Embodied carbon in buildings: an Australian perspective

Robert H. Crawford[1], André Stephan[1] and Monique Schmidt[1]

[1] Faculty of Architecture, Building and Planning

The University of Melbourne

Parkville, Victoria 3010, Australia

Introduction

This chapter explores the current status of the methodological developments, policy and industry implementation associated with embodied carbon in Australia. It provides insight into the contribution that Australia has made to the development of embodied carbon data and assessment methods. It also draws upon existing studies and building projects to highlight the extent to which embodied carbon is being addressed in Australia, as well as where Australia sits in relation to the management and mitigation of embodied carbon in the global context. The degree to which policy has been driving the consideration of embodied carbon within the Australian building sector is also discussed.

Our understanding of embodied carbon in buildings, including its magnitude, key contributing factors, ideal approaches for measuring it, and the most effective measures for its mitigation, is still very much in a state of development. Many of the aspects covered in this chapter are ongoing work and progressing at quite a rapid pace. They are primarily focused on advancing this understanding, improving the way in which we quantify embodied carbon, and supporting decision-making around how best to go about mitigating embodied carbon within our buildings. As we delve further into our understanding of the ways in which buildings contribute to our broader embodied carbon footprint, priorities and areas for further work will emerge. The chapter concludes by highlighting some of the areas that will need to be explored in our strive towards 'net-positive life cycle carbon' buildings.

Data and methods for embodied carbon assessment in Australia

This section discusses the role that Australia has played in the development of embodied carbon data and assessment methods. The past three decades have seen considerable advancements in the way embodied carbon is measured. Australia has played a significant role in many of these developments, including the creation of multi-region input-output (MRIO) models and the hybridisation of life cycle inventory data. These recent methodological advancements in embodied carbon assessment in Australia and their drivers are explained below. This includes an overview of AusLCI and BP LCI process databases, Eora and IELab input-output databases, structural path analysis (SPA), and path exchange (PXC) hybrid analysis.

The development of embodied carbon data in Australia

Process data

As is the case within many other regions of the world, Australian researchers and practitioners rely on a range of physical and financial data when quantifying the embodied carbon of buildings. With the advent of life cycle assessment in the 1990s, a concerted effort was made by the Australian life cycle assessment (LCA) community to collect physical data on the environmental flows associated with the production of a range of Australian products and processes, including building and packaging materials, energy and transport. This included life cycle inventory (LCI) data for timber, concrete, steel, PVC, aluminium, and glass which were compiled into the National Life Cycle Inventory (LCI) Database.

While initially funded by the federal government and state EPAs, ongoing data collection efforts were quite limited due to a lack of sufficient resources. However, at the time, this data was considered to form the most comprehensive database of product environmental flows for Australia. It began to be used widely within the LCA community for quantifying embodied environmental flows associated with buildings, materials and other products. The database continued to expand to include data on agriculture, fuels, food, raw materials and waste management. A renewed effort to update the National LCI Database began with the launch of AusLCI in 2006. This Australian Life Cycle Inventory Database (www.auslci.com.au) was a new initiative of ALCAS, the Australian Life Cycle Assessment Society and the CSIRO. The aim of AusLCI was to further expand the range of products and processes contained within the original database and establish more robust data collection protocols. The database now includes data on a range of products across various sectors, collected using a consistent framework and covering a broad range of resource inputs and outputs, including emissions of carbon dioxide. While quite limited in the coverage of construction materials, efforts to expand the database to cover a broader range of products are ongoing.

In parallel, the Building Products Innovation Council (BPIC) established the Building Products Life Cycle Inventory (BP LCI) (www.bpic.asn.au), a database of physical process data for over 100 different building materials and products, including concrete, concrete blocks, concrete and terracotta roof tiles, bricks, gypsum board, steel, timber and timber products, windows, glass and insulation materials. For each material, data on inputs such as fuels, raw materials, water as well as emissions of waste and pollutants are provided. Unlike AusLCI, which also includes products other than building materials and is open-access, BPIC covers only building materials, but also restricts access to registered users.

Environmentally extended input-output (EEIO) data

The scope limitations typically inherent in physical life cycle inventories have led to a significant body of work on the establishment of environmental inventories based on financial data. In this approach, input-output (IO) tables, containing information on monetary transactions between sectors of an economy, are combined with national environmental accounts (e.g. energy, greenhouse gas emissions (GHGE), and water). The resulting environmentally extended IO (EEIO) data provides information on the embodied environmental flows per monetary value of output from a particular sector (e.g. tonnes of GHGE per dollar value of construction). As this data is based on an economy-wide system boundary, it is considered to be systemically complete. However, the applicability of the use of this national average data in accounting for the environmental flows associated with a particular good or service is one of its major drawbacks, among others (Lenzen 2000).

Input-output tables are produced in over 100 countries but vary considerably in terms of their level of sectoral and regional disaggregation, and the frequency by which they are compiled. While the use of IO data for environmental assessment goes back to at least the 1960s (Isard *et al.* 1968) most applications of IO data for this purpose have occurred since the mid-1990s (Hoekstra 2010).

The Australian Bureau of Statistics (www.abs.gov.au) has produced IO tables for Australia going back to 1958. These are usually produced on an annual basis with the latest tables covering 114 industry groups (ABS 2016b). The earliest evidence of the use of these tables in accounting for environmental flows is by Karunaratne (1981) who used them to estimate the primary energy demand associated with fossil fuels. EEIO data for Australia has been made available in a number of databases, including Eora and IELab, as discussed below.

Hybrid data

In an effort to combat data gaps in AusLCI and BP LCI and deal with the non-specificity of EEIO data, researchers have also combined both sources of data to produce what is known as hybrid data. This data aims to maintain the reliability and comprehensiveness of the respective original data sources and is most typically provided in the form of resource or emission coefficients for different materials and products. Hybrid data for Australian construction materials is provided by Crawford and Treloar (2010).

Methods for quantifying embodied carbon use embodied carbon data in a variety of ways. Both physical process data and EEIO data can be used independently, or they can be combined as part of a hybrid analysis. A hybrid analysis can take numerous forms depending on how the data is combined. In essence, its main goal is to avoid the limitations inherent in process and IO analysis (Lenzen 2000) by capturing the strengths of each individual approach. Australia has played a key role in the development of hybrid analysis methods, as outlined in the following section.

Embodied carbon assessment methods: the Australian contribution

Two of the most significant contributions made to the field of embodied carbon modelling by Australian researchers are in the fields of multi-region input-output (MRIO) analysis and hybrid analysis.

Multi-region input-output analysis

Historically, the use of IO analysis to quantify carbon, as well as other environmental flows, in the form of an EEIO analysis, has occurred at a single region level (Tukker and Dietzenbacher 2013). However, environmental flows are very rarely confined within the boundaries of a single region, especially with the ever-increasing trade of goods and services between countries. In recognition of this, multi-region input-output (MRIO) analysis can be used to trace the inter-regional flows of goods and services in order to attribute the environmental effects of the entire supply chain to final demand, in a consumption-based accounting approach. This environmentally extended MRIO analysis can be performed at both a sub-national and global (country) scale by linking IO data for multiple regions.

MRIO analysis has been used since the 1950s, initially for economic accounting (Isard 1951). However, the most rapid advancements have occurred within the last decade (Wiedmann 2017). One of the major reasons for its slow uptake was the time and complexity involved in bringing together often disparate, inconsistent data sources. In recent times there have been a number of initiatives aimed at compiling large-scale global MRIO databases, including IDE-JETRO, EXIOBASE, GLIO, GTAP, OECD, WIOD and Eora. These are described in more detail by Murray and Lenzen (2013).

Researchers at the University of Sydney were responsible for conceiving and developing the Eora MRIO database (http://www.worldmrio.com). This came about by the lack of geographical and sectoral detail, continuous time series, and information on reliability and uncertainty provided by existing MRIO databases. Eora was designed to provide a disaggregation of IO data into countries and sectors at the highest possible level of detail, improving the accuracy of environmental life cycle and footprint-type assessments. Eora provides data for 187 countries across 15,909 sectors, more than any other MRIO database. It also allows for the creation of a historical time series back to 1990, greater flexibility, increased transparency, reliability and uncertainty analysis, and regular data updates (Lenzen *et al.* 2013).

During Eora's development, the research team identified the need for a collaborative effort in the creation of a global MRIO database, through the establishment of an international collaborative research platform. Data could then be pooled and shared, and MRIO tables released in a regular and timely manner (Lenzen *et al.* 2013). The Australian Industrial Ecology Virtual Laboratory (IELab) is a first attempt to establish and test this collaborative approach to MRIO compilation, initially developed as an Australian sub-national MRIO database and analytical toolbox (https://ielab-aus.info). IELab is a collaborative cloud-based platform for compiling large-scale, high-resolution, economic, social, and environmental accounts based on MRIO tables. A user-friendly GUI aims to improve access to MRIO analysis. The IELab uses a spatial classification based on the Australian Statistical Geography Standard (ASGS) which includes a Statistical Area Level 2 (SA2) subdivision of Australia into 2,196 geographical entities (ABS 2010), each containing an average population of 10,000 persons. The Input–Output Product Categories (IOPC) sectoral classification is used, which distinguishes 1,284 product groups (ABS 2012). Theoretically, it could be used to model embodied carbon for any product group or sub-national region, including temporal changes based on time series data.

Wiedmann *et al.* (2013) provide a summary of the range of studies in which the IELab has been used, which includes assessing the production of biofuel and analysing the carbon footprint of cities and electricity supply. The IELab has also been used to assess the embodied carbon of construction materials (Teh *et al.* 2017) and can act as a useful tool for providing an initial estimate of the embodied carbon of the construction sector or of sectors supplying goods or services to the construction sector. Most of these studies would not have been possible without the functionality of the IELab, strengthened by the cloud-based format that enables easy updating, as well as improved accessibility (Wiedmann *et al.* 2013).

Path exchange hybrid analysis (PXC)

Until the 1970s, methods for embodied carbon accounting tended to rely on the use of physical process data (in the form of a process analysis), or, in much rarer cases, EEIO data (in the form of an EEIO analysis). In 1978, Bullard et al. published a handbook for combining process and input-output analysis. This hybrid approach to accounting for environmental flows was developed in order to address some of the limitations inherent in the two separate methods. Process analysis suffers from truncation issues due to time and cost constraints in data collection, while input-output analysis suffers from a lack of specificity in regards to individual products (Lenzen 2000).

In the mid-1990s, Associate Professor Graham Treloar, then a PhD researcher at Deakin University in Geelong, Australia, identified a need for disaggregating input-output data into discrete paths or nodes[1] (Treloar 1997). Treloar observed that changing the transaction coefficient for a particular node in an input-output matrix would affect all supply chain paths that contain that node, even if the changed coefficients applied only to a particular path. Treloar developed a technique for extracting individual nodes from the IO data in order to avoid such undesired "global" effects inherent to previous hybrid methods. For example, the direct purchase of cement for concrete by the residential building sector can be identified, as well as cement for the indirect purchase of concrete through the concrete products sector. Treloar termed this the "path extraction technique" and demonstrated how it could be applied to the analysis of embodied energy (Treloar 1997). This approach is now commonly referred to as 'structural path analysis' (SPA) (Lenzen 2007).

Treloar demonstrated how a hybrid approach to accounting for environmental flows, such as carbon, could be achieved using SPA. The first step is to mathematically disaggregate the IO matrix into a series of mutually exclusive nodes. Specific nodes are then modified using process data that corresponds to the particular transaction. The modifications can affect either the value of the transaction, if identified as different for the particular good or service under study, or the environmental flow associated with the transaction, if specific process data is available. Using this approach, process data can be integrated for individual nodes rather than by replacing a direct coefficient in the IO matrix, which would otherwise flow through to all instances of transactions between two sectors at

[1] A node represents a good or service provided by a particular sector within an input-output matrix. Node to node connections represent a transaction between input-output sectors, i.e. the purchase of a good or service from one sector by another. A series of nodes, corresponding to a chain of transactions leading to the sector being assessed, is referred to as a path or pathway.

every tier of the supply chain. For example, if process data for the greenhouse gas emissions associated with the production of cement purchased by the residential building sector are available, this particular transaction or node in the SPA can be replaced with this data. Nodes relating to the production of cement elsewhere in the supply chain can then remain unchanged.

The approach of conducting a hybrid analysis using a SPA as the basis for the integration of process data was originally termed an 'input-output-based hybrid analysis', by Treloar (1997). It has more recently been referred to as the 'path exchange method' (PXC) (Lenzen and Crawford 2009). Treloar and fellow researchers have applied the PXC method within a range of studies, mostly in relation to embodied energy, carbon and water in the construction sector (inter alia Treloar *et al.* 2002; McCormack *et al.* 2007; Baboulet and Lenzen 2010; Crawford 2011b; Crawford and Pullen 2011). However, Treloar unfortunately did not have the opportunity to develop a general methodology, to solve a number of problems and undertake further research in relation to the PXC method as he was struck down by a terminal illness in his prime. Lenzen and Crawford (2009) continued this research, presenting a general methodology for the PXC method and illustrating the relationship between the PXC method and other methods. While the PXC method is regularly referred to in publications using hybrid methods, its application is rare and often limited to those researchers involved in its development. The complexity of this method and the amount of data to be manipulated is one reason explaining why its use has not yet become common practice.

As with most other methods for quantifying embodied carbon, using the PXC method is most commonly applied utilising material-based carbon coefficients. In this case, coefficients for building materials are compiled using the PXC method, using available process data for material production, and data from a SPA of the relevant IO sector producing the material. These coefficients cover the complete system boundary for the individual material and are multiplied by physical material quantities to determine their total embodied carbon. However, further work is needed to determine the direct and indirect embodied carbon associated with the building construction process, involving the integration of a range of materials. In this process, a SPA of the construction sector is used to identify and subtract the pathways representing the materials for which embodied carbon has already been quantified, from the total carbon intensity of the construction sector. What remains is the total embodied carbon associated with the construction process as well as any other minor materials not previously covered (Crawford 2011a).

Studies using this method have demonstrated the degree to which alternative methods that rely on a more limited system boundary may underestimate environmental flows. For example, an embodied energy analysis using the PXC method of a range of different building types showed that on average 64% of energy inputs would be excluded with the use of a process analysis (Crawford 2008).

There is a growing awareness of the benefits that a hybrid approach to accounting for embodied carbon (as well as other environmental flows) brings and hybrid analyses are becoming more common. However, there is still much work to do in its development and broad accessibility. There is a need to address the remaining limitations of hybrid analysis, many of which are inherited from process and IO approaches. There is also a range of conflicting interpretations of the hybrid analysis definition. This does nothing but create further confusion about how a hybrid analysis can be used to address the limitations of traditional embodied carbon accounting methods. A consistent, widely recognised and used definition and framework for the different hybrid methods is therefore urgently needed.

Future direction

Australian researchers continue to be at the forefront of the development of MRIO analysis and hybrid analysis. A large group of researchers from a range of Australian research institutions continue to develop and strengthen the capabilities of the Australian IELab. This work has already led to the establishment of work on an IELab for China and Indonesia (Faturay *et al.* 2017). This is part of a larger collaborative effort to establish a global IELab covering the entire world. This global IELab will integrate data from existing MRIO databases, such as WIOD, EXIOBASE and Eora, providing high-resolution, time series, automated updating, hybridisation and analytical tools. The functional capabilities will be expanded as well as the number of countries covered and product and process-level resolution will be improved. Irrespective of this, process data is still considered to be more reliable and AusLCI and BP LCI databases will need to continue to evolve with new materials and processes being added as data becomes available.

A number of projects are underway that will help with improving access to, and the application of hybrid embodied carbon analysis, particularly using the PXC method (Crawford *et al.* 2017b). A key component of this work is an attempt to automate the path exchange process to help with both the speed and usability of the PXC method (Crawford *et al.* 2017a). By linking this to the IELab it will also enable an analysis of embodied carbon at a much higher sectoral resolution than is currently possible. Automatic updating of process data used within the model will ensure the latest data is being used. Work is also being done to compile a detailed list of hybrid embodied carbon coefficients for Australian construction materials based on the latest available process and IO data that is also able to be easily updated in a semi-automated fashion. Given the global trade of materials, links to global databases, such as ecoinvent are also integral to this model.

Researchers are also in the process of defining a set of consistent terminologies and mathematical notations for the different approaches to hybrid analysis. The universal acceptance and use of these definitions may help with easing some of the confusion around existing hybrid methods and support their broader use.

The role of policy and voluntary certifications in building embodied carbon mitigation in Australia

As the operation of buildings represents over one third of final energy use, globally (IEA 2015), and 27% of total energy use in Australia (Brandon and Lombardi 2011), building regulations and certifications have been predominately focused on reducing operational carbon, particularly in relation to energy demand for heating and cooling. Energy efficiency regulations generally date back to the aftermath of the 1973 oil crisis (Nässén and Holmberg 2005) and have since evolved dramatically, both in requirements (e.g. *PassivHaus* (Contributors of passipedia.passiv.de 2013)) and in geographic coverage (OECD/IEA 2015). However, despite continuous improvement in these regulations and certifications, and their contribution to reducing operational energy and associated greenhouse gas emissions, they still broadly fail to consider embodied carbon (García-Casals 2006; Szalay 2007; Blengini and Di Carlo 2010; Stephan and Crawford 2014, 2016).

In this section, current building energy efficiency regulations and certifications in Australia are reviewed with a focus on those attempting to capture embodied requirements. Guidelines for possible future life cycle energy and carbon regulations are then discussed.

Current status

Australia's current building energy efficiency regulations are part of the Building Code of Australia (BCA), which enforces maximum heating and cooling energy demands (per square metre of useful area) for new buildings and significant modifications to existing buildings (ABCB 2016). For residential buildings, compliance with the regulatory requirements is most commonly demonstrated through the Nationwide House Energy Rating Scheme (NatHERS), which provides a 'star rating' for a building, ranging from zero stars (very poor) to 10 stars (zero thermal operational energy). The current minimum performance level that must be achieved is six stars, which allows a maximum of 114 $MJ/(m^2 \cdot a)$ for heating and cooling in Melbourne's temperate climate (NatHERS

2003). Apart from its mandatory nature, the strengths of this scheme include a very high climatic resolution and the fact that it corrects for house size.

The heating and cooling demands for a building depend largely on the climate zone in which it is located. Unlike other energy efficiency schemes that typically rely on a limited number of climate zones to define maximum energy use thresholds, e.g. Germany: a single climate zone, France: two climate zones; Spain: five climate zones (Rodríguez-Soria *et al.* 2014), Australia relies on 69 different climate zones that provide a very high climatic resolution. This is one of the key strengths of the current Australian operational energy efficiency regulations.

Secondly, the star rating scheme for residential buildings takes into account building size when determining heating and cooling requirements (Delsante 2005). This is critical in order to avoid the typical effect of smaller buildings being penalised, as larger buildings will often result in lower energy use per square metre. If anything, smaller buildings should be encouraged as they tend to result in much lower overall energy use and embodied energy and carbon per capita, as demonstrated by Stephan and Crawford (2016). The majority of operational energy efficiency regulations do not correct for building size.

However, despite these two strong attributes, the star rating scheme is far from being able to effectively reduce the life cycle energy demand and carbon of buildings. Crawford *et al.* (2016) quantified the life cycle energy benefits resulting from improving the star rating of typical houses in the Australian cities of Melbourne and Brisbane, either through improved thermal performance of the building envelope or through improved design. They found that simply increasing the thermal performance of the envelope can result in increased life cycle energy demand due to the embodied energy in insulation and high performance glazing. This supports the findings of Stephan *et al.* (2013a) related to a *PassivHaus* in Belgium and makes a case for including embodied energy and carbon in building energy efficiency regulations and certifications. Recent developments in the Australian building industry tend to point towards this same conclusion, notably the Materials Life Cycle Impacts credit in the Green Star certification, and the planned National Carbon Offset Standard for Buildings.

Green Star is a voluntary green building certification scheme (see GBCA (2015a) for more information), developed and managed by the Green Building Council of Australia (GBCA). Like its more famous US (Leadership in Energy and Environmental Design - LEED) and UK (Building Research Establishment Environmental Assessment Method - BREEAM) counterparts, it uses a score-based system to rank the environmental performance of construction projects across a range of categories. Green Star ranks a building across nine categories: management, indoor environmental quality, energy, transport, water, materials, land use, ecology, and emissions. One of the most recent features of Green Star is its incorporation of a life cycle assessment (LCA) credit and its use of environmental product declarations (EPD) as a tool to prove the environmental credentials of materials.

Since 2015, Green Star has included a Material Life Cycle Impacts credit in its scoring system, providing up to 7-8 points of a possible 100. It includes six points if a comparative LCA of the building is conducted, comparing it to a standard building of the same typology. This LCA must: (1) include six impact categories (including global warming potential), (2) be conducted by a professional LCA practitioner, (3) be peer-reviewed, and (4) be performed according to the International Standard 14040 (2006). Including five additional environmental impact categories can earn the applicant an additional point on top of the six base points for the comparative LCA. Alternatively to the comparative LCA, 3 points can be awarded for a reduced use of concrete and Portland cement, 1 point for reducing steel use and 4 other points for reusing existing materials on site where possible (i.e. retaining a façade or structure). This can bring the total points of the Materials Life Cycle Impacts credit to 8. In addition to this credit, up to 3 points can be earned for using responsible building materials. This credit focuses mostly on the use of recycled materials (such as steel), of certified and sustainably-sourced timber, and of permanent formwork that is free of polyvinyl chloride (PVC).

The total possible points awarded for LCA-related attributes in a Green Star building project therefore totals 10-11% which is significant and underlines the importance of LCA in the eyes of the GBCA. This is further supported by their statement:

> "The LCA and EPD initiatives in Green Star will be a catalyst for greater LCA use and the generation of life cycle data, both of which will improve the sustainability outcomes in the built environment." (GBCA 2015b).

However, while the inclusion of LCA-based credits in a green building certification may help support the uptake of the consideration of embodied carbon, it is not enough to address the issue. Certified green buildings represent a negligible fraction of total construction activity, in Australia and elsewhere. For instance, the reported 21 million m² of floor area of certified Green Star buildings since 2004 (GBCA 2017) represent less than 7% of the built floor area of new houses built in Australia since 2004 (excluding apartments and non-residential buildings) (ABS 2016a). This figure is much lower when all construction activity is considered. Furthermore, the voluntary nature of green building certifications does not help support a broad market penetration. In addition, the methods prescribed by the GBCA typically rely on process analysis which systematically underestimates embodied carbon (as highlighted in the previous section). A more comprehensive approach to the consideration of embodied carbon within the construction industry is needed.

Beyond the star rating scheme and the GBCA's LCA credits which are developed solely for buildings, other certifications can also play a role in reducing carbon in the Australian construction industry. This is the case for voluntary 'carbon neutral' certifications that were originally developed for consumer products and are being adapted to buildings. Such certifications typically include embodied carbon although the proposed Australian National Carbon Offset Standard for Buildings does not at this stage.

The Australian National Carbon Offset Standard, overrides its predecessor, the Greenhouse Friendly scheme (DEE 2017), which promoted low-carbon products in Australia from 2001 to 2010. The draft standard for buildings, which is currently in its final draft phase (DEE/NCOS 2016) states that Scope 1-3 greenhouse gas emissions (WRI/WBCSD 2011) should be considered. These are: Scope 1: direct emissions within the building's boundary, Scope 2: emissions associated with energy production outside the boundary but linked to activities in the building (typically electricity demand and heating) and Scope 3: all other indirect emissions. For instance, the standard mentions that emissions from transportation should be considered but that this is currently not possible due to a lack of data. Including user transport-related emissions is praiseworthy as these typically represent one third of the life cycle emissions of a residential building (Stephan and Crawford 2014) or precinct (Stephan *et al.* 2013b). However, while Scope 3 emissions would consider the embodied carbon in building materials, the draft standard explicitly states that:

> "A building's embodied emissions (including energy associated with materials introduced through renovation, fit out or upgrade) are not considered part of a building's operational carbon account and is not covered by the Standard. Embodied energy may be considered for future versions of the standard that apply to building construction." (DEE/NCOS 2016).

In other words, embodied carbon in building materials is not considered by a voluntary standard that aims to lead to 'carbon-neutral' buildings. This could be addressed by simply including embodied carbon in the standard and considering the entire life cycle at once, instead of separating the construction stage from the operational stage.

Towards embodied carbon regulations for Australia

Developing a building regulation that includes embodied carbon is a challenging endeavour, highlighted by a lack of existing schemes, globally. One of the rare (if not the only) regulation targeting embodied environmental requirements in buildings can be found in The Netherlands, as discussed by de Klijn-Chevalerias and Javed (2017). This pilot regulation converts embodied environmental requirements into a so-called 'shadow cost' expressed in euros/m² of floor area. A maximum value for the shadow cost of new buildings (similar to the maximum energy use per square metre set by some operational energy efficiency standards) is specified. While the calculation of the shadow cost relies on weighting different life cycle impact categories and on a database of underestimated environmental impacts of materials that is derived using process analysis, this pilot scheme sets a precedent in terms of implementing regulations that target embodied requirements. However, the lack of a standard life cycle inventory technique and system boundaries (Dixit *et al.* 2013) further complicates the widespread adoption of regulations addressing embodied carbon. Despite these limitations, multiple existing studies could be used to inform the development of a pilot life cycle energy efficiency and carbon regulation for buildings. This regulation would need to be developed in consultation with relevant industry stakeholders and further improved based on continuous feedback, as has been the case with operational energy efficiency regulations.

The work of the CEN/TC 350 and the multiple associated standards (notably European Standard 15643-2 (2011) and European Standard 15978 (2011)) should be capitalised upon in any new regulation. However, these standards do not mandate the use of a particular life cycle inventory technique. The use of a PXC hybrid analysis would provide the most comprehensive system boundaries while using the most reliable data where possible (Treloar 1997; Suh *et al.* 2004; Crawford 2008; Majeau-Bettez *et al.* 2011; Dixit *et al.* 2013). In addition, multiple functional units should be used to provide a variety of perspectives, including kgCO_2-e/m² for efficiency, kgCO_2-e for total global warming potential, and kgCO_2-e per occupant/user to capture the lifestyle/behaviour of occupants/users, based on recommendations from Calwell (2010) and Stephan *et al.* (2012). Furthermore, Stephan and Crawford (2016) have revealed the significance of considering house size in regulations. Notably, vertical and horizontal construction assemblies contribute differently to the embodied carbon of a building, depending on its size, and should therefore be targeted accordingly within regulations addressing embodied carbon. Regulations should also go beyond material choices to support design decisions that improve a building's life cycle carbon performance, as demonstrated by Crawford *et al.* (2016). The National Carbon Offset Standard for Buildings proposal by the Australian Government could easily be adapted to include these aspects and factor in consideration of embodied carbon.

Creating a market value for a reduction in embodied carbon could also provide an incentive for reducing building embodied carbon (Langston and Langston 2008; Ariyarante and Moncaster 2014; Wu *et al.* 2016). A carbon tax or trading system could be possible mechanisms for achieving this.

Regulations that focus on the life cycle environmental performance of buildings, including embodied carbon, are still in their infancy. More research is needed to better understand the relationship between design, building geometry, material choices and embodied carbon. More importantly, a robust and comprehensive database of embodied carbon coefficients for construction materials, based on a consistent, systemically complete assessment framework is needed. Tools for systematically, robustly and easily quantifying the life cycle carbon of buildings are also needed to help support industry in their carbon reduction efforts. The next section describes how the Australian construction industry is currently approaching the implementation of embodied carbon reduction.

What is the Australian construction industry doing to reduce embodied carbon?

With buildings accounting for almost one quarter of Australia's emissions, they represent one of the largest and most attractive opportunities to reduce emissions (Climate Works 2010). So what is Australia, one of the largest emitters of greenhouse gases per capita in the world (Climate Council 2015), currently doing to address these emissions? The previous section highlighted the fact that current Australian policies and energy efficiency regulations deal almost exclusively with operational carbon, leaving embodied carbon largely ignored. Embodied carbon has been demonstrated to represent between 10% (Ibn-Mohammed *et al.* 2013) and 70% (ASBP 2014) of a building's total life cycle carbon and approximately 20% of all carbon emissions in Australia (Schinabeck *et al.* 2016). Thus, it is critical that we consider both embodied and operational carbon in our efforts to improve the environmental performance of buildings. Several data sources and assessment methods exist to help support these efforts (as discussed earlier in this Chapter) and are constantly evolving to further improve their reliability, usefulness and accessibility. This section will provide more detail about what Australia's construction industry is currently doing to reduce embodied carbon and the barriers hindering its more widespread consideration. Four case study buildings that have used a variety of strategies for reducing embodied carbon are briefly discussed.

The state of embodied carbon assessment in Australia's construction industry

When it comes to reducing greenhouse gas emissions, the Australian construction industry is predominantly focused on the operational carbon of buildings. This is highlighted in a recent survey, completed by Fouché and Crawford (2015) for the CRC for Low Carbon Living (www.lowcarbonlivingcrc.com.au), which found that over 85% of construction industry consultants focus on providing operational energy/carbon assessment services. In total, 60% of the survey respondents, consisting predominately of LCA practitioners and sustainability consultants, provided a form of embodied carbon assessment. For the organisations that did not provide this service, almost 70% said that they would consider providing embodied carbon assessment as part of their services in the future. This demonstrates that even though the existing building stock is far from achieving carbon neutrality (Schinabeck *et al.* 2016), there is an increasing awareness of the need to address more than just operational carbon mitigation.

Compared to operational carbon assessment, 30% more of the respondents outsourced their embodied carbon assessment. This was found to be due to a lack of tools specific to the Australian context, lack of in-house expertise and concerns about reliability of data. When asked what software tools get used for embodied carbon assessment, eToolLCD (etoolglobal.com), a building-specific LCA tool developed in Australia, was only 4% less commonly used than SimaPro (simapro.com), the most popular LCA tool. There seemed to be an interest for locally developed tools and the need to address the weaknesses in existing data and tools available for embodied carbon assessment. These weaknesses include a lack of Australian specific data, inconsistent methodologies, time intensive assessments, need for expert knowledge, lack of benchmarks and compatibility with building information models (BIM). This emphasises the importance of the work discussed earlier in developing more detailed MRIO databases and hybrid embodied carbon coefficients for Australia. When asked to indicate the top features desired in new or improved embodied carbon assessment tools, over 80% selected ‘material cost’ as the most beneficial feature followed by data on recycled materials (62%) and the source of materials (57%). Other recommendations included adherence to Australian regulations and standards, options for quick analysis, integration with existing tools, ease of updating, and more transparency and consistency. This survey highlighted that the Australian construction industry seems to be interested in reducing the embodied carbon of buildings. The next four exemplar case studies provide practical examples of buildings where embodied carbon has been a key consideration.

5x4 Hayes Lane Project, Melbourne

Figure 1: 5x4 Hayes Lane. Source: Ralph Alphonso.

The 5x4 Hayes Lane Project is an inner city dwelling, completed in June 2015, set on a small footprint of 5x4 metres in East Melbourne. One of the key design strategies was to minimise the building's life cycle carbon, with the help of both passive and active measures. Driven by the One Planet Living principles (Bioregional 2015), which encouraged, amongst other things, the use of low embodied energy materials that are locally sourced and made from renewable or waste sources, an environmentally exemplar dwelling was created. The embodied carbon of eleven different floor assemblies and fifty-two different wall assemblies were analysed over a 100-year period with the use of the PXC hybrid method. The results were used to inform the selection of these building elements and identify strategies for further embodied carbon reductions. The project made use of phase change materials, timber from sustainably harvested forests, and focused on sourcing local materials where possible. Most of the superstructure was prefabricated off-site, which can help reduce the time, waste and cost of a project (Moncaster and Song 2012). This, in turn, can lead to embodied carbon reductions due to greater production and material efficiencies (Sturgis and Roberts 2010). This building acts as an educational tool with information publically available (the occupant's operational carbon emissions are monitored and shared online – www.5x4.com.au) and can be used as a vehicle to showcase, demonstrate and inform the practical incarnation of a carbon conscious building (Johnson 2014).

Forte, Melbourne


Figure 2: Forte. Source: Lend Lease (2012).

Forte is a 10-storey apartment building, containing 23 apartments located in Melbourne's Docklands precinct. At 32.2 metres tall, and constructed of cross-laminated timber (CLT), it was until 2017 the worlds' tallest modern timber apartment building (Wood Solutions 2013). It was also the first CLT building in Australia. While local production of CLT did not exist at the time and the CLT panels had to be imported from Austria, which increased the transport-related embodied carbon, timber has a lower embodied carbon content than other materials such as concrete and steel, which would typically be used for a building of this type (Milne and Reardon 2013). The lighter weight of the structure also reduced the size of the footing system, leading to further embodied carbon reductions for the building.

Melbourne School of Design, Melbourne


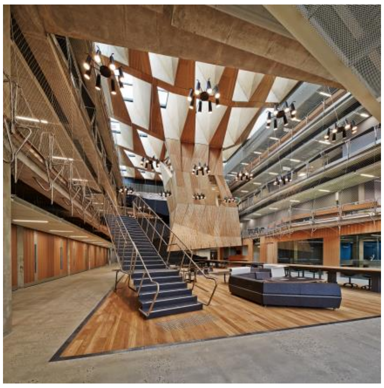

Figure 3: Melbourne School of Design. Source: John Gollings/Peter Bennetts.

The Melbourne School of Design building is an education building completed in 2014 at the centre of the University of Melbourne's Parkville campus. This 6-Star Green Star-rated building's entire roof is constructed from Laminated Veneer Lumber (LVL) with a long span of 22 metres across the atrium. The use of LVL, instead of typical roofing materials such as steel, delivers significant environmental benefits, reducing the embodied carbon of the building. Timber has been used extensively elsewhere in the building also, for wall linings, staircases, and floor finishes. Reducing embodied carbon was also a consideration in the selection of the external shading system. Perforated zinc was chosen due to its lower embodied carbon compared to the typical alternative of aluminium (Irwinconsult 2013). One of the keys to the building achieving the highest Green Star rating for an educational building was it being awarded the maximum number of points available for the Materials Life Cycle Impacts credit.

Barangaroo, Sydney

Figure 4: Barangaroo. Source: Title Magazine (2015).

Barangaroo is a 22-hectare precinct development on a former container terminal on the western edge of Sydney Harbour in which embodied carbon mitigation has been a major focus. The project aims to reduce embodied carbon across the entire site by 20% compared to standard construction (Boral 2014). The aim is for the precinct to be climate positive with the stated ambition of being 'Australia's first carbon neutral community'. As concrete represents over a quarter of the embodied carbon of the project and the cement binder component of this concrete is one of the key contributors (Lend Lease 2014), reduction in the concrete-related embodied carbon was achieved through the use of Supplementary cementitious materials (SCMs), such as fly ash and ground granulated blast furnace slag. The concrete manufacturer also built a tailored onsite batching plant to reduce the transport-related carbon emissions (Lend Lease 2014). The embodied carbon of steel was also reduced with a 20% reduction target in carbon intensity of the reinforcing steel. Another interesting aspect to note was that the tender process also included an embodied carbon awareness element. The embodied carbon performance of different concrete mixes and supply options were assessed and the information was used to inform the selection process. This can be an innovative way of selecting the most appropriate suppliers. In addition, the project has a commitment of carrying out a life cycle assessment on the top 20 materials, in terms of volume, used on site. The project has some ambitious goals as highlighted by the developer:

> "This project is to act as a catalyst for change in the wider industry to help incentivise suppliers to examine the life cycle impacts of their products, encourage the publication of EPD and to support greater collaboration between builders and product suppliers" (Lend Lease 2014).

These case studies demonstrate that from a small residential scale (5x4) to a larger precinct scale (Barangaroo), the Australian construction industry is starting to incorporate strategies for improving the embodied carbon performance of buildings. The next section describes some of the constraints preventing the widespread implementation of more projects of this type.

Current barriers and future direction

Even though Australia has been at the forefront of developments in the field of embodied carbon assessment tools, methodologies and research, the uptake of embodied carbon considerations in practice has been slow. Some of the key barriers affecting this uptake within the construction industry were highlighted in a report published by ASBP (2014) that placed consistency of method at the top of the list followed by availability of comparable data, and mandatory legislation. The inconsistency and lack of availability of comprehensive embodied carbon data is often quoted as a key barrier affecting both embodied carbon and life cycle assessment (Ariyarante and Moncaster 2014; Dixit *et al.* 2015; Schinabeck *et al.*

2016) and was discussed in detail in the first section of this Chapter. The lack of mandatory legislation was described in the previous section. The Australian CRC for Low Carbon Living survey (Fouché and Crawford 2015) identified several other critical barriers such as a lack of project budget (the most prevalent barrier with 60% of the respondent votes), client disinterest and no clear profit incentive. The effect of budgetary constraints on the uptake of embodied carbon considerations was also identified by Ariyarante and Moncaster (2014); Langston and Langston (2008) and Wu *et al.* (2016). These studies emphasise that the cost of embodied carbon reduction is not well understood and more research is required to gain further understanding as to the role of financial cost in embodied and life cycle carbon reduction.

Conclusions

This Chapter has provided an overview of Australia's contribution to addressing embodied carbon, from a methodological, policy and implementation perspective. Despite the relative insignificance of building embodied carbon in Australia, in a global context, the country has played a pivotal role in the methodological developments underpinning some of the more sophisticated approaches for quantifying embodied carbon, and our growing understanding of its significance. An increase in the uptake of more comprehensive embodied carbon assessment methods, such as MRIO analysis and the PXC hybrid method is needed and will help to ensure that our carbon mitigation efforts are appropriately targeted. These developments also highlight the need for further work such as improving the quality and completeness of data, and improving access to information and tools that support embodied carbon mitigation.

While historically, policy and regulatory-based approaches to mitigating carbon in Australia have focused on building operation, recent developments in green building certifications and policy-based discussions have starting to consider embodied carbon. The National Carbon Offset Standard for Buildings that is currently being developed is a much needed framework for carbon accounting for buildings. Its contribution could be significantly enhanced with the inclusion of embodied carbon, something that it does not yet address. Whether it is this standard or something else, there is a pressing need for a mandatory scheme that enforces robust designs that aim to reduce the life cycle carbon of buildings. With no regulatory drivers, embodied carbon considerations are currently entirely voluntary within the Australian construction industry. The lack of awareness of embodied carbon amongst construction clients and construction industry professionals does nothing to encourage more than what is currently a very rare and piecemeal approach to mitigating embodied carbon.

Exemplar buildings are starting to emerge, much the way they did when addressing building operational carbon became a priority. Regulations, education, financial incentives and improved industry practices have made the consideration of operational carbon an integral part of the building design process, in most cases. These same strategies are likely to be needed to ensure embodied carbon mitigation is seen as an equally important part of the building design process.

While Australian researchers are contributing to world-leading methodological advancements in embodied carbon assessment, its application and the implementation of initiatives targeting embodied carbon reduction generally lag behind many other regions of the world. In light of this, a case exists for greater sharing and collaboration across global boundaries to accelerate the management and mitigation of embodied carbon within Australia's buildings. International collaborations are also critical to ensure consistency in data collection and embodied carbon assessment, but also to help facilitate the integration of data, enabling modelling of global supply chains.

Even though there is still much to be learnt about embodied carbon in buildings, we are no longer able to ignore it. There is enough evidence to show that limiting our efforts to operational carbon will not lead to the considerable carbon savings that are needed to address the pressing environmental challenges of our day. A more holistic approach is needed, one that has the ultimate aim of creating buildings that are 'net-positive life cycle carbon'.

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