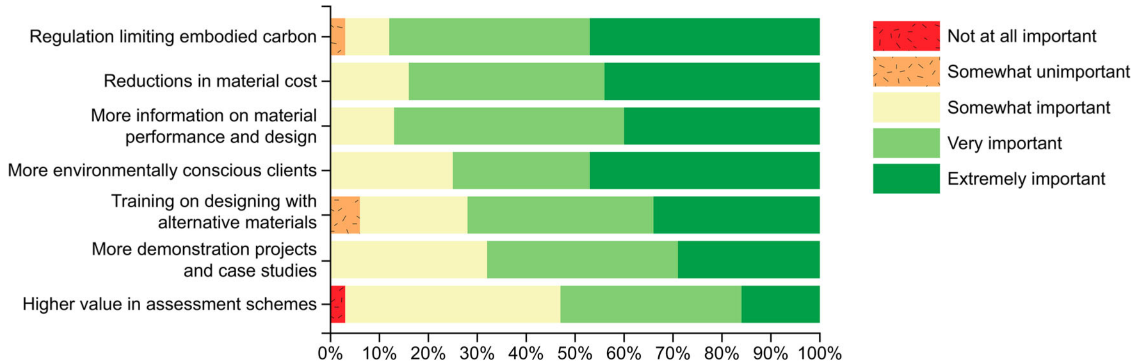

Figure 10 Future drivers of alternative material use (response to survey question: How important do you believe the following developments could be in encouraging greater use of alternative materials and construction products?)

obliged to use low impact material' and 'client required it' (Figure 9). This supports the finding of Persson and Grönkvist (2014) that the personal convictions of individuals are a strong driver of low carbon construction. This suggests that changing motivations of clients and construction professionals could drive demand for low carbon materials in the short-term. 'Client required it' was a particularly common factor for natural materials such as hemp and straw bale. Whereas 'felt morally obliged to use low impact material' was spread across a range of materials. 'Earned points towards assessment scheme' (such as BREEAM) was also frequently selected, mostly for recycled and reclaimed materials, as well as CLT.

When asked in general terms about future drivers, 88% of respondents stated that 'regulation limiting embodied carbon in construction' was either very important or extremely important in encouraging greater use of alternative materials and construction products (Figure 10). Reductions in material cost and more information on material performance and design were also identified by over 80% of respondents as being very or extremely important. Perhaps surprisingly, higher value in assessment schemes (such as BREEAM and LEED) was the least popular potential driver. One architect commented that 'fewer clients seem to be demanding BREEAM than before the recession' – suggesting that this downturn in demand would limit the effectiveness of any assessment scheme changes. Future rises in energy costs were also identified as a potential driver by multiple respondents.

Other comments

Many respondents expressed a concern about the lack of consistent and comparable methods of calculating and reporting embodied carbon. Several also noted a definitive lack of enthusiasm for change amongst their colleagues. Some expressed a concern that a persistent industry focus on technological solutions that reduce operational emissions is making it harder to engage clients and other professionals on material issues. One respondent expressed a concern that low carbon materials are typically grouped together and discounted as a whole by the industry as a 'hippy fad'. Such generalized negative perceptions of a diverse range of materials may, in part, explain the discrepancy between the generally reported barriers to adoption of alternative materials and the experiences of practitioners with specific materials.

Interview results and discussion

All interviews were recorded and transcribed in NVivo 10. Transcriptions were then coded and analysed according to a thematic framework. Select quotes populate the following discussion which draws together results from the interviews. The discussion is framed by the core themes that emerged from the analysis, and in some instances, refers back to the survey results which were revisited during analysis of the interview transcripts.

Discussion

GHG emission reduction targets. Interviewees generally agreed that the construction sector should be aiming for an 80% reduction in emissions – consistent with UK targets – and did not deserve any special dispensations compared with other sectors such as transport. However, all interviewees, except one, believed such a target was unlikely to be achieved. In spite of this, they saw value in the targets setting out a broader aim and principal. On a day-to-day level, interviewees preferred to approach the problem in terms of actions not numbers. Interviewees also believed that radical not incremental change is needed even to approach the targets; and that an increased focus on embodied carbon would be a key component of this. Interviewees believed fundamental changes in industry attitudes and the introduction of regulatory requirements will be essential in driving this change.

Barriers

Allocation of responsibility for embodied carbon reduction

When asked to rank all professions, survey results suggested that a small number of professions (architects, clients and civil/structural engineers) should be primarily responsible for material selection and embodied carbon reduction. When asked to rank these professions, the architect was clearly identified as the profession that should be most responsible for embodied carbon reduction. However, when this topic was explored with interviewees, a more nuanced view emerged. Most interviewees stated that in practice it is hard to pin responsibility for material selection and embodied carbon reduction on one party as so many actors influence project decisions; and the principal concern should be establishing a continuous chain of responsibility to ensure solutions make it into the finished building. Some interviewees felt that were this only to be driven by one professional, there is a significant risk that solutions will be compromised by other parties. To ensure the support and active participation of all project professions, several interviewees believed that responsibility for embodied carbon reduction should not be allocated to one individual but should be motivated by collective incentives for all parties in the contract structures. The desired full flow through the supply chain must then be driven by the client. At a practical level, this may require that the client designate an individual on the development team to monitor embodied carbon throughout the project and hold all project professionals to account.

Availability of data and product information

Interviewees complained it is still ‘really really hard’ to access good-quality data on embodied carbon and that they were disappointed by the quality of information received from product manufacturers, not just on embodied carbon but on performance in general. The detail and presentation of information from small manufacturers of low carbon construction products will need to improve if it is to be competitive with current market leaders. Interviewees were also critical of the growing dependence on generic datasets (such as Inventory of Carbon and Energy (ICE); Hammond & Jones, 2008), which were seen to encourage a thoughtless approach to embodied carbon assessment. Interviewees also expressed concern about the inconsistencies between datasets.

Some interviewees advocated the creation of a UK or EU database of Environmental Product Declarations (EPDs). It was suggested that this platform would provide a market incentive for suppliers to produce data and compete on that basis. This increased competition could unleash innovation in the supply chain. It was also felt by many interviewees that data availability would improve substantially if legislation mandating measurement of embodied carbon was introduced.

> If we get the right sort of processes and incentives in place then we’ll see an amazing amount of innovation. I think what’s interesting about the construction industry as a whole, is that, whilst there are a lot of embedded ways of doings things – there’s a lot of inertia – when the right incentives come around then there is a lot of innovation. I think we’ll see massive innovation especially amongst the supply chain [. . .] suppliers want to be better than the next door supplier because they’ll get the job.
>
> (Chair of Embodied Carbon Task Force)

Interviewees noted that despite a growing willingness amongst the industry to collaborate, a change in mind-set is still needed to overcome the protective attitude towards embodied carbon data and calculation methods. The process of undertaking a carbon calculation is not especially complicated and should not be viewed as specialist knowledge. The specialist knowledge (of commercial value and perhaps requiring protection) should reside in the corresponding measures to reduce embodied carbon.

Industry culture

A strong resistance from other project professionals was noted in the survey and confirmed anecdotally by the interviewees. Interviewees stressed that individual practitioners are not inherently neophobic and the unwillingness to adopt unfamiliar materials is largely a consequence of the risk-averse and litigious culture that pervades the industry. Where innovations are seen as convenient, or liability rests with another party, there is a willingness to adopt new products. Several interviewees felt that contract structures and procurement routes were largely responsible for creating an endemic ‘build and defend’ attitude. Consequently, if a material or practice is shown to work then there is little desire to explore alternatives. In this way existing practice becomes entrenched under the mantra of ‘it’s the way we’ve always done things’. This leads to the common industry view that imperceptibly slow change is typical and radical change almost unimaginable.

This is compounded by the industry’s reluctance to discuss failures. Owing to an understandable fear of damaging their reputation, few firms speak openly about their failures, and many outwardly present only success stories. Consequently, the valuable learning generated from failures is not transferred between firms. This results in the same basic mistakes being made time and again by different practitioners. Anecdotal stories of such failures pass around the industry, which in turn reinforces a general scepticism of alternative materials. By this means myths and misinformation are disseminated in the absence of guidance that could prevent failures.

Interviewees felt that many of these entrenched attitudes could be overcome by earlier engagement of specialists further down the supply chain. For example, encouraging design teams and contractors to work with technical experts from material producers can help allay concerns about performance and highlight required changes in the construction programme. Changes in contract structures and a move away from the typical competitive tender route based solely on price could also contribute to changing this culture. However, concerns of this nature are longstanding, with numerous reports offering similar criticism over a period of decades.

> The attitude is 'build and defend'. It's defend your position. People get defensive very easily because 9 times out of 10 if something happens and there's a mistake, there's a cost to it and then it's on somebody's doorstep. The client won't want to pay for it so they'll go for the contractor first, and the contractor will go for us and it's just a merry-go-round. We'll go to the supplier, the supplier will go to the sub-contractor and it's just such an unproductive approach. I think it purely comes about through the procurement of the building contracts and how that interaction works.
>
> (Architectural Technologist, specialist architectural practice)

Costs

> In the work that we've done [. . .] we've found a very direct link between managing embodied carbon and reducing costs. You do one, you'll get the other.
>
> (Chair of Embodied Carbon Task Force)

Survey results suggested a perception of high costs was restricting the uptake of low carbon materials. Yet all interviewees, except one, believed that reducing embodied carbon should not increase costs. Interviewees highlighted a common perception that low carbon options may incur a 'green premium' or additional consultancy costs that may not deliver value. However, they believed that this green premium had diminished over recent years and that relatively low consultancy costs are usually justified by material savings. In many cases the additional cost is not incurred directly in the material purchase but in consequent changes to the construction programme; often a result of late material substitution or changes in design. Furthermore, many alternative materials are not seen to offer savings on an elemental basis but can be demonstrated to yield savings in the total project cost. The earlier alternatives are included in designs, the easier it is to avoid costly changes to the construction programme and overcome the limitations of elemental costing.

> I think there are a lot of opportunities missed by not thinking about things holistically all the way through the process. There's diminishing returns the later you start considering these things, the less reduction you're going to achieve and probably the more it is going to cost. I think that's one of the biggest barriers, people think it'll cost more. You know, sometimes it might but often it won't if you just took the time to think about it.
>
> (Senior Engineer, large multidisciplinary consultancy)

Interviewees also stated that effective life cycle costing was critical to increasing uptake of alternative materials. Despite significant industry lip service to the contrary, most interviewees felt that life cycle costing was not being implemented and, consequently, materials that require less frequent replacement or offered potentially greater end of life value were being overlooked. Opportunities to implement such options are further restricted by the tendency of clients that are not the end users to prioritize options with the lowest up-front cost.

> Cost with embodied carbon for me is the biggest issue. There's a lot of cost neutral stuff you can do to reduce some of the high impact areas but I think the real business case only gets made if you look over the life of the building. I think that doesn't happen enough. We're not life cycle costing [. . .] it's not happening even though it is supposed to happen.
>
> (Sustainability Manager, multinational contractor)

In essence, whilst in some instances low carbon materials may cost more, in many cases increased costs are really a symptom of other barriers. Encouraging early consideration of design options and building a business case around life cycle costing can mitigate concerns about cost.

Low value of materials

Materials still retain a low value relative to total project costs, limiting consideration of material reduction strategies. Current valuation schemes also fail to assign any significant end of life value to materials. There is a widespread perception that once materials are on a building they are simply 'waste in waiting'. Interventions are required to change the perception of buildings approaching end of life from being liabilities (associated with high demolition costs) towards being valuable 'material banks'. However, interviewees felt a substantial market for recycled or reused materials would not emerge without government intervention. The European Commission set out their intention to investigate this issue in a recent communication, however, this work remains at an early stage (European Commission, 2014). Interviewees also felt that manufacturers needed to bear a greater degree of responsibility and that building rating schemes could better address this issue.

> We need to have a greater value somehow of materials once they are no longer wanted in a building. [. . .] People don't think they are resources as soon as they're on a building. Once they're on a building it's basically waste in waiting. It's really bizarre.
>
> (Senior Engineer, large multidisciplinary consultancy)

Knowledge, understanding and skills

Current industry understanding of embodied carbon varies widely across professions, firms and between individuals within those firms. Interviewees expressed a common opinion that the importance of embodied carbon and material selection is still regularly underestimated. One interviewee described it as 'terrifying how little people knew in the industry about it'. Whilst over recent years understanding of the basic terminology has improved, only a small minority of professionals in the industry are engaged in regular embodied carbon assessment. The core challenge is in spreading their knowledge throughout a highly fragmented industry.

Interviewees stressed the need for improving information exchange between professions, as it is only if all project participants are engaged and understand the theory as well as the practice that progress will be made. A number of interviewees stressed the need for greater support by professional institutions (*e.g.* UKGBC, Royal Institute of British Architects (RIBA), IStructE) in encouraging this communication, knowledge and data sharing. The maintenance of common repositories for information sharing, such as the UKGBC's Pinpoint platform (UKGBC, 2014b), are key in reaching the broadest audience.

Many companies are still hampered by an inability to roll over learning from project to project effectively. This is particularly the case for smaller companies that cannot afford specialist staff to develop in house expertise. In companies of all sizes, establishing routine processes that allow building through incremental learning will be critical in supporting this knowledge development.

The introduction of simple assessment tools could be invaluable in supporting the spread of embodied carbon assessment to smaller construction firms. This could be further supported by legislation that encourages recognition of embodied carbon without requiring full assessment. For example, the introduction of a series of approved solutions for embodied carbon as an Allowable Solution would encourage architects at small firms to specify a solution with lower embodied carbon without the need for a full, complex assessment. Sustainability consultants also have a crucial supporting role to play in the coming years until larger practices bring these skills in house.

Several interviewees also emphasized the need for universities to include a greater focus on embodied carbon in undergraduate courses. Greater training for tradesmen and installers will also be necessary to ensure familiarity with a broader range of materials and products and adherence to the often higher quality of installation and finish that is required.

> I know our company quite well and even within our company there is a huge range from people who understand all the complexity of the detail to people who still are not even sure what carbon footprinting is, let alone why you should do it or how to do it [. . .] the general awareness and knowledge is definitely increasing but it's not particularly high yet.
>
> (Senior Engineer, large multidisciplinary consultancy)

Demonstration projects and product testing

Most interviewees identified a need for more shared case studies to prevent designers from reinventing the wheel each time. For many, proving real world performance is the only way to overcome industry scepticism and demonstration projects are seen as the best way to do this. Underperformance of construction products is commonplace in the industry, as evidenced by widely documented performance gap problems (Zero Carbon Hub, 2014). This has resulted in a lack of faith in figures from manufacturers and models. This can only be overcome through greater in situ testing and post occupancy evaluation. Unfortunately, many within the industry are reluctant to confront real-world performance and potential failures because of the associated liability and reputational risk. One interviewee cited example performance studies of public buildings that have been suppressed either because they failed miserably or because they performed exceptionally and participants were reluctant to share their secret.

Early engagement

A lack of early engagement was consistently noted by interviewees as a significant barrier. Opportunities to adopt more sustainable solutions were regularly overlooked because they were only considered late in the project. Contractors and sustainability specialists were often not consulted until after critical design decisions had been taken; and the flow of information between specialists and the design team was often not on a sufficient cycle to allow the greatest impact. Early engagement of the full supply chain, including subcontractors and suppliers, is critical in leveraging the broadest combined knowledge and specialist insight, which will lead to better design decisions and prevent the need for expensive redesign or rework. This requires allocating sufficient time at the early design stages to allow for such engagement and consideration of material options. This supports the findings of the Arup study that on more sustainable projects material choice is generally considered earlier in the design process and for longer (Arup & WBCSD, 2012).

> Early engagement is a thing we need to do [. . .] as with all sustainability issues, we're always saying they need to be considered earlier because they're not. As a contractor [. . .] we tend to get involved slightly later and we see instances all the time where issues are being brought up, either we're bringing them up or they've been left to this stage, but basically too late. Design decisions have already happened or contracts have already been put in place. To go back would mean a load more money, re-work, re-drawing. [. . .] We need early engagement with all stakeholders but the supply chain really [. . .] because that's where the solutions come. Either contractor, sub-contractor or supplier or ideally all three.
>
> (Sustainability Manager, multinational contractor)

Negative perceptions of low carbon materials

Scepticism towards many alternative materials clearly remains amongst some parts of the industry. Advocates for low carbon construction are often not taken seriously, with many interviewees offering anecdotes about colleagues responding with an attitude of 'here's the green person banging on about something green'. There remains a significant challenge in changing these entrenched attitudes.

The core challenge lies in taking embodied carbon into the mainstream, positioning it as compatible with existing goals and prominent campaigns (such as resource efficiency and circular economy principles) and associating it with a broader array of materials. One interviewee drew a pertinent parallel with operational energy, which over the preceding 20 years has gone from a 'niche, hippy thing to do' to a routine consideration.

Drivers and opportunities

Moral convictions

In the absence of significant regulatory or client drivers, the moral convictions of individuals have been driving progress on embodied carbon. Interviewees felt that many individuals within the industry were deeply passionate about the built environment and exhibited a strong desire to minimize environmental impacts. However, pragmatic considerations about cost, quality and buildability will regularly trump personal convictions about sustainability. Consequently, there remain limited instances where moral reasons drive material decisions. In these instances the individual is usually supported by a like-minded client.

There are limited historical precedents for moral convictions driving change in the construction industry. In cases where this has been successful, such as the greatly improved attitudes towards on-site health and safety, these good intentions have been supported by strong regulation. Thus, whilst in the short-term there remains some scope for further change to be driven by the moral convictions of clients and practitioners; in the long-term additional regulatory or financial drivers will be needed as few within the industry are in a position to act on personal convictions.

> I think we need to make sure that the regulations make it happen. Without that it'll be left to the moral leaders to continue their work but it won't become an industry.
>
> (Chair of Embodied Carbon Task Force)

Establishment of an embodied carbon community

Leading industry practitioners are increasingly sharing best practice and a nascent embodied carbon community is forming. There are a growing number of industry events on the topic with increasing attendances and interviewees expect this community to continue expanding. This will drive interest and action on embodied carbon and improve the dissemination of information and best practice.

> I feel the community has come a long way in the past 12 months and we sit in rooms and have coffee together and talk about how we do things and how we could do things better or more consistently as an embodied carbon community. I think that's quite important.
>
> (Senior Engineer, large multidisciplinary consultancy)

Client requirements

Major clients are increasingly incorporating environmental and social considerations into their project evaluation processes. A growing number have shown an interest in embodied carbon with several now making clear assessment or reduction commitments (*e.g.* British Land, 2014; Marks & Spencer, 2014; The Crown Estate, 2013). A group of large developers are regularly communicating on this and other issues. This will help spread best practice, ensure client demands are robust and lead to further interest from smaller clients. Anecdotal evidence of this was reported by the interviewees. However, many feared a perception of increased cost could prevent demand from spreading to the smallest clients.

Much of the current client interest is driven either by increasing commitments to corporate social responsibility or by the moral convictions of individuals within those firms. An opportunity exists to engage further clients in consideration of embodied carbon by targeting key individuals, such as directors, in those firms. However, in the long-term, only ensuring buy in from select individuals will not be sufficient, as development teams must be convinced of the value in addressing embodied carbon, otherwise requirements may be introduced but not enforced.

Interviewees made it clear that greater guidance for clients would be welcome. In the absence of clear and simple guidance, such as a client procurement guide, some clients may over analyse options and suffer from a paralysis of choice. Clear targeted reductions, such as British Land's commitment to targeting five key materials (British Land, 2014), or M&S's focus on 'carbon hotspots' (Marks & Spencer, 2014) can help in this regard. Ultimately, clients are in a strong position to drive embodied carbon assessment and do not require enabling legislation. Consequently, increasing client demands are likely to be the greatest driver of embodied carbon assessment in the near term.

> We talk very much about our social, economic and financial contribution as a whole. Every decision you make you have to look at the financial bottom line but what's the environmental bottom line as well? What's the social bottom line? [. . .] You can justify maybe coming below the hurdle for financial return [. . .] if you can say environmentally or socially we're doing this, this and this. [. . .] We have people in the business now starting to think like that. They're thinking not just about the financial bottom line, they're thinking of everything else as well.
> (Assistant Head of Sustainability, large client)

Business opportunities

There is a growing business case for tackling embodied carbon that is principally motivated by four factors: perceived cost savings associated with a reduction in material use; establishment of a reputation for good environmental management; increased resilience to resource scarcity and price rises; and the opportunity to be 'ahead of the curve' with regards to future legislation (WRAP, 2014b). Generally speaking, embodied carbon assessment is seen as a means of promoting resource efficiency, which many interviewees felt could yield significant long-term savings. Numerous companies have already demonstrated associated costs savings. For example, Anglian Water have realized significant savings in capital cost whilst achieving a 41% reduction in embodied carbon emissions between 2010 and 2014 (Anglian Water, 2014). However, most interviewees felt this business case had yet to be effectively disseminated throughout the industry.

Some interviewees perceived opportunities for UK companies to be world leaders in a growing industry of embodied carbon assessors. As global interest grows there are opportunities to export services calculating embodied carbon, advising on reduction strategies, or training local practitioners on these techniques. Examples already exist of UK based companies advising on overseas projects. One interviewee felt that if this opportunity was not swiftly seized – by developing skills and nurturing the UK market – it was likely that other nations would overtake the UK and provide these services.

> The activity of measuring carbon and advising on how to reduce it in buildings is obviously a part of the green economy. It keeps people in work and it's an expertise that we may have an advantage here in the UK on, which can be sold abroad. It's good for international competition and income, exporting that kind of expertise. In that sense I think it is obviously a good thing.
> (Sustainability and life cycle assessment expert, research technology organization)

Regulation

Survey results suggested that 'regulation limiting embodied carbon in construction' could potentially be the greatest driver of alternative materials use. Regulation has long been a critical driver of change in the construction industry and interviewees felt it would be essential in addressing embodied carbon. Whilst moral convictions, the demands of particular clients and perceived business opportunities may drive some uptake of low carbon materials, interviewees felt that a significant proportion of the industry would only respond to legislated requirements.

> At the end of the day, the drivers will always be statutory requirements put upon them to do these things, a huge proportion of the marketplace will only respond to that.
> (Sustainability and LCA expert, research technology organization)

Interviewees suggested a variety of means of implementing regulation, including: forming a new Part of the Building Regulations governing embodied carbon; including embodied carbon in the Zero Carbon definition; introducing measures addressing embodied carbon as Allowable Solutions; and simply mandating measurement of embodied carbon as part of the planning process. The best means remained a source of much debate, with interviewees stressing the need for a holistic approach that balanced embodied and operational emissions. Some interviewees believed better product and building level data would be required before regulation would be feasible or effective. Others argued that the simple act of mandating measurement would generate such data in short order.

Many interviewees believed the current government lacked the political appetite for introducing additional regulation, fearing it may be perceived as another costly layer of 'unnecessary bureaucracy' on an already 'over-burdened' industry. However, several interviewees believed such regulation would be received enthusiastically by many in the industry as it would provide them with justification for dedicating time to an issue they perceive to be important. A key factor in how such regulation would be received is whether or not it is seen to contribute in a positive and flexible way to the design process. When drafting such regulation the emphasis should be on encouraging a variety of good practices not generating additional compliance calculations. Many interviewees felt that the introduction of such regulation could support improved building design; drive significant innovation in product supply chains and rejuvenate the market for recycled and reused materials.

> Architects and engineers want to produce better buildings. If by managing embodied carbon, as well as operational carbon, you're producing a better building then there'll be no resistance at all. But you've got to think about the drivers for that. The drivers need to be cost and regulatory. If you've got the drivers there it'll just get done. No-one will even begin to question it.
>
> (Chair of Embodied Carbon Task Force)

Benchmarks. Interviewees repeatedly expressed concern about the lack of robust benchmark data on embodied carbon. At a building level, designers are currently restricted to RICS (2012) benchmarks, WRAP resource efficiency benchmarks (WRAP, 2014a), entries in the WRAP embodied carbon database (WRAP & UKGBC, 2014) or results from past projects. These sources cover a limited range of building types and are based upon small samples. Component level benchmarks are not yet available. Even within these data sets there is limited scope for accurate benchmarking owing to the variety of data sources used and the impact of project specific factors on total results. For example, foundations can constitute a significant share of the total embodied carbon but depend heavily on site ground conditions. For similar reasons, there is limited scope for benchmarking against notional reference buildings. The gathering of more robust benchmark data will undoubtedly require a massive data collection effort over a period of years. Several interviewees felt the simplest way to accelerate this process would be to mandate measurement through regulation.

> I think the starting point will be to work on a benchmark per sector. For example, there's a 12 storey office block with air conditioning would be roughly x. Then people can start looking at how they can reduce that in the same way as we look at how we'd reduce cost.
>
> (Director of Sustainability, professional institution)

In addition to this, there exists a gap in translating sector level emission reduction targets into project level benchmarks. Ensuring future benchmarks are consistent with national targets will be key to achieving the required level of emissions reduction (GCB, 2013). Currently, there is no means by which to bridge this divide.

> I think that a top-down approach is the only way to link on-the-ground activities to national targets. I think it is an essential link, analogous to reporting and collecting data on the economy. It is the only real way you can manage the country.
>
> (Sustainability and LCA expert, research technology organization)

Role for institutions. Professional institutes play a critical role in the construction industry. Interviewees felt that, thus far, there had been minimal engagement on embodied carbon from the institutes, with some notable exceptions such as RICS (2012) methodology. There is a great opportunity for professional institutes to provide legitimacy and impartiality to data sharing schemes (such as Carbon Buzz (RIBA & Chartered Institution of Building Services Engineers (CIBSE), n.d.) and the WRAP embodied carbon database (WRAP & UKGBC, 2014)); facilitate knowledge transfer between firms; and support the development of an embodied carbon community. Institutions can also help address the current shortage of skills through training courses and guidance and provide funding for demonstration projects and testing of novel materials. Further targeted support for small firms, such as the provision of basic calculation tools and benchmarks, would also be welcomed. There may also be opportunities for institutions to motivate action through implementing voluntary standards for embodied carbon. However, it is important to remember that voluntary standards, whilst desirable, are not necessarily effective in embedding change. This can be seen in the recent failure to meet targets for on-site emissions set out in the Strategy for Sustainable Construction, and waste reduction targets from the Halving Waste to Landfill Commitment (Adams, 2014). Whilst the suggested actions varied, interviewees' unanimous desire was that institutions take a more active role in the embodied carbon debate.

Study limitations and further research

The study was limited by a number of factors. The survey's relatively small (47 respondents) convenience based sample, whilst not intended to be representative, fell below the desired sample size; and a particularly poor response rate was observed from certain professions (*e.g.*, quantity surveyors). This may be explained by a combination of the survey length and the more general phenomenon of declining response rates attributable to survey fatigue. The online platform, means of distribution and survey title may also have biased the survey towards respondents from particular demographics and with specific positive or negative experiences that they wished to share.

The qualitative approach of the study, whilst providing useful insight into many questions, provides incomplete or conflicting answers to some questions and depends upon unbiased reporting of experiences by practitioners. Whilst many of the presented results support those accumulated from other studies of 'sustainable' or 'green' building, it remains difficult to determine if these results reflect established 'myths' within the industry or real, commonplace, experiences. By offsetting survey questions in both general terms and across an array of specific materials an attempt was made to distinguish the differences between perceptions and experiences. Triangulation with interview results also helped to provide a more nuanced interpretation of survey results. However, there remain many unresolved questions. Definitive answers to some questions, such as whether or not low carbon materials increase project costs, can only ultimately be resolved through the collection of real world cost data. This research gap could be addressed through case studies or a data collection project by an established industry body, such as the RICS. In the absence of such data, studying perceptions and the root of cost increases can still provide insight, as it is often perceptions rather than reality that influences uptake.

Other research gaps exist in understanding how concerns around embodied carbon spread within client organizations, and exploring the implications for material manufacturers of a low embodied carbon future. Reduced use of conventional materials, and the greater uptake of alternative materials, has the potential to interfere with the existing dynamics of the sector, reducing the market share of currently dominant producers. This in turn has the potential to inflict substantial structural changes on the economy. It is apparent that more work needs to be done to develop a thorough understanding of these potential impacts. Much additional data gathering is needed to develop robust project level benchmarks and a methodology is needed to link these with sector emission reduction targets. Further research is also required to resolve the debate around the most appropriate means of regulating embodied carbon and detailed proposals require development.

Conclusions and recommendations

The principal objective of this study was to understand the economic, technical, practical and cultural barriers preventing construction professionals from selecting a variety of materials commonly identified as being lower in embodied carbon. A review of previous studies assessing barriers to reducing operational emissions and adopting more sustainable practices in the construction industry revealed a common set of cultural and institutional barriers. The results presented in this paper strongly suggest that these barriers also prevent alternative material choice as a means of mitigating embodied carbon emissions. Many of these barriers are common across materials with uptake restricted by: perceptions of high costs; a shortage of knowledge and skills; inadequate design time to allow consideration of novel options; inadequate information from material producers and an inability to establish an effective or collective chain of responsibility. Design teams are also hampered by the poor availability of product and building level carbon data and benchmarks.

The construction industry can seek to overcome these barriers by encouraging earlier engagement of supply chains, effective use of whole-life costing, and changes to contract and tender documents. Additional training is required for many practitioners and firms engaging in their first embodied carbon assessments must have structures in place to ensure learning is rolled over from project to project and disseminated internally. The industry must also share the accumulated knowledge on embodied carbon. This includes uploading data to common repositories to allow for benchmarking; sharing standardized reporting forms and openly discussing their successes and failures. The industry must not wait on regulation to act but continue to build upon the growing business case and be proactive in encouraging clients to engage in assessment.

A growing number of firms have worked on projects where embodied carbon has been measured and reduced. Successful projects typically benefit from a highly motivated client that places clear and challenging requirements in the tender documents, common incentives in contracts, and encourages early engagement of the full supply chain. There is a clear opportunity for clients to motivate further action on embodied carbon without enabling legislation. Clients must also be proactive in sharing their expertise and experiences, allowing for mutually beneficial improvements such as standardizing embodied carbon-reporting forms for subcontractors. Engaged individuals within client organizations should seek to include embodied carbon assessment within their mandatory or voluntary carbon disclosure to embed consideration and continuous improvement within their organization.

There is a role for professional institutions to facilitate this knowledge transfer between firms, and foster an embodied carbon community. Institutions can provide training courses and guidance; fund key demonstration projects; independently gather cost data to flesh out the business case; and help disseminate lessons learnt by early actors. Ultimately, however, regulation will also be required to build upon the early work of moral leaders.

In a number of major countries, there is a growing industry acceptance that embodied carbon should be regulated in some form. Governments can provide clarity by setting a long-term trajectory for such regulation. In the UK, the focus should be on providing certainty by swiftly establishing a replacement for the expected Zero Carbon regulations and consulting on a preferred means of regulating embodied carbon. There is a clear role for institutions and industry advocacy groups to contribute to this debate, by facilitating events such as, the Alliance for Sustainable Building Products Embodied Carbon: Why, how and when? Debate (Alliance for Sustainable Building Products, 2014). In the meantime, governments may also wish to consider more radical regulatory options; an example would be including embodied carbon of new facilities within the UK's mandatory GHG emission reporting requirements for quoted companies, and extending this legislation to cover additional firms. Local authorities may also wish to introduce their own mandatory requirements within the planning process or provide financial incentives such as reduced council tax or business rates for exemplary low carbon properties. Furthermore, public sector clients can also lead by example, by introducing mandatory requirements for embodied carbon assessment; and encouraging use of alternative materials on public projects. The Government through their associated research organizations may also wish to fund projects to develop key information sources for practitioners such as a centralized database for UK EPDs and Life Cycle Inventory data.

There is a clear opportunity for embodied carbon reduction to play a significant part in meeting increasingly challenging carbon budgets in many countries. Early action and regulation could support swift development of expertise, faster data gathering and the growth of an industry with significant export potential. There is a clear opportunity for early actors to become world leaders in a growing industry that will support skilled jobs, develop the market for alternative materials and achieve significant reductions in GHG emissions.

Acknowledgements

The authors thank sincerely all the individual practitioners who contributed to the research findings. Their time and participation in both the survey and the follow-up interviews is greatly appreciated. The authors also thank Ray Edmunds, Dr Sally Russell, and the numerous architects and engineers who provided feedback on the pilot survey. They are also indebted to the organizations and individuals that helped distribute the survey.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was financially supported by the Engineering and Physical Sciences Research Council [grant number EP/G036608/1]. The contribution of the second author was supported by the RCUK Energy Programme [grant number EP/K011774/1].

Supplemental data

Supplemental data for this article can be accessed at doi:10.1080/09613218.2016.1086872

References

Abdul, Y., & Quartermaine, R. on behalf of BRE & Sweett Group (2014). *Delivering sustainable buildings. Savings and payback*. ISBN 978-1-84806-366-2

Adams, S. (2014). Construction industry fails to meet own carbon emissions targets. Retrieved October 15, 2014, from http://www.c-r-l.com/construction-industry-fails-meet-carbon-emissions-targets/

Alliance for Sustainable Building Products. (2014). *Embodied carbon: Why, how and when? Debate*. Retrieved from http://www.asbp.org.uk/news/detail/?nId=74

Anglian Water. (2014). *Greenhouse gas emissions annual report 2014*. Retrieved from http://www.anglianwater.co.uk/_assets/media/GHG_Emissions_Annual_report_2014.pdf
Arora, S. K., Foley, R. W., Youtie, J., Shapira, P., & Wiek, A. (2014). Drivers of technology adoption — the case of nanomaterials in building construction. *Technological Forecasting and Social Change*, *87*, 232–244. doi:10.1016/j.techfore.2013.12.017
Arup & World Business Council for Sustainable Development (WBCSD). (2012). *Material choice for green buildings*. Retrieved from http://www.wbcsdcement.org/pdf/WBCSD_Material choice for green buildings_201201(Jan).pdf
Battle, G., et al. (2014). Embodied carbon industry task force recommendations. Proposals for standardised measurement method and recommendations for zero carbon building regulations and allowable solutions.
Bayne, K., & Taylor, S. (2006). *Attitudes to the use of wood as a structural material in non-residential building applications: opportunities for growth*. Published by Australian Government Food & Wood Products Research & Development Corporation. Retrieved from http://www.fwpa.com.au/sites/default/files/PN05.1020.pdf
BRE. (2004). Barriers to the enhanced use of wood in Europe: Particular attention to the regulatory barriers (Client report number 714–393): Commissioned for CEI-Bois.
British Land. (2014). *Supporting communities and enhancing environments: Sustainability brief for developments*. Retrieved from http://www.britishland.com/~/media/Files/B/British-Land/downloads/investor-downloads/bl-sustainability-brief-2014.pdf
Clark, D. (2013). *What colour is your building?* London: RIBA.
Connor, J. O., Kozak, R., Gaston, C., & Fell, D. (2004). Wood use in nonresidential buildings: Opportunities and barriers. *Forest Products Journal*, *54*(3), 19–28.
The Crown Estate. (2013). *Development sustainability principles*. Retrieved from http://www.thecrownestate.co.uk/media/5214/urb-development-sustainability-principles.pdf
De Ia Rue du Can, S., & Price, L. (2008). Sectoral trends in global energy use and greenhouse gas emissions. *Energy Policy*, *36*(4), 1386–1403. doi:10.1016/j.enpol.2007.12.017
Egan, J. (1998). *Rethinking construction*. London: Published by Department of Trade and Industry, URN 03/951.
European Commission. (2014). Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions on Resource Efficiency Opportunities in the Building Sector. COM(2014) 445 Retrieved from http://ec.europa.eu/environment/eussd/pdf/SustainableBuildingsCommunication.pdf
Green Construction Board. (2013). *Low carbon routemap for the UK built environment*. Retrieved from http://www.greenconstructionboard.org/otherdocs/Routemap final report 05032013.pdf
Giesekam, J., Barrett, J., Taylor, P., & Owen, A. (2014). The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy and Buildings*, *78*, 202–214. doi:10.1016/j.enbuild.2014.04.035
Gold, S., & Rubik, F. (2009). Consumer attitudes towards timber as a construction material and towards timber frame houses – selected findings of a representative survey among the German population. *Journal of Cleaner Production*, *17*(2), 303–309. doi:10.1016/j.jclepro.2008.07.001
Hammond, G., & Jones, C. (2008). Inventory of carbon and energy (ICE).
Heinonen, J., Säynäjoki, A., & Junnila, S. (2011). A longitudinal study on the carbon emissions of a new residential development. *Sustainability*, *3*(12), 1170–1189. doi:10.3390/su3081170
Hemström, K., Mahapatra, K., & Gustavsson, L. (2011). Perceptions, attitudes and interest of Swedish architects towards the use of wood frames in multi-storey buildings. *Resources, Conservation and Recycling*, *55*(11), 1013–1021. doi:10.1016/j.resconrec.2011.05.012
Holton, I. on behalf of BRE. (2003). *A review of the potential use of secondary and recycled aggregates in self-compacting concrete*. DTI Project Report 211–997 Retrieved from http://www.sustainableaggregates.com/library/docs/wrap/L0317_CCC_SCC.pdf
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, a. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings*, *66*, 232–245. doi:10.1016/j.enbuild.2013.07.026
Intergovernmental Panel on Climate Change (IPCC). (2014). Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)], pp. 151. Geneva, Switzerland: IPCC.
Kershaw, T., & Simm, S. (2013). Thoughts of a design team: Barriers to low carbon school design. *Sustainable Cities and Society*, *11*, 40–47. doi:10.1016/j.scs.2013.11.006
Knoeri, C., Binder, C. R., & Althaus, H.-J. (2011). Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling*, *55*(11), 1039–1050. doi:10.1016/j.resconrec.2011.05.018
Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., & Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. *Ecological Economics*, *68*(10), 2696–2705. doi:10.1016/j.ecolecon.2009.05.007
Marks & Spencer. (2014). *Plan a report 2014* (p. 28). Retrieved from http://planareport.marksandspencer.com/downloads/M&S-PlanA-2014.pdf
Matthews, H. D., Solomon, S., & Pierrehumbert, R. (2012). Cumulative carbon as a policy framework for achieving climate stabilization. *Philosophical Transactions of the Royal Society. Series A, Mathematical, Physical, and Engineering Sciences*, *370*(1974), 4365–4379. doi:10.1098/rsta.2012.0064
McKinsey & Co. (2009). Pathways to a low carbon economy, version 2 of the global green house gas abatement cost curve, 2009. Retrieved from http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/cost%20curve%20pdfs/pathways_lowcarbon_economy_version2.ashx
Misra, S., Rao, A., & Jha, K. N. (2007). Use of aggregates from recycled construction and demolition waste in concrete. *Resources, Conservation and Recycling*, *50*(1), 71–81. doi:10.1016/j.resconrec.2006.05.010
Moncaster, A., Hinds, D., Cruickshank, H., Guthrie, P. M., Chrisna, N., Baker, K., . . . Jowitt, P. W. (2010). Knowledge exchange between academia and industry. *Proceedings of the ICE - Engineering Sustainability*, *163*(September), 167–174. doi:10.1680/ensu.2010.163.3.167
Osmani, M., & O'Reilly, A. (2009). Feasibility of zero carbon homes in England by 2016: A house builder's perspective. *Building and Environment*, *44*(9), 1917–1924. doi:10.1016/j.buildenv.2009.01.005
Persson, J., & Grönkvist, S. (2014). Drivers for and barriers to low-energy buildings in Sweden. *Journal of Cleaner Production*. Advance online publication. doi:10.1016/j.jclepro.2014.09.094
Pinkse, J., & Dommisse, M. (2009). Overcoming barriers to sustainability: An explanation of residential builders' reluctance to adopt clean technologies. *Business Strategy and the Environment*, *18*(8), 515–527.
Prologis. (2015). Case studies – Sainsbury's at Prologis Park Pineham. Retrieved from http://www.prologis.co.uk/our-customers/case-studies/sainsburys/
Rhys, J. (2011). Cumulative carbon emissions and climate change: Has the economics of climate policies lost contact with the

physics?. Retrieved from http://www.oxfordenergy.org/wpcms/wp-content/uploads/2011/07/EV-571.pdf

Royal Institute of British Architects (RIBA) & Chartered Institution of Building Services Engineers (CIBSE). (n.d.). CarbonBuzz. Retrieved from http://www.carbonbuzz.org/

Roos, A., Woxblom, L., & McCluskey, D. (2010). The influence of architects and structural engineers on timber in construction – perceptions and roles. *Silva Fennica*, *44*(5), 871–884.

Royal Academy of Engineering. (2010). Engineering a low carbon built environment. The discipline of Building Engineering Physics.

Royal Institution of Chartered Surveyors (RICS). (2012). Methodology to calculate embodied carbon of materials IP 32/2012.

Säynäjoki, A., Heinonen, J., & Junnila, S. (2012). A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. *Environmental Research Letters*, *7*(3), 034037. doi:10.1088/1748-9326/7/3/034037

Sturgis, S., & Roberts, G. (2010). Redefining Zero: Carbon profiling as a solution to whole life carbon emission measurement in buildings. RICS Research.

Tam, V. W. Y. (2011). Rate of reusable and recyclable waste in construction. *The Open Waste Management Journal*, *4*, 28–32. doi:10.2174/1876400201104010028

Tashakkori, A., & Teddlie, C. (2003). *Handbook of mixed methods in social & behavioral research*. Sage Publications. ISBN: 0761920730.

UK Green Building Council (UKGBC). (2014a). *Embodied carbon week – seeing the whole picture*. Retrieved from http://www.ukgbc.org/resources/publication/embodied-carbon-week-2014-report

UK Green Building Council (UKGBC). (2014b). Pinpoint embodied carbon resources. Retrieved October 14, 2014, from http://pinpoint.ukgbc.org/resource.php?search=EMBODIED+CARBON

UK Green Building Council (UKGBC). (2015). *Tackling embodied carbon in buildings*. Retrieved from http://www.ukgbc.org/resources/publication/tackling-embodied-carbon-buildings

Wang, L., Toppinen, A., & Juslin, H. (2014). Use of wood in green building: A study of expert perspectives from the UK. *Journal of Cleaner Production*, *65*, 350–361. doi:10.1016/j.jclepro.2013.08.023

Watson, N., Walker, P., Wylie, A., & Way, C. (2012). Evaluating the barriers to entry for non-conventional building materials. In *IABSE Conference Cairo*. International Association for Bridge and Structural Engineering Publishing.

Williams, K., & Dair, C. (2007). What is stopping sustainable building in England? barriers experienced by stakeholders in delivering sustainable developments. *Sustainable Development*, *15*, 135–147. doi:10.1002/sd.308

Wong, P. S. P., Owczarek, A., Murison, M., Kefalianos, Z., & Spinozzi, J. (2013). Driving construction contractors to adopt carbon reduction strategies – an Australian approach. *Journal of Environmental Planning and Management*, *57*(10), 1465–1483. doi:10.1080/09640568.2013.811402

WRAP. (2011). *Cutting embodied carbon in construction projects*. Retrieved from http://www.wrap.org.uk/sites/files/wrap/FINAL PRO095-009 Embodied Carbon Annex.pdf

WRAP. (2014a). Resource efficiency benchmarks for construction projects. Retrieved November 30, 2014, from http://www.wrap.org.uk/content/resource-efficiency-benchmarks-construction-projects-0

WRAP. (2014b). *The business case for managing and reducing embodied carbon in building projects*. Retrieved from http://www.wrap.org.uk/content/business-case-managing-and-reducing-embodied-carbon-building-projects

WRAP & UK Green Building Council (UKGBC). (2014). WRAP embodied carbon database. Retrieved October 12, 2014, from http://ecdb.wrap.org.uk/Default.aspx

Zero Carbon Hub. (2014). *Closing the gap between design and as-built performance. Evidence Review Report*. Retrieved from http://www.zerocarbonhub.org/sites/default/files/resources/reports/Closing_the_Gap_Between_Design_and_As-Built_Performance-Evidence_Review_Report_0.pdf

Zhang, C., & Canning, L. (2011). Application of non-conventional materials in construction. *Proceedings of the ICE - Construction Materials*, *164*, 165–172. doi:10.1680/coma.900061

Endnote

[1]Commonly the term 'embodied carbon' is used to refer to emissions incurred in the building life cycle outwith operational use. However, the precise definition varies between studies despite the introduction of the BS EN 15978:2011 standard (Figure 1). Some authors define embodied carbon solely as those emissions incurred within the product and construction process stages (A1–A5), so-called 'cradle-to-end-of-construction' emissions; others utilize broader 'cradle-to-grave' boundaries (A1–A5, B2–B5, C1–C4) incorporating repair, maintenance and end-of-life considerations. Optional stage D, accounting for the positive impacts of processing or reusing materials, is also incorporated into some analyses.