REDUCING EMBODIED CARBON IN THE BUILT ENVIRONMENT: A RESEARCH AGENDA

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ABSTRACT

In spite of significant global efforts, the International Energy Agency suggests that buildings-related emissions are on track to double by 2050. Whilst operational energy efficiency continues to receive significant attention by researchers, a less well-researched area is the assessment of embodied carbon in the built environment in order to understand where the greatest opportunities for its mitigation and reduction lie. This paper reports on available mitigation strategies to tackle embodied carbon identified through a systematic review of the available academic evidence. It also investigates the scope and scale of current academic investigations to highlight where significant gaps are for impactful further research on the topic. In total, 17 mitigation strategies have been identified from within the existing literature which have been discussed individually. Results reveal that a one-size-fits-all approach is unlikely to yield beneficial results and future research should be diverse in breadth and scope, locally accurate, and significantly interdisciplinary.

INTRODUCTION AND THEORETICAL BACKGROUND

The built environment puts incredible pressure on the natural environment. In the European Union, it accounts for 50% of all extracted materials, 42% of the final energy consumption, 35% of greenhouse gases (GHGs) emissions (EC, 2011) and 32% of waste flows (EEA, 2012), and global figures are not much different (Khasreen et al., 2009). Considerable effort across policy, academia and industry has therefore gone into improving the energy efficiency of buildings. However, until recently political effort has focused almost entirely on the operational stage (occupancy phase) of buildings, with one example being the European Union final deadline for nearly Zero Energy Buildings (nZEB) from 2020 (EU, 2010). The reason given for this focus is that operational energy (and carbon) accounts for the greatest share of life cycle energy (and carbon) of a building.

In spite of these efforts CO_2 emissions are continuing to rise, with the International Energy Agency (IEA) suggesting that emissions are on track to double by 2050 (IEA, 2014). Part of the reason appears to be that the higher energy efficiency leads to rebound effects from increased energy demand, due to, for instance, "more heated space, higher temperatures, and for longer periods" (Rovers, 2014). However a less well-researched reason may be due to the unnecessary dichotomy between operational and embodied impacts, which has the unintended consequences both of ignoring the effects of increased construction and in some cases of shifting the environmental burdens from one life cycle stage (occupancy) to the others (Pomponi et al., 2016a). There is now robust evidence that the embodied impacts of buildings are a significant contributor to global emissions, and that as a percentage of whole life impacts of buildings they can account for more than 50% (Crawford, 2011), with 70% calculated for some cases in the UK (Ibn-Mohammed et al., 2013).

Out of several potential measures, 'embodied carbon equivalent' (CO_{2e}[1]) is useful for several relevant reasons:

- It measures and indicates the contribution of buildings and their products to global warming and climate change, which is increasingly critical (Moncaster, 2015, IPCC, 2014);
- Through considering the carbon intensity of the energy carrier it is more comprehensive than embodied energy (Pomponi et al., 2015);
- While it may not accurately represent all additional ecological and environmental impacts (Pomponi et al., 2016a, Asdrubali et al., 2015a, Turconi et al., 2013), it correlates well with several impact categories of more comprehensive impact assessment methods (e.g. ReCiPe) (Heinonen et al., 2016), thus acting as a useful indicator also for impacts other than climate change.

The substantial growth of related literature from outside academia (ASPB, 2014, RICS, 2012, UKGBC, 2015, IEA, 2016, ICE, 2015, BRE, 2015), which addresses the themes of EC reduction and mitigation, also confirms the importance of embodied carbon.

In spite of this growing interest and understanding of the issue, the body of academic knowledge on strategies to tackle embodied carbon has not previously been investigated systematically. This paper reports on previous research by the authors (Pomponi and Moncaster, 2016) and presents seventeen

[1] Carbon dioxide equivalent emissions, measuring unit of the Global Warming Indicator (GWI)

mitigation strategies that have been identified to address embodied carbon reduction in the built environment.

The following section introduces the method whereas section three discusses each of the mitigation strategies identified and includes the meta-analysis of all collected data to identify existing trends and issues. The fourth section concludes the paper.

METHODOLOGY AND METHODS

The choice of a systematic approach to review the existing literature is done to ensure thoroughness, rigour and objectivity. This approach is widely used in other disciplines (Tranfield et al., 2003, Delbufalo, 2012) but also in built environment research (Pomponi et al., 2016b). A further technique often combined with this process is the meta-analysis of data to quantitatively integrate research findings across a wide number of studies (Delbufalo, 2012) in order to reveal and map significant trends (Pomponi et al., 2016b) through the harmonised use of reviewed data (Asdrubali et al., 2015a, Pomponi et al., 2016b). Ultimately, the purpose of a systematic literature review and meta-analysis is to make sense of key elements within a large collection of sometimes-contradictory studies to facilitate decision-making and action with an aim to inform both policymaking and practice (Tranfield et al., 2003).
In this paper the following strings[2] and combinations thereof have been searched across main literature database[3]:

- Embodied carbon mitigation (+strategy)
- Embodied carbon reduction (+strategy)
- Embodied carbon management (+strategy)
- Embodied carbon building(s)
- Life cycle assessment building(s)
- LCA building(s)
- Life cycle carbon building(s)

Due to the rapidly developing field, search results were temporally limited to 10 years and given existing disputes over reliability, data quality, and system boundaries within LCA, results were also limited to peer-reviewed journal articles. In total, after removing duplicates, 876 manuscripts matched the initial search criteria but only 102 were eventually relevant to this research. Due to the page limit for this paper it was not possible to report all details of the studies reviewed but the interested reader could refer to the full article of the extensive research for more information (Pomponi and Moncaster, 2016).

EMBODIED CARBON MITIGATION STRATEGIES

Seventeen mitigation strategies (MSs) were identified in the reviewed literature, which are presented and discussed in turn.

[2] The search was limited to Title, Abstract, and Keywords of manuscripts to avoid completely unrelated results.
[3] Web of Knowledge, Web of Science, Science Direct and Google Scholar.

MS1: Use of materials with lower embodied energy and carbon

The use of alternative materials with low EE and EC to mitigate the contribution of the built environment to climate change was a particularly common solution (e.g. Yu et al., 2011, Ng et al., 2012). In many studies, this approach involves the use of natural materials (e.g. timber, bamboo, hemp-lime composites). For instance, Reddy (2009) investigated the use of stabilised mud blocks (SMB) as a substitute for load bearing brickwork and found nearly a 50% reduction in embodied costs. With a focus on using alternative building materials over more traditional ones for a 28-storey residential building in Hong Kong, Cui et al. (2011) quantified the related embodied carbon savings, obtaining a 34.8% reduction. Switching from material level to a full house project, Salazar and Meil (2009) assessed the GHG impacts of what they call a 'wood-intensive' house in comparison to a typical one with brick cladding in Canada and found extremely significant differences between the two: 20 tCO_{2e} for the former vs. 72 tCO_{2e} of the latter. The enormous potential of a broader adoption of wood as a construction material seems confirmed by Upton et al. (2008) who, in a US residential-sector-wide study, indicated savings of 9.6 $MtCO_{2e}$/annum by using wood as an alternative to concrete- and steel-based building systems under the assumption of 1.5 million single-family new houses built each year. Vukotic et al. (2010) also found a timber structure school building to have lower impacts than the steel frame alternative, but recommend that "rather than encouraging debate about which material is 'better' than any other", the best use is made of chosen materials in any particular situation (Vukotic et al., 2010). It is worth noting that in some comparative studies, the use of materials with lower EE/EC may also involve commonly-used materials, such as in the work of You et al. (2011) who found a 4.2% CO_2 reduction in preferring steel-concrete structures over masonry-concrete structures; an aspect which leads to the importance of design discussed in the next sub-section.

MS2: Better design

Good design practice and appropriate choices at the design stage, as well as techniques such as design for deconstruction, were identified as crucial strategies for EC reduction and mitigation. Acquaye and Duffy (2010) conducted an input-output analysis of the Irish construction sector; they suggest that their results showed that better design could have reduced indirect emissions by 20% and direct emissions by 1.6% totalling 3.43 $MtCO_{2e}$. In examining refurbishment of high-rise concrete buildings in Hong Kong, Chau et al. (2012) also found a determinant role of design. They argued that "the most effective option is to maintain 15-30% of the existing structural and non-structural building elements as it can reduce the CO2 footprint by 17.3%". This view is echoed and supported by Cuéllar-Franca and Azapagic (2012) who reflect on the longevity of decisions taken at the design stage and call for a sustainable home design which considers the impact that design choices exert over the building's life cycle. The centrality of design is also emphasised by Häkkinen et al. (2015) who recommend a gradual and systematic procession through all different phases and stages of design to accurately assess GHG emissions and achieve low-carbon buildings.

MS3: Reduction, re-use and recovery of EE/EC intensive construction materials

Basbagill et al. (2013) investigated in detail the application of LCA to help designers understand and reduce the environmental impacts of building materials and components. They found that by optimising key parameters (e.g. thickness of piles and footings, and of external and internal walls) "anywhere from 63% to 75% reduction in the building's maximum total embodied impact is possible"

(Basbagill et al., 2013). Garcia-Segura et al. (2014) assessed the reduction of GHG emissions due to a reduced use of Portland cement and its substitution with blended cement, which has a higher content of fly ash (FA) and blast furnace slag (BFS). Such an approach promises to lead to 7% - 20% fewer emissions (Garcia-Segura et al., 2014). Similar environmental benefits following a reduction in use of cement are echoed by Atmaca and Atmaca (2015) and Miller and Doh (2015). Moynihan and Allwood (2014) investigated the utilisation of structural steel in buildings and concluded that by designing to minimise the material used rather than the cost, the use of steel in building and the associated embodied impacts could be dramatically reduced.

MS4: Tools, methods, and methodologies

Despite the populated panorama of existing tools, assessment methods and methodology, it still seems this is seen as a key area to bring about embodied carbon reduction with the parallel aim of building a better and stronger EC culture amongst the built environment stakeholders. This may take the form of coupling EC assessment with building information modelling (BIM) (Ariyaratne and Moncaster, 2014) or combining BIM with dynamic energy simulation tools (Peng, 2016). In some other cases, new methodologies aim at refining existing ones by, for example, coupling a life cycle carbon assessment with an analysis of the value created by the specific activity/product under investigation (Li et al., 2013).

MS5: Policy and regulations (Governments)

Perhaps unsurprisingly, the implementation and/or revision of policy and regulations by Governments also emerged as a commonly cited strategy for EC reduction (e.g. Dakwale et al., 2011, Blengini and Di Carlo, 2010, Giesekam et al., 2014). In some studies (Giesekam et al., 2014) this strategy is mainly intended as a means to support other mitigation strategies, like a wider use of low EE/EC materials, whereas in others policy has a broader reach. For instance, Dhakal (2010) reports on Chinese and Japanese contexts where a 50% CO_2 reduction could be achieved through the impact of policies on design and construction practices.

MS6: Refurbishment of existing buildings

A few scholars believe the greatest opportunity for EC mitigation lies with the upkeep of existing buildings. This appears to be especially true in developed countries where the existing building stock forms the vast majority of the built environment. Gaspar and Santos (2015) assessed the potential saving for a detached house in Portugal built in the late 1960s, concluding that refurbishment would be 22% more efficient than demolition and rebuild. A strong case for refurbishments can be also found in the work of Power, who demonstrated that the case for large scale demolitions "is greatly weakened" when considering EC as well as operational figures, for the EC of an average refurbishment project to bring an existing house up to modern standards is around one third of that of a new house (Power, 2008, Power, 2010).

MS7: Decarbonisation of energy supply/grid

Just as the idea of decarbonising the energy supply is seen as one pathway to operational-carbon-free buildings (Rovers, 2014), some scholars point out that there is the same opportunity for embodied costs (Chang et al., 2011, Heinonen et al., 2011, Jiang and Tovey, 2009). For instance, in the study from Heinonen et al. (2011) a specific ‘greener’ energy mix would cut 6% off the total emissions figure.

MS8: Inclusion of waste, by-product, and used materials into building materials

A further beneficial effect may be brought about by the inclusion of waste and by-products into building materials (e.g. Lee et al., 2011, Napolano et al., 2015), in light of cradle-to-cradle design and circular economy approaches which have recently received increased attention as a valid and viable alternative to the traditional linear make-use-dispose paradigm. Intini and Kuehtz (2011) investigated the use of recycled plastic bottles to manufacture thermal insulation in Italy and concluded that recycled polyethylene terephthalate (PET) can reduce environmental impact as much as 46% with respect to GWP. Some researchers also highlight the importance of considering the necessary supply chain to realise this (Densley Tingley and Davison, 2011).

MS9: Increased use of local materials

Several studies reported the EC reduction due to an increased use of local materials which would reduce transportation impacts (e.g. Asdrubali et al., 2015b, Chou and Yeh, 2015, Gustavsson et al., 2010). In a detailed assessment of stone production carried out in accordance to PAS 2050 guidelines, Crishna et al. (2011) argued that depending on the stone type and the country of origin, the use of UK-based stones can save between 2% - 84% of the EC of stones sourced from abroad. It is also worth considering that such strategy would benefit local or national economies as well as the environment.

MS10: Policy and regulations (Construction sector)

For some scholars, the strength of policies and regulations lies not (or at least not only) with governments but with bodies and stakeholders within the construction sectors (e.g. Acquaye and Duffy, 2010, Alshamrani et al., 2014). For instance, Alshamrani et al. (2014) developed an integrated LCA – LEED model for sustainability assessment and believe there would be positive consequences if it were voluntarily adopted and used in the construction sector.

MS11: Social ‘component’ - change driven by strong demand from all BE stakeholders

This cluster groups ‘social’ elements for a built environment with lower EC, such as an aesthetic demand for “buildings [with] sustainable credentials” (Monahan and Powell, 2011), or solutions related to people’s skills such as the contractors’ ability to plan resources, their management skills and construction performance mentioned by Sandanayake et al. (2016). Also, social or cultural aspects have been identified as barriers to EC reduction, such as the inertia of builders towards environmentally conscious regulations in China reported by Li and Colombier (2009).

MS12: More efficient construction processes/techniques

In some studies, a gain in efficiency in the construction sector is seen as an important opportunity for EC reduction (e.g. Sandanayake et al., 2016, Roberts, 2008, Monahan and Powell, 2011). This is often intended as a more efficient manufacture of building materials, the use of innovative and less wasteful processes during the construction stage, or a combination of the two. This strategy also includes the reduction of delays, the impact of site conditions, and the use of more energy efficient machinery.

MS13: Carbon mitigation offsets, emissions trading, and carbon tax

Some scholars see the solution to the EC problem in carbon mitigation and trading, and in fewer cases carbon taxing. For instance, Dalene (2012) reports on a case study of a residential building where all "GHG emissions were offset by carbon mitigation programs and certified carbon offsets were purchased" to achieve carbon neutral status. At a broader scale, Kennedy and Sgouridis (2011) developed a carbon accounting framework for cities to categorise and determine urban emissions strategies.

MS14: Carbon sequestration

The carbon sequestration approach found in few studies (e.g. Dhakal, 2010, Gustavsson et al., 2006) is to some extent linked to the previous strategy but it deserves a separate category due to different underlying principles: while carbon offsets and emissions trading offer a policy solution to EC reduction, carbon sequestration looks at the technological side of the issue exploring new materials or innovative uses of existing ones to capture and store carbon. For instance, Sodagar et al. (2011) studied the use of biotic materials in a social housing project in the UK and concluded that the carbon lock-up potential could reduce carbon emissions by 61% over the 60-year lifespan of the houses.

MS15: Extending the building's life

Intuitively, extending a building's life span would delay and therefore reduce the EC associated with deconstruction and demolition, waste processing and rebuild. However, this strategy is only considered by a handful of studies in the existing literature (e.g. Densley Tingley and Davison, 2011, Toller et al., 2011, Yung and Chan, 2012). In some of the studies, this strategy does not simply consider aiming for a longer service life of the building but is also about designing the building with the necessary flexibility to be durable and adaptable.

MS16: Increased use of prefabricated elements/off-site manufacturing

This category is somewhat linked to more efficient construction processes but due to a clear stream within the existing literature oriented towards off-site manufacturing and prefabrication it was coded separately. In some studies, the emission savings of this strategy alone have been quantified. For instance Mao et al. (2013) found that semi-prefabrication would emit 3.2% less than conventional construction. Off-site manufacturing has been also investigated in combination with other strategies (e.g. the use of low embodied carbon materials) such as in the case of Monahan and Powell (2011).

MS17: Demolition and rebuild

In a very few cases, such as Dubois and Allacker (2015), it has been suggested that a truly significant carbon reduction in the built environment would only be achievable through wide campaigns of demolition and reconstruction with the belief that embodied costs of such activities are negligible compared to the benefits of new build. In another study (Boardman, 2007), a demolition level higher than current practice is considered a "sensible compromise" to tackle climate change.

Table 1 shows the meta-analysis done on the correlation across all mitigation strategies (blue = higher correlation / red = lower correlation).

As evident in Table 1 some MSs are more strongly correlated with others. It is important to clarify that low or null correlation does not necessarily mean that there is not a synergy to exploit between a specific pair of MSs but might as well mean that the potential has not yet been investigated. As such, those specific pairs of MSs are interesting avenues for further collaborative and interdisciplinary research.

Table 1 - Meta Analysis of Correlation Across All Mitigation Strategies

MS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	100%	47%	43%	27%	20%	14%	20%	18%	18%	10%	12%	8%	4%	10%	10%	6%	0%
2		100%	48%	38%	27%	23%	21%	21%	8%	21%	13%	8%	13%	8%	10%	2%	2%
3			100%	29%	10%	24%	10%	24%	14%	2%	5%	5%	5%	10%	12%	5%	0%
4				100%	30%	9%	12%	12%	6%	24%	18%	0%	9%	6%	6%	0%	0%
5					100%	25%	25%	8%	4%	29%	33%	8%	21%	8%	8%	0%	8%
6						100%	16%	11%	16%	5%	16%	5%	5%	11%	5%	5%	0%
7							100%	13%	19%	6%	19%	6%	6%	13%	6%	6%	0%
8								100%	20%	7%	20%	7%	7%	13%	7%	7%	0%
9									100%	8%	23%	8%	8%	15%	8%	8%	0%
10										100%	25%	8%	8%	17%	8%	8%	0%
11											100%	8%	8%	17%	8%	8%	0%
12												100%	11%	22%	11%	11%	0%
13													100%	22%	11%	11%	0%
14														100%	13%	13%	0%
15															100%	14%	0%
16																100%	0%
17																	100%

CONCLUSIONS

This paper has reported on part of the outcomes of a substantial systematic review of academic knowledge on the topics of life cycle assessment of buildings and embodied carbon reduction in the built environment. We have chosen to develop the paper around the mitigation strategies identified in the existing literature as these might as well form very important directions for future research in the field. The seventeen mitigation strategies span across several disciplines and surely involve a plurality of stakeholders. As a consequence, the problem of EC does require a pluralistic solution because no single mitigation strategy is seen to be effective in EC reduction; this aspect should hopefully foster collaborative and interdisciplinary research even more in the future.

The analysis has also shown the interconnectedness of the role of the designer with those of the researchers, the materials manufacturers and the policy makers. For instance, the development and use of materials with low EC is intertwined with a better design which in turn is seen as the key element to also reduce, re-use and recover EC-intensive construction materials, such as steel and concrete. New tools, methods and methodologies are also needed to facilitate the transition to a low-carbon built environment, as are policies at both government and construction sector levels. These however require support from the society at large (social 'component') if a substantial change is to be achieved. In developed countries, the upkeep of the existing building stock also stood out as a crucial element. In most cases, this was simply seen as the need to refurbish existing buildings although there are growing signs of more specific research activities in extending the building's life during a refurbishment project in a design-for-longevity aim.

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