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Embodied carbon: A framework for prioritizing and reducing emissions in the building industry

Natalie C. Wheating
nwheating@dons.usfca.edu

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This Master's Project

Embodied carbon: A framework for prioritizing and reducing emissions in the building industry

by

Natalie Wheating

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ABSTRACT

Global climate change is one of the most impactful environmental issues in modern times, and the construction industry is known to be one of the largest contributors to carbon emissions—one of the key causes of climate change. Embodied carbon emissions of buildings are an often overlooked, but significant, influencer of a building's overall carbon footprint. This gives rise to the need for improved life cycle analysis of buildings and identification of opportunities to reduce the total carbon footprint of a building throughout its life cycle. This paper analyzes the current state of the building industry that limits the consideration of reducing embodied carbon in buildings, evaluates opportunities available for identifying low embodied carbon strategies, and offers recommendations for manufacturing optimization, construction best practices, and policy framework implementation to appropriately integrate consideration of all carbon emissions in construction to reduce the overall carbon footprint of the building industry. For successful reduction of embodied carbon, streamlined assessment models must be established and policy must be implemented, in order to encourage innovation for carbon footprint reduction in the marketplace. Proper collaboration, communication, and education are critical for effective, overall carbon reduction.

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List of Acronyms

AIA	American Institute of Architects
AWJV	Austin-Webcor Joint Venture
BIM	Building Information Modeling
BREEAM	Building Research Establishment Environmental Assessment Method
BFS	Blast-furnace Slag
CCI	Construction Carbon Index
CY	Cubic Yard
CO2	Carbon Dioxide
EPD	Environmental Product Declarations
EPA	Environmental Protection Agency
FA	Fly-ash
GBR	Green Building Rating
GHG	Greenhouse Gas
GPP	Green Public Procurement
GWP	Global Warming Potential
ICE	Inventory of Carbon and Energy
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Lifecycle Assessment
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
OPC	Ordinary Portland Cement
PCR	Product Category Rule
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal
SCM	Supplementary Cementitious Material
SFO T1 BAB	San Francisco International Airport Terminal 1 Boarding Area B
UK	United Kingdom
USGBC	United States Green Buildings Council
WBLCA	Whole Building Life Cycle Assessment
WRAP	Waste & Resources Action Program

Introduction

People and Climate

The climate is changing and humans are driving it. A 2014 synthesis report released by the Intergovernmental Panel on Climate Change (IPCC) explained it simply:

"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (IPCC, 2014).

The warming of the globe in response to the increased greenhouse gases in the atmosphere is resulting in a variety of environmental impacts across the globe, including the melting of artic sea ice, glaciers, snow cover and permafrost, altered plant and animal life cycle events due to changed annual temperatures, causing a decoupling in species relationships such as predator-prey dynamics or plant seed distribution and animal migratory patterns (IPCC, 2007). Climate change is not only threatening wildlife populations (IPCC, 2007). The rising sea level, storm surges, heat waves, and extreme weather events pose significant risks to human dependent economies and systems as well (NASA, 2017). More frequent and severe weather events threaten to destabilize essential components of human livelihood, including food production, transportation, infrastructure, and water management, leading to disease, displacement, economic hardship, and death thereafter (Ternberth, Meehl, Masters, & Somerville, 2017).

Reducing Anthropogenic Factors

The impacts of climate change have become exacerbated in recent years. For example, with the 2003 European heat wave, the 2005 hurricane season in the North Atlantic, and the severe droughts in Australia and California (Samson, Berteaux, Mcgill, & Humphries, 2011). These natural disasters have sparked public interest in understanding the role of global warming in driving extreme weather (Ternberth et al., 2017) and mobilized populations to take action to mitigate and reduce anthropogenic contributions to climate change (IPCC, 2007). By understanding that greenhouse gas emissions are the driving force behind climate change and global warming, the public has begun reflecting on major sources of greenhouse gas emissions by industry sector and identifying opportunities for emissions reduction strategies within each sector (Y. Chen & Ng, 2015). GHGs mainly comprise six gases with global warming effects: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), with carbon dioxide, methane and nitrous oxide together accounting for about 97% of total global warming potential (Akbarnezhad & Xiao, 2017). Industry contribution to greenhouse gas emissions can take place directly, through direct emissions of greenhouse gasses to the atmosphere, or indirectly, through consumption of resources that require the emission of greenhouse gases, the most important resource being energy and electricity, which is commonly produced from fossil fuel, a major source of greenhouse gas emissions (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013).

From these assessments, the building sector revealed itself to be one of the largest sources of anthropogenic greenhouse gas emissions (Ibn-Mohammed et al., 2013). Studies assessing the impact of buildings globally have shown that they account for more than 40% of total energy use (Ahn, Lee, Peña-Mora, & Abourizk, 2010) and 20-40% of greenhouse (GHG) emissions (Abd Rashid & Yusoff, 2015). Cities in particular serve as focus points for mitigating climate change, as they occupy only 2% of the Earth’s surface but use 75% of all human consumed resources and generate 75% of all waste (Lugaric & Krajcar, 2016). It is projected that by 2050, almost 70% of the world population will live in cities that carry a tributary footprint over 50x as large as their own size (Kiss, Jansen, Castaldo, & Orsi, 2015). Without major improvements in buildings’ energy efficiency, the current surge of urbanization could lead to a doubling of GHG emissions associated with the building and construction industry in the next 20 years (Akbarnezhad & Xiao, 2017). Given the significant role that buildings play in GHG emissions and ultimately contributing to climate change, buildings serve as a major opportunity for emissions reduction strategies, mitigating anthropogenic contributions to climate change.

The Lifecycle of Buildings and Overlooked Impacts

The first step in carbon footprint reduction in buildings comes from determining the total impact of a building and identifying where and when the major sources of GHG emissions take place. In order to facilitate comparison and comprehensive reporting when accounting for the total global warming potential (GWP) of a given process, all greenhouse gas GWP values are combined and converted into a single carbon equivalent value (Akbarnezhad & Xiao, 2017). Additionally, GHG emissions are commonly a byproduct of energy production, and therefore throughout this paper, when studies of carbon or energy are referenced, both terms can be inferred to connect to the emissions of all relevant greenhouse gases and their contribution to climate change.

Whole building life cycle analysis is a commonly used approach for analyzing building impacts. Life cycle analysis is a holistic approach for analyzing all inputs and outputs of a given product, process or activity, encompassing extraction and processing of raw materials; manufacturing, transport and distribution; re-use; maintenance recycling and final disposal (Thormark, 2002). Life cycle analysis can be used to assess the environmental burdens associated with designing and operating a supply chain which ultimately tie to a building's footprint (Bojarski, Laínez, Espuña, & Puigjaner, 2009). The International Organization for Standardization (ISO) has created a harmonization of methods and procedures, known as the ISO 14040 standard series, that has resulted in a generally consistent methodological framework for assessment, making it easier to compare different LCAs (Buyle, Braet, & Audenaert, 2013). In response to a whole building lifecycle assessment, two approaches can be carried out for reducing a building's total impact: comparison/selection in materials and improvement of design (Bojarski et al., 2009).

A breakdown of energy consumption in various phases of a building's life can be observed in Figure 1. As previously mentioned, energy consumption can be closely tied to greenhouse gas emissions, and addressing the amount of energy used during each stage of a building's lifecycle can directly reflect the amount of GHG emissions tied with that phase. The lifecycle energy footprint of a building can be broken into two major parts: embodied energy and operating energy. Embodied energy can be characterized as the energy consumed in the development of a building to its functional state (Schinabeck & Wiedmann, 2014). This includes energy consumed in materials' extraction, production and delivery to the construction site, the energy consumed from construction of the building, as well as 'recurrent' embodied energy used in the maintenance and refurbishing processes of the building and disposing of materials (Franzoni, 2011). The operating energy of a building's lifecycle is linked to the energy emissions during the occupation phase of the building through ongoing operations (Eleftheriadis, Mumovic, & Greening, 2017). This includes the energy used for the building's active systems such as heating, cooling, lighting, ventilation, and equipment use (Eleftheriadis et al., 2017). The operational impacts accumulate over time and can be significantly influenced by occupants' pattern of energy use and systems' efficiencies, while embodied energy values are identified in processes that often take place offsite and contribute to the lifecycle footprint of a building in one single value (Eleftheriadis et al., 2017).

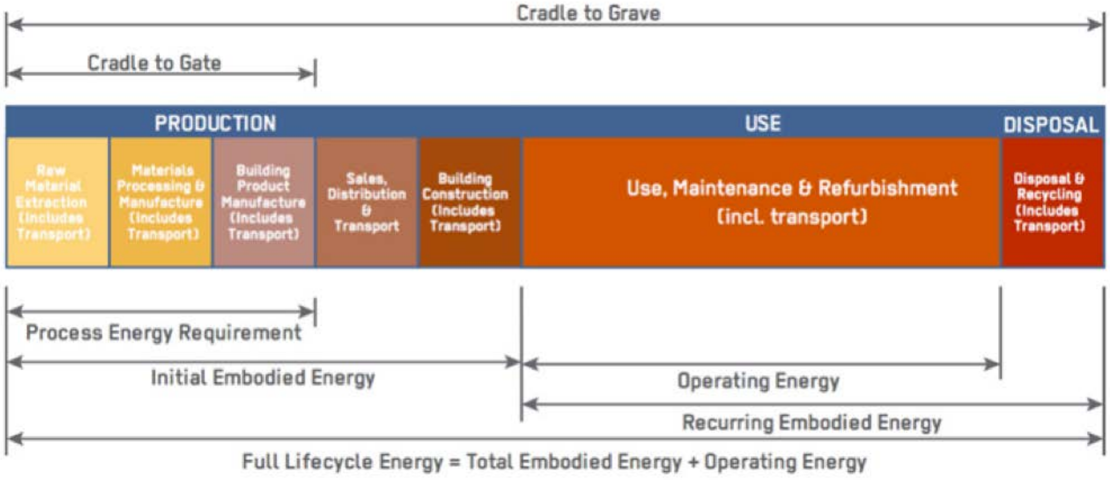


Figure 1 Energy Requirements (and associated carbon emissions) of buildings by life cycle stage (Schinabeck & Wiedmann, 2014).

To date, the building industry has prioritized improving the operational stage of a building's life cycle (i.e. increasing efficiencies and performance), however a significant portion of carbon emissions throughout a building's lifecycle occurs before any activity takes place on the project construction site (Copiello, 2016). The initial embodied energy from building materials in a single-story building could account for up to 67% of its operating energy in or over a 25 year period (J. Wu, 2014) and current research indicates that up to 30% of buildings' life cycle emissions can be minimized through the careful selection of low-carbon materials (Y. Chen & Ng, 2015). As technology advances continue to improve the energy efficiency of buildings by reducing energy demands during their operational stage, the embodied energy of the materials that make up these buildings becomes an even greater portion of a building's total carbon footprint (X. Zhao, Pan, & Lu, 2016). Even while building materials are known to contribute to a significant portion of a building's carbon footprint and carbon has been recognized as a leading contributor to climate change, current building material procurement processes and green building rating systems do not account for embodied carbon or total carbon emissions within a building's lifetime (Lee, Trcka, & Hensen, 2011). Given the significance of carbon emissions and the scale in which the building and construction sector contributes to these emissions, there exists a gap in accounting for the total impact that building materials have on buildings' lifecycles, as well as their environmental impact as a whole.

Study Approach and Objectives

The purpose of this paper is to investigate the value that embodied carbon holds in the total lifecycle carbon emissions of buildings and identify opportunities to improve assessment methods and reduce the overall footprint of buildings and their contribution to anthropogenic greenhouse gas emissions. To provide context in regards to the current state of the building industry, this paper will provide a brief overview of the history of the development of sustainability in buildings. This paper aims to address the current state of tools available for proper carbon footprint assessment, project delivery methods, stakeholder dynamics, and policies and programs to identify challenges and opportunities for process improvement to better incorporate and prioritize reducing embodied carbon throughout the lifecycle of a building. The outcome of this research is intended to help frame future policy and programs around integrating embodied carbon considerations into building construction decision making processes and best practices. To note, this paper is focused solely on the impact that a building has as it is related to greenhouse gas emissions and contribution to climate change. Reasonably, there are numerous other factors that must be considered when constructing a building, and there are many other areas that require further investigation for optimization, such as human health impacts of building materials, environmental impacts of land management and development, product pollution in their life cycle, and much more. Some of these additional aspects will be touched on throughout this paper, but the purpose of this research is focused on greenhouse gas emissions due to buildings and opportunities to mitigate buildings' contribution to climate change.

The History of Sustainable Buildings

In the timeline for the history of development and construction practices, sustainable design and construction is a relatively new concept. It was first coined by the Bruntland Commission in 1987, and was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their needs" (Vyas & Jha, 2017). In the three decades since then, sustainable construction has gained momentum, changing the physical structures and working principles of organizations, and impelling professionals engaged in all phases of building process to rethink their roles in the building delivery process (Alvarez & Rubio, 2015).

Green building practices have largely fluctuated in popularity in response to political climates at the time. For example, the higher fuel costs resulting from the oil embargo in the 1970s pushed the American Institute of Architects (AIA) to form a Committee on Energy aimed at developing both passive building designs, such as reflective materials to reduce lighting, and technological solutions, such as the use of triple-glazed windows to reduce air conditioning and heating costs (The Marble Institute, 2017). When energy concerns subsided, the momentum behind green building slowed as well, but architecture firms and advocates continued improving the efficiency of solar panels, water reclamation systems, daylighting strategies and more. These advances and discoveries for improving energy efficiencies for a building's operations continued through modern times (The Marble Institute, 2017). Conceptually, green buildings could provide users with healthy, comfortable living, working and activity space, while implementing efficient use of resources and minimal impact on the environment (D. X. Zhao, He, Johnson, & Mou, 2015).

Developing Green Building Standards

In response to increasing demand for sustainable buildings, a large number of building environmental assessment and green building rating (GBR) tools were created to better identify best practices in green building construction (Zhong & Wu, 2015). In 1990, the first GBR system was established in the United Kingdom, Building Research Establishment Environmental Assessment Method (BREEAM), followed shortly after by the Leadership in Energy and Environmental Design (LEED) in the United States (D. X. Zhao et al., 2015). Many countries thereafter established similar GBR systems, including Green Star in Australia, Hong Kong Building Environmental Assessment Method (BEAM-Plus), Singapore Green Mark, and Green Globe in Canada (Zhong & Wu, 2015). LEED has been the most widely adopted GBR system across the globe, with certified projects in over 162 countries (McCadden, 2016). GBR tools provide a comprehensive assessment of various environmental impacts of buildings through the evaluation of performance of on-site management, energy efficiency, air and atmosphere, materials, water efficiency, indoor environmental quality, transport, global warming, waste and pollution, ecology and more (Y. Chen & Ng, 2015). These GBR systems have been able to facilitate sustainable design processes by providing individual assessment tools in which strategies used to improve sustainability of buildings can be evaluated according to a common set of rules (Lee et al., 2011).

The Overlooked Significance of Embodied Carbon

While significant progress has been made in the sustainable building industry in reducing building energy consumption, there are still prominent flaws in the practice and opportunities for improvement. In the efforts to reduce energy consumption from buildings, the majority of research and influential policies has been focused on improving the operational energy of a building's life cycle with little regard for its embodied energy (Copiello, 2016). Practical measures have included energy efficiency improvement from the demand side through efficient building services equipment, improved thermal insulation, and changing users' behavior (Y. Chen & Ng, 2015). However, a significant portion of carbon emissions from a building's life cycle occurs before any activity takes place on a construction site (Copiello, 2016). The distribution of embodied carbon versus operational carbon can vary greatly depending on the building type and function (Akbarnezhad & Xiao, 2017). The embodied carbon of conventional buildings has been reported to vary from as low as 20% of the total building lifecycle carbon footprint to as high as 80% in low-energy buildings like warehouses (Akbarnezhad & Xiao, 2017). In a study of a single-story building over a 25-year period, Wu (2014) determined that the initial embodied energy from building materials could account for up to 67% of its operating energy. In a study of low-energy houses, the share of embodied energy was reported up to 40-60% of the total lifecycle (Akbarnezhad & Xiao, 2017). Chen and Ng (2015) determined that up to 30% of buildings' life cycle emissions can be minimized through the careful selection of low-carbon materials.

The focus on improving only the operational energy of a building can lead to negative impacts of the embodied energy of the building's lifecycle. The more energy efficient a building can be, the greater the impact embodied energy can have on a building. For example, a high-efficiency apartment housing project in Sweden revealed that embodied energy accounted for 45% of the building's total energy over a life span of 50 years (Copiello, 2016). Additionally, a separate study of 97 apartment-type buildings in Portugal discovered that the embodied energy of the buildings was estimated to be nearly four times the operational energy for a service life of 50 years (Pacheco-Torgal, 2014).

Additionally, case studies have revealed that the more complex a building is, the higher embodied energy it contains. This trade off can be seen in several building types in Figure 2 below. A case study analysis performed within the Belgian context revealed that a passive house model may be responsible for an embodied energy far higher than the operating energy, about two-fold higher, revealing that careful consideration must take place when reviewing materials for procurement (Copiello, 2016).

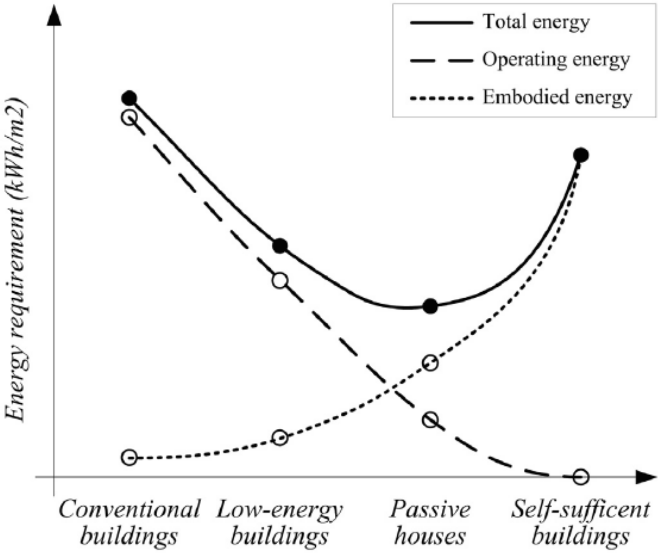


Figure 2 The trade-off between embodied and operating energy for several kinds of buildings (Copiello, 2016)

Unlike operational carbon emissions, embodied carbon emissions cannot be reversed. Once they have been released the opportunity for improvement has passed. In contrast, if a building is constructed with poor operational carbon emissions, while not ideal, the building can still be improved at any point in the lifetime of that building, for example by implementing a range of energy efficiency measures (Jones, 2016).

Figure 3 presents a graph of the cumulative energy versus the total operational energy of an average house over a 100-year lifetime (Adams, Connor, & Ochsendorf, 2006). As can be observed, from a 100-year scale, the operational energy footprint of a building is significantly higher than the embodied energy footprint. However, scale must be taken into consideration when looking at a building’s total lifecycle. Regarding operational energy consumption, there is a lot of potential for technological improvements in energy efficiency for building operations. For example, the lighting industry have seen significant improvements in lighting design as lighting technologies have advanced from traditional incandescent to LED light bulbs, the latter being 72% more energy efficient than the former (DOE, 2017). With this understanding, the rate of operational energy consumption is very likely to decrease in time. Additionally, given the level of urgency regarding climate change, it can be widely accepted that immediate actions regarding GHG emission reduction need to be executed in order to mitigate climate *now* (Strain, Simonen, Yang, & Webster, 2017). From the perspective of immediate emissions reduction strategies, looking at the lifecycle impact of a building over ten or twenty years, embodied energy becomes much more significant, and its necessity for consideration and reduction becomes critical.

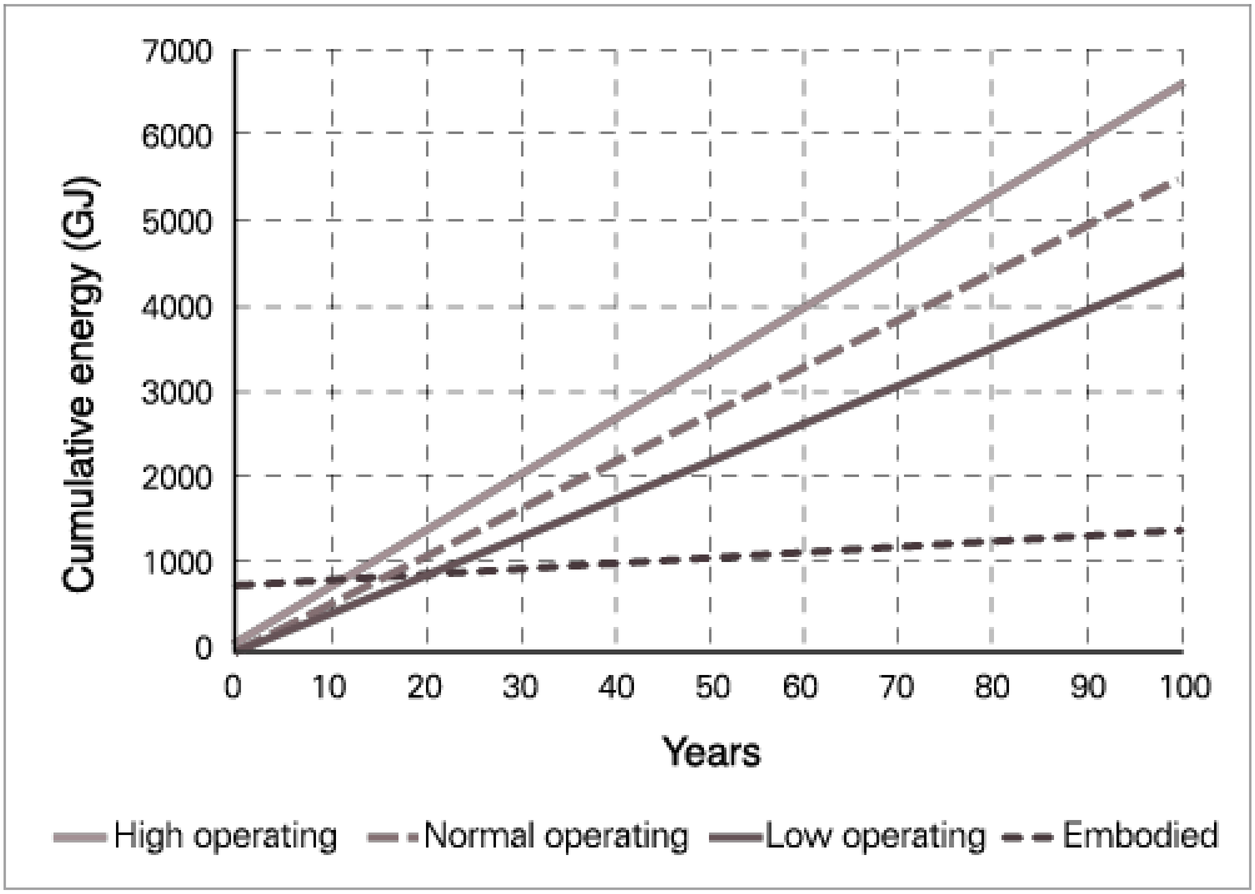


Figure 3 Cumulative comparison of operating and embodied energy of a building over time (Adams et al., 2006)

Missing Priorities in Policy and Rating Systems

Governments around the globe have recognized the importance of reducing GHG emissions, especially in the buildings sector. The Kyoto Protocol of 1997 propelled nations to advance greenhouse gas (GHG) emissions reduction targets to help cope with climate change (Zhong & Wu, 2015). It was understood that the building sector had to be tackled, given their energy- and emission-intensive roles in construction and operation, yet many policies and green building rating systems to date have not sufficiently incorporated embodied carbon (Zhong & Wu, 2015). For example, the European Union has passed the program Horizon 2020 program aimed at promoting smart, sustainable and inclusive growth, emphasizing that “all new buildings will be nearly zero-energy and highly material efficient” (Pacheco-Torgal, 2014). While embodied energy does not explicitly address embodied carbon, the European strategy addressed the overall environmental impact of construction and building materials in the new Construction Products Regulation, which includes energy consumption as well (Pacheco-Torgal, 2014). In the United States, there is very little policy framework benefiting reduced embodied energy in buildings in the same way that operational energy receives benefits, such as power purchase agreements and the American Recovery and Reinvestment Act, which offers financial support for operational energy efficient investments (X. Zhao & Pan, 2015).

Considered robust and comprehensive, green building rating tools such as LEED and BREEAM put much greater emphasis on operational energy consumption. When pursuing certification under LEED, BREEAM, Green Star, and BEAM Plus, the evaluation of materials' embodied GHG emissions are present for credit, but these evaluations are either optional or have low influence over the BEA schemes' overall assessment (Y. Chen & Ng, 2015). Without federal enforcement or certification bodies like LEED prioritizing embodied energy in buildings, the industry will not face the necessary encouragement to pursue preferential procurement for low embodied energy construction materials. Additionally, few current GBR tools provide a comprehensive and systematic assessment to help in low carbon material selection, meaning there is limited guidance for clients on delivering projects in an environmentally friendly way by selecting low-carbon materials (Y. Chen & Ng, 2015).

Poorly Perceived Risk in GHG Emissions and Climate Change

While climate change and its anticipated impacts has become widely accepted among the global population, actions to mitigate climate change have been limited to date. Given the large scale in which climate change can impact the global, the issue of climate change is widely perceived to be a temporally and spatially distant problem (Frondel, Simora, & Sommer, 2016), i.e. few people feel a personal vulnerability to climate change impacts. In survey of young adults in the United States, most participants generally agreed that climate change is occurring and expressed awareness of the consequences and risks associated with the issue, however many of the participants focused more on the impacts that climate change can have on non-humans (i.e. animals and plants), without considering the potential risks to humans, such as dislocation, economic costs, and disease (Besel, Burke, & Christos, 2015). This study revealed that the general perception of climate change impacts was projected onto other recipients but little understanding of the potential risk of climate change impacting the actual survey participants.

Without a personal connection to risk of climate change impacts, society will be far less likely to change its structure in order to be more resilient. Research has shown that the more personal experience individuals have with damages to natural hazards associated with climate change, such as flooding and heat waves, the more strongly individuals perceive climate change as a significant risks and as such, approve more proactive strategies for climate change mitigation (Frondel et al., 2016). Given this understanding, and the understanding that climate change related events will be more frequent and more intense in the coming years due to increased concentrations of greenhouse gases, public advocacy for climate mitigation strategies are more likely to be widespread, pushing industries to restructure their practices to accommodate for such demands and reduce their contribution to GHG emissions in response.

Current State of Embodied Carbon Assessment and Reduction

In recent years, the International Organization for Standardization (ISO) has released four standards describing a framework for investigating sustainability of buildings and the implementation of Environmental Product Declarations (EPDs) (Buyle et al., 2013). EPDs are lifecycle assessment reports that can be conducted for products that disclose several environmental impact values of that product (Ibáñez-Forés, Pacheco-Blanco, Capuz-Rizo, & Bovea, 2016). This information is based on complying with a set of pre-established standard operating rules based on that given product category, known as Product Category Rules (PCRs), making it possible to compare product impacts within a given category (Ibáñez-Forés et al., 2016). One of the values reported in an EPD is the global Warming Potential (GWP) of that product, which is determined by calculating the total GHG emissions of that product in its lifecycle. The International EPD System launched in 1999 and a fair number of PCRs and EPDs have been established since its founding (Ibáñez-Forés et al., 2016). As shown in Figure 4 below, the number of EPDs reported across the globe for construction products has grown significantly in the last ten years, however, as shown in Figure 5, only one construction product in the United States is shown to have an EPD (Ibáñez-Forés et al., 2016). Given that a building can incorporate hundreds of different products when constructed, these numbers reveal that the amount of carbon footprint information available through EPDs is very limited.

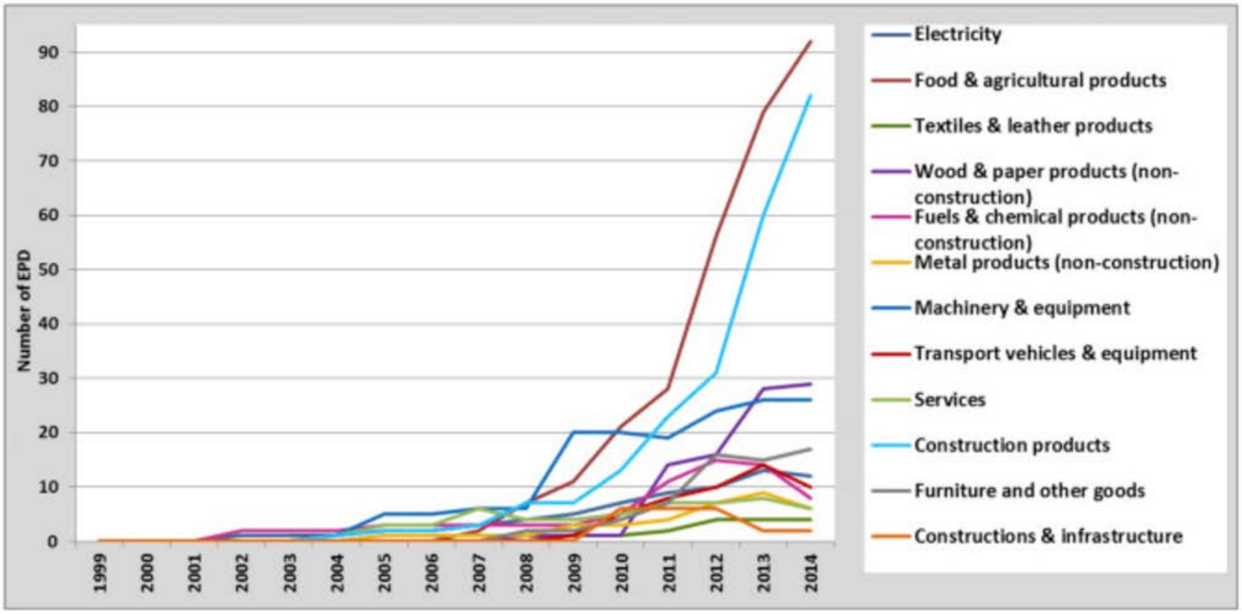


Figure 4 Product EPDs Developed by Industry (Ibáñez-Forés et al., 2016)

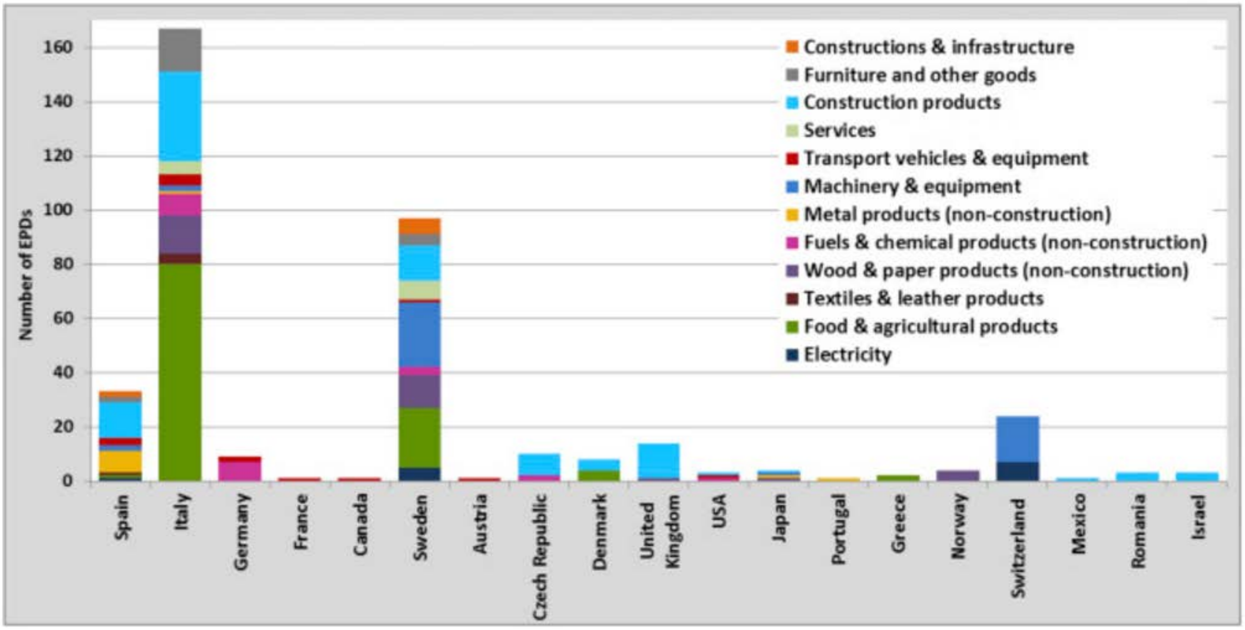


Figure 5 Product EPDs Developed by Country (Ibáñez-Forés et al., 2016)

GBR systems have attempted to better incorporate the issue of embodied carbon into their assessments. In 2013, the U.S. Green Building Council (USGBC) launched LEED Version 4, or LEED v4, its latest scoring system for buildings with several variations in its scoring process from the rating systems in previous version (USGBC, 2017b). The most significant change in the context of embodied carbon, was a restructure of the Materials and Resources credit to incorporate three credits for conducting a whole-building lifecycle assessment and overall reduction, as well as a materials point for acquiring a minimum of 20 EPDs for materials used in the building (USGBC, 2017b). However, when the new rating system was released in 2013, the industry quickly reacted with claims that they weren’t ready to comply with the new requirements, and the USGBC delayed enforcement of using the LEED v4 rating system until October 31, 2016 (Long, 2014). The intention of the USGBC is to communicate the goals and requirements of the new rating system while giving the manufacturing, design, and construction industry time to adjust in response to these new requirements (Long, 2014). After October 31, 2016, all new projects pursuing LEED certification must be registered under the new LEED v4 rating system (Long, 2014). To date, only 2,248 project have been registered under LEED v4, with only 145 projects currently completely certified (USGBC, 2017c). The new credit allocation of LEED’s new rating system is seen to help push the industry toward the disclosure of environmental impacts, however, given how recently this rating system has been implemented, the effect it has on transitioning the building industry to carbon disclosure and reduction is yet to be seen.

This information provides a high level overview of the state of the construction industry today as it relates to the carbon footprint of buildings and the development of incorporating embodied carbon as a factor for consideration in regards to buildings’ total impact. The next section of this paper will take a look at material components of building, addressing the currently available tools and challenges in assessing the carbon foot print of building materials. This section will also identify which building components account for the largest embodied carbon footprint of a building and the potential opportunities for alternative materials to reduce the carbon footprint of a building.

Material Assessment and Optimization

Although there is no universally accepted definition of ‘green building materials’ (Franzoni, 2011), material selection for buildings can make a significant impact on buildings’ carbon footprints. Reducing the embodied carbon footprint of a building starts at the material level. The incorporation of low or high carbon materials in the construction of a building can accumulate to either a high or low embodied carbon footprint of that building in response. In the UK, the construction materials sector alone accounts for 5-6% of total UK carbon emissions

(Ibn-Mohammed et al., 2013). In order to make informed decisions between material choices, there needs to be solid information available for those materials' carbon footprint.

Assessing Material Footprints: The Need for Common Carbon Comparison

The biggest challenge in determining the ideal construction material for a building based on its embodied carbon footprint is the lack of a universal point of reference for comparison between potential products. The first step in combatting this issue is by establishing a common playing field through which to compare products. A carbon labeling scheme has been presented as a possible solution. A carbon labelling scheme allows for suppliers and/or manufacturers of construction materials to communicate to their consumers in terms of the carbon footprint of their products (Y. Chen & Ng, 2015). There are several carbon labelling schemes currently being used across the globe, notably the CO_2 Measured Label and the Reducing CO_2 Label in the UK, CarbonCounted in Canada, and the Hong Kong Carbon Labelling Scheme (P. Wu, Feng, Pienaar, & Xia, 2014). Carbon labelling strategies use LCA approaches in order to analyze the raw materials and energy used in the creation of a given product and report emissions of carbon dioxide equivalent over a 100-year period as a final carbon value (P. Wu et al., 2014). The inputs accounted for include the raw material extraction and processing; manufacturing processes, transportation and distribution of the raw materials and final product; product operation (i.e. use and maintenance); and end-of-life management, such as reuse, recycling and final disposal (P. Wu et al., 2014). The carbon footprint of a product can be audited and reported by a certified carbon auditor and calibrated and verified by a greenhouse gas validation/verification body, resulting in a carbon label that discloses the product's carbon rating (Yuan Chen & Thomas Ng, 2016). Due to the uncertainty of the operational and end-of-life stages in materials, many carbon labelling strategies use only partial life-cycle data, such as cradle-to-gate (accounting up until the product leaves the manufacturing facility) and cradle-to-site (accounting until the product reaches the project site), for evaluating the carbon footprint of a product (P. Wu et al., 2014). The final output of a carbon label for a product is a single value that can be used for comparison against other products (P. Wu et al., 2014).

Challenges to Carbon Labelling Strategies

There are several challenges and limitations that exist with current carbon labelling schemes. When looking at the assessment of materials based on technologies, there is a risk of variability in values depending on the LCA assessment tool being used. The process of accounting for carbon emissions for multiple materials in a building is very complex and time consuming, and therefore only a few countries have implemented the practice. Additionally, the limited availability of reliable and transparent data for impacts related to materials and transport can lead to varying final results for embodied carbon values for materials (De Wolf, Pomponi, & Moncaster, 2017). Even when a material has limited stages in its life cycle, there are still numerous variables that can come into play in calculating its lifecycle footprint, such as the emission value of the equipment used in the raw material extraction, the emission value of the vehicle used for the raw material transportation, and the source of energy used in manufacturing process. In a study conducted by Sinha et al comparing LCA tools Swedish Environmental Load Profile, GaBi and SimaPro, the results from the three tools revealed significant differences (De Wolf et al., 2017).

A comprehensive overview of a simplified, applicable embodied CO_2e assessment approach with reliable datasets is yet to be defined for wide use in the construction industry. Many individual case studies of LCA approaches exist in academic literature and industry reports. However, the freedom of boundary conditions and assumptions of the assessor still leads to a wide variability in the results (De Wolf et al., 2017). Recently, carbon labelling strategies have developed to incorporate product category rules (PCRs), which are a set of specific rules, requirements and guidelines for the assessment of greenhouse gas emissions for a given product category, aimed at ensuring consistency among assessments and enabling comparisons of materials and products within the same product category (P. Wu et al., 2014). This approach enables a ‘apples to apples’ comparison among different manufacturers and helps to establish multiple products on the same playing field. Since the International Organization of Standards (ISO) established a framework of assessment criteria and boundaries, building materials have become assessed on a common set of grounds. A variety of product lifecycle assessment tools have developed in response to the framework set forth by the ISO to accommodate needs for assessing the impact of a given product (Hitchcock, Schenk, & Gordy, 2011). Some of the most common software tools for product lifecycle assessment include GaBi 4, eVerdEE, and SimaPro (Hitchcock et al., 2011). Conducting lifecycle assessments of products can benefit manufacturers because the audits can identify major energy sources in the production process of a given material, from which manufacturers can develop pragmatic solutions to cut back on fuel or electricity consumption (Yuan Chen & Thomas Ng, 2016). This benefits the manufacturer by saving on energy costs while also reducing the overall embodied energy footprint of the product in response (Yuan Chen & Thomas Ng, 2016). An added benefit includes the opportunity for positive marketing in regards to better corporate social responsibility (Yuan Chen & Thomas Ng, 2016).

Consumer Challenges in Decision Making

From an end-user perspective, utilizing carbon labeling schemes for decision making in material procurement, while forward thinking and advancing technologies regarding material transparency, may at the same time not be an easy process for comparison or truly identify low-carbon products. The information presented on a carbon label may be misleading or limited and often does not present the full set of data to understand the context of the final result presented (P. Wu et al., 2014). Additionally, if a consumer is comparing products from different manufacturers that have used different LCA tools with different system boundaries, each carbon labelling scheme may vary, limiting the credibility of the comparison (P. Wu et al., 2014). Product Category Rules are helping to fix this issue in the industry, however, these rules are still being established among many product categories and rely on the participation and contribution of manufacturers within that product category (Ritchie, 2017). Carbon labelling strategies, while able to provide customers with an easy-to-interpret option for understanding the environmental performance of products, cannot yet provide a complete and transparent method for empowering customers to make informed decisions for procurement (P. Wu et al., 2014). For example, ecolabels can serve as valuable means for presenting an assortment of environmental impacts of a given product to a potential consumer, many customers feel confused by the terminology used and layout in which the label is presented, leading to uncertainty in decision making(P. Wu et al., 2014). Additionally, consumers need a better context of materials in comparison with each other, rather than on a case by case basis. In a survey by Hartikainen, 85% of the participants who responded preferred carbon labels that allow for easy comparisons to be made between different products regarding carbon footprint (P. Wu et al., 2014). With these limitations in mind, the best approach for reviewing materials on an even playing field comes from utilizing a benchmarking strategy.

Benchmarking for Better Decision Making

Comparisons are one of the most commonly adapted and easy to use strategies by customers to choose low impact materials (P. Wu et al., 2014). Benchmarking incorporates the

LCA results of a specific product against international or national databases, as available (P. Wu et al., 2014). Benchmarking has been used in many other widely used environmental labelling strategies, such as Energy Star, the internationally recognized building energy assessment tool, which uses a score system of 1-100, and which is based on a comparative scale to assess buildings in the industry (P. Wu et al., 2014). For example, a building with a score of 80 would perform better than 80% of similar building types (P. Wu et al., 2014). Within a specific product's lifecycle, manufacturers can create benchmarks for specific life cycle stages (P. Wu et al., 2014). Benchmarking can also be incorporated into these labelling strategies to enable more knowledgeable purchasing decisions based on multi-level information assessment (P. Wu et al., 2014). These benchmarks can empower customers to compare the performance of different products side by side and make an educated decision accordingly (P. Wu et al., 2014).

Benchmarking can be used as a strategic tool to encourage manufacturers to restructure their manufacturing process. By placing materials on a comparative plane, manufacturers will be encouraged to achieve competitive advantages from each other in order to stand out and be selected (P. Wu et al., 2014). Similar to competitively low pricing, benchmarking carbon labeling schemes would encourage competitively low carbon footprints of materials for consumers to compare during their material selection process. Benchmarking therefore can have a positive influence on manufacturing processes as well as customers purchasing behavior (P. Wu et al., 2014). The success of benchmarking implementation in carbon labelling strategies is largely dependent on three key factors:

- The development of material carbon footprint databases
- Incorporating customer requirements to identify key benchmarking areas
- Supporting informed decisions by customers through adopting various labelling practices to help customers make informed decisions (P. Wu et al., 2014)

Database Development

The development of databases is necessary for benchmarking to truly have power in influencing building footprints and databases have been developed across the globe in response to this need. Some key examples of these databases include the Inventory of Carbon and Energy (ICE) by the University of Bath, the Construction Carbon Index (CCI) by the University of Singapore, and the U.S. Life Cycle Inventory which assist in the determination of a given product’s embodied carbon released over the product’s lifecycle (P. Wu et al., 2014). It should be noted that ICE and CCI were established before there were any product category rules, meaning that there may be confusion and inconsistencies regarding product comparisons, since the boundaries of assessment were variable at the time (P. Wu et al., 2014).

It is notable that the world's first carbon label was only introduced in 2006 by the Carbon Trust in the UK (P. Wu et al., 2014). While a lot has developed in the context of carbon reporting, there is still a long way to go in regards to accuracy, communication, comparison and application of carbon labels for decision making.

Building Carbon Culprits

While the processes for assessing the lifecycle impact of building materials have evolved over time, a lot of research has resulted identifying specific building materials with high embodied carbon footprints. Generally, the materials in buildings with the greatest embodied carbon are materials of large quantity or materials with the high energy use intensity during their production (Strain, Simonen, Yang, & Webster, 2017). Additionally, complex, lightweight materials are often more energy-intensive to make compared with conventional construction approaches (Ibn-Mohammed et al., 2013). In the construction industry, concrete and steel often account for the largest percentage of materials in a building, as they are the most common material for providing the structural frame of a building, and therefore often contribute the highest percentage of embodied carbon to a building's footprint as well (Zhong & Wu, 2015).

Figures 6 and 7 below show the distribution of materials in a building based on two different roles. Figure 6 shows the contribution of different materials by weight in tons for a given building while Figure 7 shows the total GHG emissions contribution in tons of CO_2eq to the building's total embodied carbon footprint (Strain et al., 2017). It can be observed that concrete is responsible for the majority of materials volume by weight, however, by carbon footprint, the role of concrete, while still large, is dramatically reduced as other materials are revealed to have a much higher carbon footprint by volume, particularly steel. Evaluations of the embodied carbon of several office buildings made with different building materials revealed that the highest share of embodied energy in these buildings belonged to the structural materials (concrete and reinforced steel), accounting for 50-66% of the total embodied energy of a building (Akbarnezhad & Xiao, 2017). In a study looking at eight construction materials in a single family house (timber, concrete, glass, aluminum, slate, ceramic tiles, plasterboard, damp course and mortar), the highest level of embodied energy was from concrete, accounting for 61% of the total embodied energy of the house, followed by timber and ceramic tiles, at 14% and 15%, respectively (Ortiz, Castells, & Sonnemann, 2009).

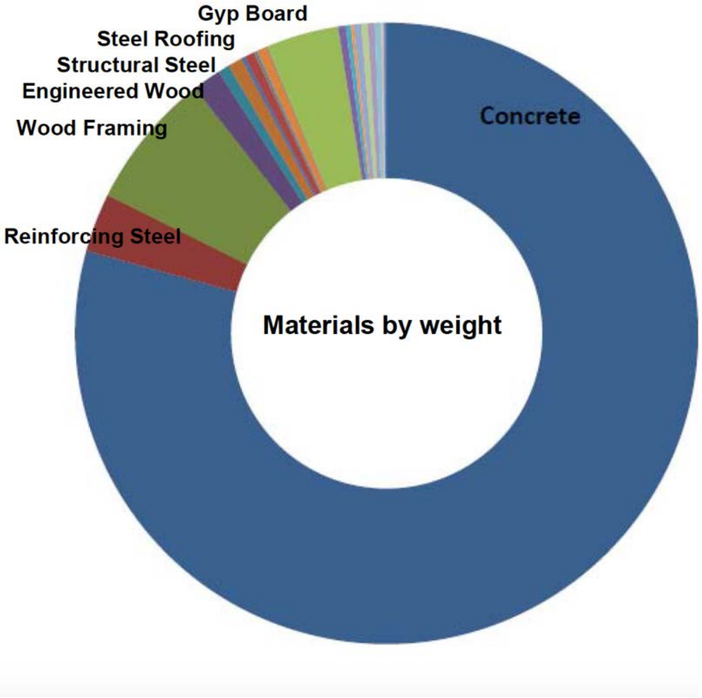


Figure 6 Material weight distribution by volume in a small commercial building (Strain et al., 2017)

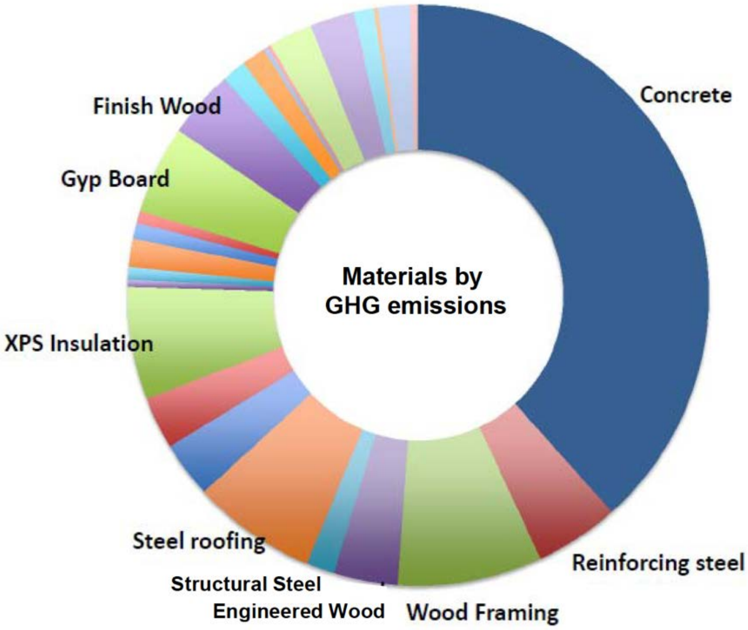


Figure 7 Embodied carbon emissions by material in a small commercial building (Strain et al., 2017)

It is worth noting that insulation can account for a significant amount of embodied carbon emissions as well in a building. Insulation is often seen as a hugely beneficial material for reducing GHG emissions during a building's lifecycle because insulation can reduce the amount of energy used for heating and cooling during the operational stage of the building's lifecycle (Wilson, 2011). Common construction practice advocates "the more insulation the better" when aiming to achieve goals of net-zero energy or carbon-neutral performance of a building (Wilson, 2011), yet when the entire lifecycle of the building is taken into consideration, the footprint of insulation can be seen differently. Common foam insulation materials have very high energy intensities for production and the blowing agents used in their application can release high levels of GHGs, resulting in very high overall carbon footprints for the material (Wilson, 2011). When reviewing insulation materials for incorporation in a building, the payback in regards to operational emissions reduction versus embodied emissions contribution must be considered when reviewing the level of insulation to be applied for the building.

Given the magnitude of steel and concrete used in large scale construction projects, steel and concrete are a major focus in the industry for embodied carbon emissions reduction.

Carbon in Concrete

Concrete is one of the most widely used building materials in roads, buildings, and other infrastructure projects (Y. Chen & Ng, 2015). Ordinary Portland Cement (OPC), used as a binder in concrete, is the primary source of concrete carbon emissions (Y. Chen & Ng, 2015). The cement industry alone accounts for 5% of anthropogenic greenhouse emissions (Y. Chen & Ng, 2015). On average approximately one ton of concrete is produced each year for every one human being in the world (Van Den Heede & De Belie, 2012). It is estimated the world produces nearly 3.6 billion metric tons of OPC every year, projected to rise to 5 billion metric tons by 2030 (Imbabi, Carrigan, & Mckenna, 2013). Projections of CO_2 emissions from the cement industry in a 2002 study revealed that if no changes are made to current production methods, CO_2 emissions will have increased by almost five times the emissions levels in 1990 (Imbabi et al., 2013). This can be observed in Figure 8.

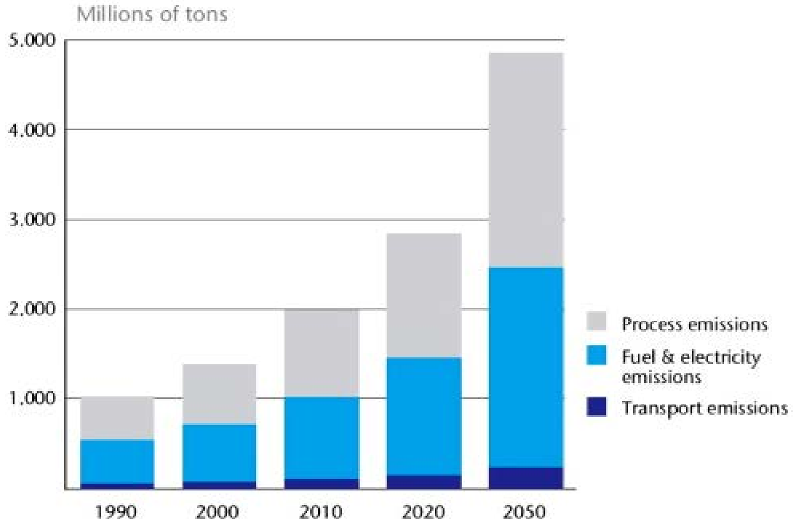
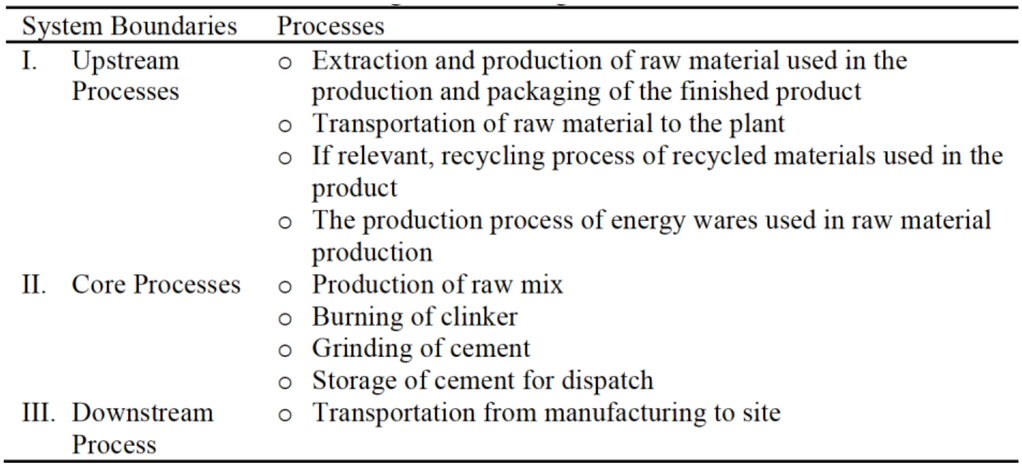


Figure 8 Projected global cement industry referent CO2, million metric tons (Imbabi et al, 2013)

Concrete mixes are comprised of coarse aggregates, such as crushed rock, fine aggregates, and a cement binder, mixed with water and performance enhancing ad-mixtures to produce a final product (Imbabi et al., 2013). Concrete mixes can vary depending on the performance needs of the concrete's application, for example, concrete in parking structures would have different performance needs than concrete used in a 40-story building (Imbabi et al., 2013). It is estimated that for every 1kg of OPC produced, .9kg of CO2 is released as a byproduct (Imbabi et al., 2013). Carbon emissions due to OPC occur in three key processes, upstream, core, and down steam, see Figure 9 (Y. Chen & Ng, 2015). A large portion of emissions are due to the calcination process (an energy intensive process in which calcium carbonate and silica are fired together to produce calcium silicate, known as clinker, and CO_2) and carbon emitted from energy use in processing the additional materials in the mix (Van Den Heede & De Belie, 2012). Given that carbon dioxide is a byproduct in the breakdown of calcium carbonate, the construction industry has investigated alternatives to replace this raw material with a material that does not produce carbon dioxide in the process (Imbabi et al., 2013).



System Boundaries	Processes
I. Upstream Processes	o Extraction and production of raw material used in the production and packaging of the finished product o Transportation of raw material to the plant o If relevant, recycling process of recycled materials used in the product o The production process of energy wares used in raw material production
II. Core Processes	o Production of raw mix o Burning of clinker o Grinding of cement o Storage of cement for dispatch
III. Downstream Process	o Transportation from manufacturing to site

Figure 9 Carbon Emitted during Different Stages of Production of Portland Cement (Y. Chen & Ng, 2015)

Carbon in Steel

The high embodied carbon value of concrete results from the sheer volume of concrete that is commonly used in projects. Steel on the other hand, is not used in as high of a volume in buildings, but the energy use intensity of producing steel is significantly higher than for concrete. Steel production accounts for about 6.6% of global anthropogenic CO_2 emissions (Erlich, 2017). Iron ore, the main raw material used in steel production, is one of the most abundant elements in the earth's crust (Erlich, 2017). The process of refining iron ore on a massive scale is very energy intensive. The majority of emissions during steel production come from the blast furnaces, which use coal for operation, to heat materials up to 2,000^{O}F for 18 or more hours at a time during processing (Erlich, 2017). Major opportunities exist in reducing emissions during steel production by transitioning away from blast furnaces to more efficient electric arc furnaces (Erlich, 2017). Between 1990 and 2010, the percent of steel production using electric arc furnaces in the United States rose from 38% to 61% as the amount of energy required to produce steel dropped by 37% (Erlich, 2017). However, worldwide, 70% of steel is still made using blast furnaces (Erlich, 2017).

Since concrete and steel are widely recognized as the largest contributors to the embodied carbon footprint of a building, these two materials should be the first focus of interest when identifying embodied carbon reduction strategies within a building. The next section of this paper will present alternative strategies for common materials used today. Even when carbon and steel are the major culprits for embodied carbon, there are still opportunities for alternatives in other building materials that can together accumulate to an even larger footprint reduction overall.

Alterative Materials for Reducing Building Footprints

Several studies have taken place comparing embodied carbon among material substitutions in buildings, revealing the importance of materials selection and review in the design process of building construction. In a comparison of beams for an airport outside Oslo, Thormark (2006) discovered that the energy consumption in producing steel beams is two to three times higher, and the use of fossil fuels 6-12 times higher, than the manufacturing of glued laminated timber beams. Results from a study of Dutch residential construction revealed that an increase in wood use could reduce carbon emissions by almost 50% compared with traditional Dutch construction, which primarily uses bricks (Thormark, 2002).

Concrete Alternatives

In recognition of the global impact of cement and concrete, the World Business Council has developed the *Cement Sustainability Initiative* which brings together major cement producers to confront the issue of emissions in the concrete world and share ideas on reducing these impacts (Imbabi et al., 2013). The initiative has collaborated on establishing a database for tracking carbon emissions and energy performance Figures for the significant players in the global cement industry (Imbabi et al., 2013). Given the significant impact that concrete has on a building's overall footprint, changing the mix design of concrete can greatly reduce the embodied footprint of the material (Ortiz, Castells, & Sonnemann, 2009). When reviewing mix applications for a concrete framed building, consideration should include both the strength and durability needed for the concrete based on the amount needed for a given mechanical load and predefined service life of a building (Van Den Heede & De Belie, 2012), meaning that concrete mixes should be established based on the needs of the building application and not as a prescriptive strategy for a mix known to have maximum strength capacity. For example, Gartner discussed the practicality of replacing Portland cements with alternative hydraulic cements in order to allow for lower carbon emissions per unit column of concrete with equivalent performance (Ingrao et al., 2015).

The concrete industry has aimed at combating the carbon footprint of concrete by restructuring concrete mixes to utilize waste byproducts of other industries, known as supplementary cementations materials (SCMs) (Lee et al., 2011). These material include blast-furnace slag (BFS), a byproduct from iron smelting, fly-ash (FA), a byproduct of coal combustion, and silica fumes, a byproduct of silicon production, are the most common SCM alternatives for traditional mixes (Imbabi et al., 2013). Concrete mix alternatives have shown to improve the quality of the concrete while eliminating the environmental impacts of disposing the waste byproducts (Lee et al., 2011) and have shown to reduce carbon emissions due to concrete by up to 25% (Van Den Heede & De Belie, 2012).

Replacing the raw material used in concrete mixes can reduce the embodied carbon in material greatly, while another aspect of reducing concrete footprint can be in the utilization of an alternate fuel for the processing stage (Imbabi et al., 2013). Cement clinker kilns are traditionally fired by coal or petroleum coke, or occasionally by gas or fuel oil (Imbabi et al., 2013). By using alternative fuels such as biomass, the emissions from fuel in processing could be 20-25% less than those from coal (Imbabi et al., 2013).

In recent years, companies have emerged in the concrete industry aimed to tackle carbon emissions from both fuel burning and raw material processing in concrete production (Higuchi, Morioka, Yoshioka, & Yokozeki, 2014). This process involves attaching an extension to the exhaust of any carbon emitting facility, such as a power plant or cement manufacturing facility, that captures the carbon dioxide emitted from the facility and converts it into a calcium carbonate mineral, known as synthetic limestone aggregate (Constantz, 2015). This process uses carbon capture and mineralization technology to mimic natural processes of using calcium carbonate for hardening tissues in living organisms, similar to the way that coral and seashells are made (Constantz, 2015). By converting production emissions to aggregates, this process can tackle the two largest courses of embodied carbon in concrete, reducing the amount of emissions from fuel burning and reducing the amount of emissions from cement production by using synthetic limestone aggregates as SCMs (Constantz, 2015).

Three concrete mix designs can be seen in Figure 10: a normal mix design, a 20% fly ash mix, a mix with 50% synthetic limestone aggregate, a normal mix with carbon capture methods attached to the cement plant, and a mix with cement made from carbon capture at the plant along with 100% synthetic limestone aggregate. This table shows that using fly ash as an SCM only reduces the embodied carbon footprint of the concrete mix by 20%, from 600 lbs CO_2 per cubic yard (lbs CO_2/cy) to 480 lbs CO_2/cy. By using 50% of the synthetic limestone aggregate, made from carbon capture methods and containing a negative embodied carbon value, the embodied carbon of the 50% synthetic limestone aggregate mix was negative, at -97lbs CO_2/cy. If a cement plant did not use any SCMs, but connected the carbon capture technology for making a traditional concrete mix, the embodied carbon of cement would come out to 0 lbs CO_2/cy, since all of the emissions from the processing would be capture and converted into the synthetic limestone aggregate. The greatest impact reduction strategy in producing concrete would be to use both the carbon capture method at the cement processing plant as well as incorporating 100% synthetic limestone aggregates in the mix design, which would result in an embodied carbon of -1,394 lbs CO_2/cy, allowing the possibility for a building to have an overall negative embodied carbon footprint (Constantz, 2015). For comparison, the average commercial building in 2005 emitted ~12,000kg of CO_2/yr (CBPA, 2016), meaning that 18.94 cubic yards of the synthetic limestone aggregate with cement plant carbon capture (SLACPC) could offset one year operation for a typical commercial building. A typical 1,500 square foot home requires about 66.5 cubic yards of concrete (Campbell, 2017). This means that the embodied carbon in typical house built SLACPC concrete would contain enough sequestered carbon to offset the annual carbon emissions of a commercial building for over three years. As of 2012, the average size of a newly constructed commercial building in the United States was 19,000 square feet (EIA, 2015), meaning there is an enormous amount of potential to offset total lifecycle emissions in commercial buildings by simply incorporating SLACPC concrete mixes into their construction.

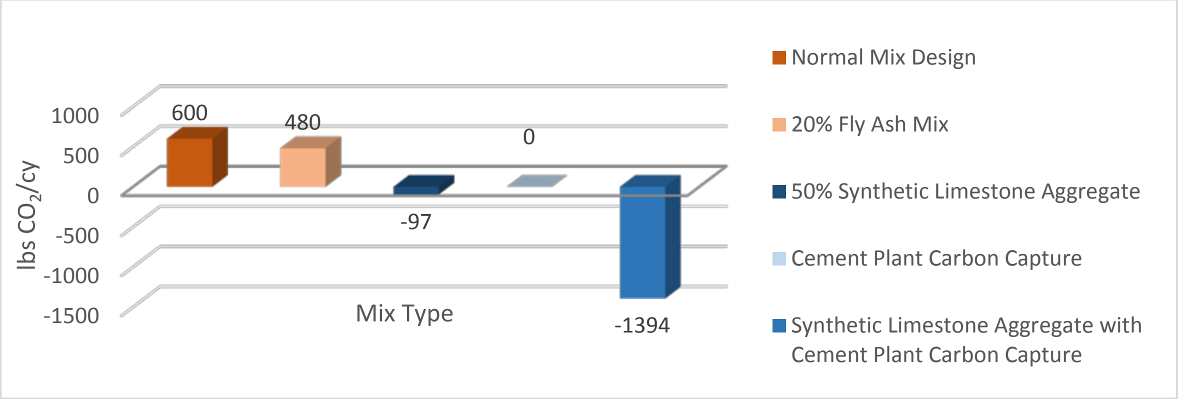


Figure 10 Embodied lbs of CO2/cy by concrete mix design (Constantz, 2015)

The practice of converting carbon emissions into aggregates is a recent development and still a fair amount of research has to be conducted in order to insure that performance of the concrete is not compromised by using this alternative mix. Blue Planet, one of the first manufacturers to patent this technology, is still conducting research and testing for feasibility within the application of this product for commercial use (Constantz, 2015).

Bio Based Alternatives

Bio based materials have become an area of focus as alternative options for building materials with lower embodied carbon footprint, particularly because bio based options have greater renewability and are less energy intensive to produce (Abd Rashid & Yusoff, 2015). For example, stabilized mud blocks are energy efficient eco-friendly alternatives to burnt clay bricks since they enable saving around 60-70% of the energy used in burning the bricks (Ingrao et al., 2015). Developments in research on natural fibers, such as hemp, flax, and jute, have revealed opportunities for producing high performance materials from renewable resources and energy efficient natural materials (Ingrao et al., 2015). These materials have the potential to not only reduce the carbon footprint of a building, but limit the amount of unhealthy chemical ingredients used in commercial manufacturing processes as well (Madurwar, Ralegaonkar, & Mandavgane, 2012). Cotton stalk fiberboard can be made with no chemical additives, an alternative to common fiber board which often uses many chemicals in their process (Madurwar et al., 2012). Fiber board has also been produced from banana bunches as well as tissue paper manufacturing waste and corn husks (Madurwar et al., 2012).

Bio based materials can not only reduce the embodied footprint of a building, but improve the operational performance and indoor environmental quality of the building as well. Studies conducted on hemp hurds, the woody inner stalk of the hemp plant, revealed that incorporating hemp hurds into concrete could increase thermo-acoustic properties while also serving to improve indoor air quality by serving as a regulator of indoor moisture content (Ingrao et al., 2015). Being a vegetal product, hemp enables carbon sequestration during plant growth. In a study comparing three types of walls over a 60-year lifespan, concrete/rock wool, wood studs/wood fiber, and wood studs/hemp-lime concrete, it was discovered that conventional concrete and rock wool had the highest embodied carbon of the three and that the wood studs and hemp-lime concrete wall additionally had moisture buffering qualities, making it an optimal material choice from an energy efficiency perspective as well as improving indoor environmental quality (Ingrao et al., 2015). Even steel, generally seen to be a unique manmade high-performance product, has potential for bio based alternatives, in regards to rebar replacements for reinforced concrete beams. A study on the load behavior of bamboo reinforced concrete beams revealed that bamboo has a relatively high tensile strength and could be used as a replacement to steel in construction applications (Madurwar et al., 2012). Bamboo reinforced concrete beams are capable of increasing the carrying capacity of a concrete beam by 2.5 times that of plain concrete with the same dimensions (Madurwar et al., 2012)

Insulation

Building insulation presents a great opportunity for improvement for not only reducing embodied carbon within a building, but reducing additional environmental impacts as well, since building insulation is commonly realized using materials obtained from petrochemicals (mainly polystyrene) or from natural sources processed with high energy consumption (glass and rock wools) (Asdrubali, D'Alessandro, & Schiavoni, 2015). In a study of unconventional thermal insulation materials in comparison with common insulation materials summarized in Appendix A, Asdrubali et al (2015) concluded that there was high environmental performance for unconventional materials with lower global warming potential. Thermal conductivity is the ability for a given material to transfer heat, meaning that high performing insulation materials would have a low thermal conductivity and would perform well as an insulation material. For example, sheep wool provides a thermal conductivity of .038W/m*K, while carrying a global warming potential of 1.457 $kgCO_{2eq}$ per functional unit, a relatively low embodied carbon value (Asdrubali et al., 2015). In a prospectus for carbon-neutral housing, The Athena Sustainable Materials Institute identified the opportunity for using cellulose insulation, such as recycled waste paper, as an alternative insulation material in buildings (Salazar & Meil, 2009). Further studies on bio based materials have shown that several possible materials could serve as replacements to current insulation materials being used today, including rice husk, coconut coir, corn stalk, durian peel, and palm oil leaves, based on their physico-mechanical performance and low thermal conductivity (Madurwar et al., 2012). The challenge of integrating any of these materials comes in limited large scale applicability for use, and therefore the integration of alternative bio-based materials comes in applying regionally specific analysis for integration of such materials for use on a given project.

Material Recyclability

Recyclability of materials is an equally important factor in reducing the total embodied energy of materials, given that much less energy is consumed in transforming an already made product than sourcing the raw materials and constructing an entirely new product from scratch. Recycling and closing the material loop are efficient strategies for reducing the environmental impacts that a building can have (Saghafi & Hosseini Teshnizi, 2011). The concept of recyclability can be incorporated for both considering materials’ potential for recyclability at the end use of their life in a building as well as selecting for materials with recycled content in order to reduce the initial embodied carbon in those materials. In a Swedish study aimed at utilizing a large proportion of recycled materials and components for a single-family house built in 1997, the energy saved from material reuse was about 40% (Thormark, 2006). Another study analyzing an energy efficient apartment building in Sweden over an anticipated lifetime of 50 years revealed that the recycling potential of the building could save up to 15% of the total energy used in that building (Abd Rashid & Yusoff, 2015). In an embodied carbon study of a core-outrigger building, Gan et al discovered that using 100% recycled steel scrap for the structural steel would reduce the embodied carbon footprint of the building by over 60% (Gan, Cheng, Lo, & Chan, 2016). According to Ng and Chau (2015), recycling of building materials could reduce the total life cycle energy of a building by 30%. Utilizing recycled steel or aluminum could provide savings in embodied energy by more than 50% (Ng & Chau, 2015). The Steel Recycling Institute claims that recycling a ton of steel can conserve 2,500 pounds of iron ore, and 1,400 pounds of coal for production (Erlich, 2017). The energy associated with different waste management strategies was calculated to identify the waste management option that could produce the highest savings in embodied energy (Ng & Chau, 2015). Recycling was found to have the highest energy saving potential of 53%, while the energy saving potential of reusing was 6.2% and that of incineration was only .4% (Ng & Chau, 2015). Recycle versus reuse potential varies depending on the type of material being assessed. For example, doors and windows have higher energy savings from reuse rather than recycling (door: 50% vs 8%; windows: 48% vs 26%, respectively) (Ng & Chau, 2015). Therefore, reuse and recyclability of building materials must be considered during the initial review for installation on a building. Both initial recycled value and recyclability of products at the end of their life can result in significant reductions of a building’s embodied carbon value over its total lifecycle.

Further Material Footprint Research Needed

A lot of research has taken place investigating the feasibility of alternative materials based on performance factors and renewability of these given material, such as utilizing waste byproducts in industrial applications or researching the performance of fiber-based materials in comparison with traditional industrial types (Madurwar et al., 2012). The results based on performance and waste reduction have overall been positive, but little research has been conducted on the embodied carbon footprint of these materials. It has been generally understood that by using a bio based material or waste product as the raw material in your final product, the embodied footprint will likely be lower than industrialized construction materials, however, further research must be done to truly understand the carbon footprint of these materials independent of the performance applications they would be used for.

Material Footprints and their Holistic Role

When reviewing materials for use within a building based on their carbon impact, analysis cannot take place by looking at the material's carbon footprint as an independent item. It is important to note that building materials with low embodied energy do not necessarily have a low life cycle energy (Abd Rashid & Yusoff, 2015). The embodied footprint of materials come mainly from the production stage, i.e. using non-renewable materials and fossil fuel energy consumption, and the disposal stage, i.e. problems in reusing or recycling products at the end of their lives (Asdrubali et al., 2015). However, the application of a material and its impact throughout its operational stage can dramatically change a building's overall life cycle carbon footprint. For example, using an insulation material with a low embodied carbon footprint may seem ideal, however, if the material has poor insulative properties, then the operational stage of the material could be much more impactful due to its impact on energy used for heating and cooling of the building. In a lifecycle assessment of three identically designed residential buildings with different materials used within the core of the building, light construction (consisting of timber frame), concrete construction, and light construction with superinsulation, concrete and super insulated buildings produced a higher initial embodied energy compared with light construction by 8% and 14% respectively. However, both concrete and super insulated buildings had lower life cycle energies by 5% and 31%, respectively (Abd Rashid and Yusoff, 2015), revealing the necessity to assess the entire life cycle of a building and the necessity to review material applications before deciding upon them based solely on embodied energy factor.

Building materials are the foundation on which a building is constructed and the type of material used can have a significant impact on the total embodied carbon footprint of a given building. The process in which a material is incorporated into a building comes from the decision making process from the construction and design team involved. The next section of this paper reviews the process of constructing a large scale building from conception to execution and identifies opportunities for process improvements and best practices where embodied carbon consideration can be incorporated for maximize embodied carbon footprint reductions in buildings.

Improving Construction Best Practices

The Business Model of Building Construction

In order to influence the building industry in an effective way, it is necessary to understand the business model behind the construction of a building. Business models for construction generally include risk, financing, process and activities (X. Zhao et al., 2016). The building process and activities are the more crucial components of the business model, as they determine the project delivery method and organization structure for the entire process (X. Zhao et al., 2016). Challenges and limitations to uptake of green building practices include: social-cultural challenges, such as customers' awareness and behaviors and the fragmented structure of the construction industry, greatly affect the awareness of customers and builders, and impede the uptake of new technologies (X. Zhao & Pan, 2015). Looking at Figure 11, it can be observed that the complex interaction of infrastructures, technologies, stakeholders and institutional context can impact the feasibility of uptake of new sustainable building strategies (X. Zhao & Pan, 2015). There are multiple types of contracts in which buildings are constructed, where the risk is distributed differently depending on the project type. The contract type can influence the flexibility of a project to pursue innovative design approaches for a new building. When approaching a new strategy for incorporation, these factors must be considered for success.

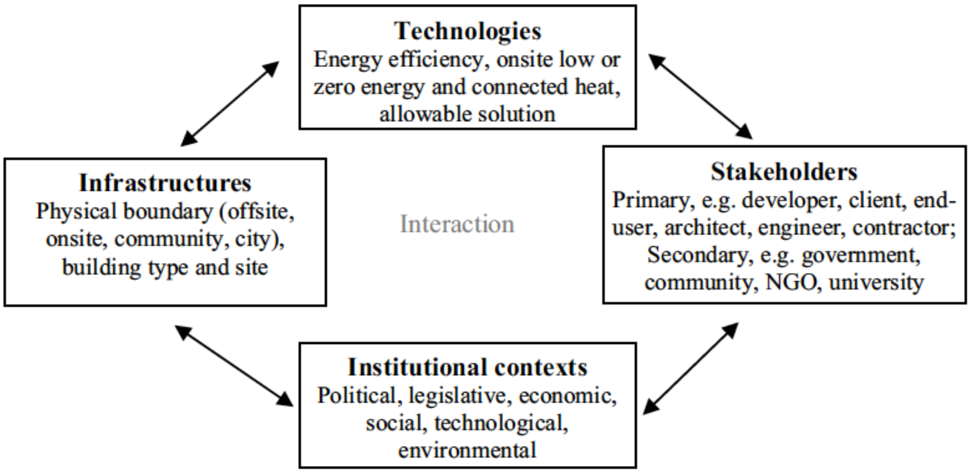


Figure 11 A theoretical framework for green building system boundaries (X. Zhao & Pan, 2015)

Key Factors in Constructing a Building

The first step in implementing change within building construction practice comes from understanding how the industry currently works and why. Therefore, the process of constructing a building must be analyzed by looking at the players involved in the process and assessing how they interact throughout the design, construction, and completion of a given project. This section addresses the important aspects of building design and construction, identifying the stakeholders involved and opportunities to integrate embodied carbon reduction strategies into a variety of aspects. To note, this section does not address the actual construction process of a building, where construction equipment is being used.

Key Players in Building Construction

Building construction is considered a service industry, where the main customer is the owner, also known as the client, and the service is the design and construction of a building is the service. The owner is the final determinant for what the project will include (known as the scope), the time frame of the project (known as the schedule), and how much the project will cost (known as the budget). Owners can be either a public agency or a private organization (Gould, 2005). Public projects are supported by public parties and must follow established statutes in their construction process, while private projects have more freedom in their development process. Typically, the owner decides who will be the design professional and the constructors of a building. Design professionals are responsible for outlining the project’s scope, budget and schedule while preparing construction documents to be used to build the project (Gould, 2005). The general contractor, also known as constructor or builder, is responsible for managing the means and methods of constructing the project (Gould, 2005). For a large scale construction project, the general contractor divides the work of the project among several specialty contractors, known as subcontractors (Gould, 2005). The means in which these different players interact depends on the delivery method in which the owner decides upon for the construction of the project.

The Influence of Project Delivery Methods

A delivery method is the approach used to organize a project team so as to manage the entire designing and building process of a project. This includes determination of the type of contract to be executed, when to hire the designers and when to hire the general contractors. The delivery method in which a client determines that a project should be built can serve as a valuable opportunity for optimizing embodied carbon footprint reduction, as it sets the groundwork for how key players involved in the design and construction process of a building are expected to collaborate together.

The most common type of delivery method is the design-bid-build arrangement, where the owner hires a designer who assembles a complete set of contract documents for the project, which in turn become bid out to a general contractor who is responsible for carrying out the scope of work established by the designer. This project delivery method can be seen in Figure 12. The design-bid-build delivery method has been the standard framework for years, meaning industry professionals are familiar with the system, coordination is relatively streamlined, and the owner has a firm, fixed price before any work begins. The disadvantage of this structure is that the general contractor and subcontractors have no input in the design and scheduling of the project, leading to issues during construction of required materials being unavailable, structural designs being unfeasible or scheduled for completion in an inefficient manner, or deliverables being priced well over budget (Gould, 2005). All work is typically conducted autonomously, with the designer designing for the owner's requirements without collaboration or input from the contractor, leading to issues down the road.

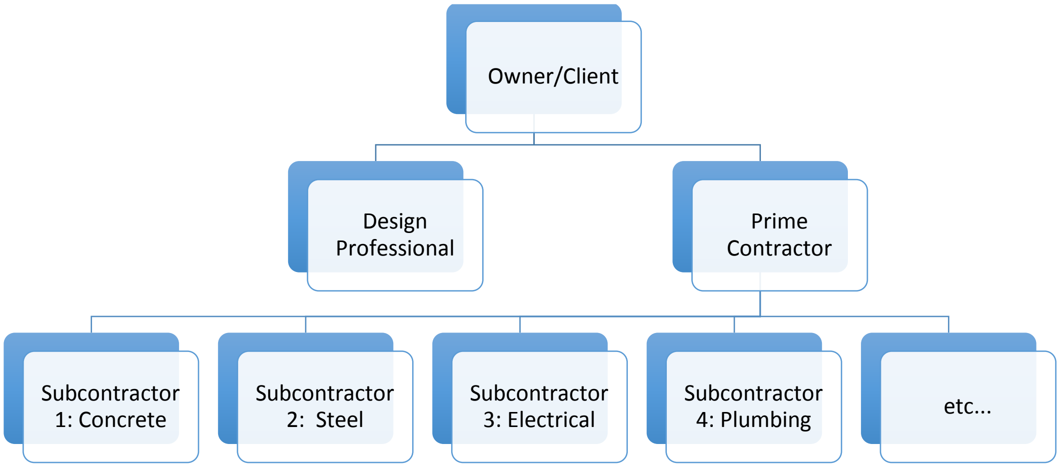


Figure 12 Design-Bid-Build Organizational Structure

One major opportunity to mitigate the issues that arise from a design-bid-build delivery method is to have a design-build delivery method instead. In a design-build arrangement, the designer and general contractor presented to the owner as a combined unit that designs and builds the entire project together, shown in Figure 13 (Gould, 2005). This kind of arrangement can largely benefit the final result of the project because it ensures good communication between the design and construction teams at the very beginning of project conception (Gould, 2005). Having the general contractor on board early enables the contractor to provide construction input during the design phase, allowing for constructability analyses and optimal coordination throughout the entire process (Gould, 2005). By having both the designer and the prime contractor involved in the project discussion early, the design of the final project will benefit from the input of experts on both teams. As will be addressed in the next section of this paper, the design of a building is a crucial factor in ensuring a low embodied carbon footprint for the completed building.

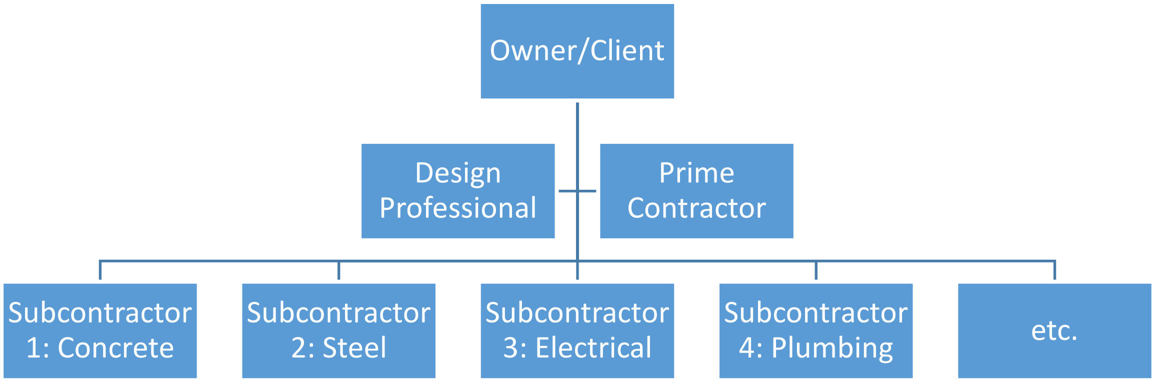


Figure 13 Design-Build Organizational Structure

Optimizing Building Design

As previously mentioned, design-build contracts provide opportunities to bring the designer and the general contractor working on a project together early to collaborate on the design and construction of a given project. This allows the contractor to provide input on constructability, material availability, design, and performance of a building while the design is still in development rather than after the fact. The greatest influence on the final impact of a building takes place at the early stage of building design and therefore, sustainable development considerations must be taken into consideration as early as possible (Iwaro & Mwasha, 2014).

Building sustainability in construction can be properly incorporated if the concept and principle of sustainable development is taken into consideration at an early stage of building design (Häkkinen, Kuittinen, Ruuska, & Jung, 2015). Embodied energy can only be reduced if low energy intensive materials and products are selected at the initial stages of building design (Dixit, Fernández-Solís, Lavy, & Culp, 2010). During the design phase, clear targets can be established for building performance and environmental impact restrictions, which can guide in the selection process for materials based off of these parameters (Häkkinen et al., 2015). Construction professionals on both the architect and contracting side have agreed that the design decisions made during the conceptual design stage of a building have the largest impact on the final overall performance and footprint of the building (Häkkinen et al., 2015). For example, a survey of 67 buildings found that 57% of technological decisions were made in the conceptual design stage, compared with only 13% in the detailed design stage, the next design stage of a building during preconstruction (Häkkinen et al., 2015).

Research indicates that by being aware of the embodied energy of different building parts and materials, designers are able to radically alter the building's design (Häkkinen et al., 2015). One study conducted by Häkkinen et al. showed that the total embodied carbon of a building was reduced by over 30% through redesign. These results emphasize the need for alternative design approaches for sustainable buildings. However, from the designer point of view there are three concerns/restrictions: (1) calculating lifecycle assessments of a design is time-consuming because the tools for design and lifecycle analysis work independently and the data input has to be done manually, (2) comparison of alternatives is not easy and the designer has to repeat the process for different design options, (3) lifecycle assessment tools do not support design comparison in early phases of design because the designer often lacks a complete list of building materials (Häkkinen et al., 2015). Building on the previously stated point, expanding universal databases with relevant material information can assist in helping designers in the initial phases of the building design process to compare alternatively available materials, resulting in a reduced footprint overall for the completed building.

During the design process, there are best practices as well as software tools that can be incorporated to achieve a successful building design that not only performs efficiently, but is constructed efficiently with a low carbon footprint. The following sections will address the opportunities available in the building design phase that can best benefit the final building.

Material Minimization

A quick approach for achieving a low embodied carbon building is to reduce the amount of material used to make it. The embodied carbon footprint of a given building is directly proportional to the quantity of material used within that corresponding building, which logically makes sense: the more materials used the larger footprint the building will likely have (Akbarnezhad & Xiao, 2017). Therefore, as part of the building design process, materials cannot be compared individually by their embodied carbon value but additionally in the design process calculated by the total quantity of materials to be used within the building (Akbarnezhad & Xiao, 2017). For example, a research study looked at the carbon footprint of two seven-story residential buildings which were constructed with similar concrete foundations, but executed in different ways; one building was constructed with in situ case flooring, where the concrete was poured on site using concrete forming, and one was constructed with precast concrete, where the frame was poured at a facility offsite and delivered ready for installation (Abd Rashid & Yusoff, 2015). The precast concrete floor was able to have a longer span between beams, lessening the number of columns and footing needed in the building and reducing the total concrete used for the precast concrete building (Abd Rashid & Yusoff, 2015). Overall, the precast concrete building was able to have a carbon footprint 12.2% less than the in situ concrete floored building (Abd Rashid & Yusoff, 2015).

Whole Building Lifecycle Analysis

Earlier in this paper, material life cycle analysis was discussed as a means to address the carbon footprint of materials on an individual scale. That approach can be beneficial for identifying major sources of embodied carbon within a building, but as mentioned, is not a holistic strategy for determining the footprint of a building as a whole. Whole building life cycle analysis identifies all materials used in the construction of a building as well as all the energy flows associated with the production of those materials and also the application of those materials in constructing the building, operating the building, as well as the final deconstruction of the building, and quantifying the corresponding environmental impacts of the entire building's life cycle (Akbarnezhad & Xiao, 2017). Through a whole building lifecycle assessment (WBLCA), individual materials can be identified for scale of contribution to the total embodied carbon footprint of a building, and can reveal how their performance impacts the entire lifecycle carbon footprint of the building as well (Akbarnezhad & Xiao, 2017). Different products can be switched out in the building lifecycle model to determine how they can impact the building's lifecycle footprint overall and reduce the total building's footprint (Akbarnezhad & Xiao, 2017). The disposal of a material at the end of its service life can have a significant impact on its overall embodied footprint. Designing a building for disassembly at the end of its service life can greatly recover its initial embodied energy (Abd Rashid & Yusoff, 2015). Detailed WBLCAs are currently costly and time consuming, causing them to not be commonly used in the construction industry, but serve as a valuable resource in optimizing building design and construction in the long run (Akbarnezhad & Xiao, 2017). Additionally, as with the issue with LCA tools for products, several WBLCA software tools are available, including ATHENA, nova-EQUER, ELODIE and IMPACT, with variable assessment models that can produce variable lifecycle assessment values (Fouquet et al., 2015). This causes inconsistencies in final values of WBLCAs depending on the software used for the assessment.

Building Information Modelling for Universal Conversation

Building Information Modeling (BIM) is a comprehensive 3-D modeling information management and analysis technology that has been a useful tool for the analysis and design of buildings (Issa & Olbina, 2015). BIM contains a standardized set of formations that can be used to organize construction information and contain data rich details on a building design down to the individual parts and measurement dimensions that make up a building all on one platform that both designers and contractors can use collaboratively (Ewe-Modrich, 2017). It can review multiple options for a given system and qualify building products side by side to determine which materials meet certain criteria (Liu & Cui, 2016). BIM compatible tools can potentially assess the carbon footprint of a given building design in a step-by-step way as integrated tools into the design process of a building (Häkkinen et al., 2015). Through BIM technology, the environmental impact of products can be part of an integrated, BIM-enabled environmental feedback process (Häkkinen et al., 2015). BIM technology can be utilized when conducting WBLCAs by having access to all known materials used in a building in one place as well as using the 3-D model for conducting energy modeling during the building’s operational phase. BIM technology can also support designers to focus on decisions that can make a large impact during the early design phases by understanding which decisions have the biggest effect on a building’s embodied greenhouse gas impact (Häkkinen et al., 2015). Sensitivity analysis can be performed in order to inform designers which building components’ embodied carbon footprint consistently contribute significantly to a building’s environmental impact across designs (Häkkinen et al., 2015). To note, BIM technologies are only as useful as the data that they are provided and therefore optimal utilization of BIM technologies is necessarily limited by the amount of carbon information available (Häkkinen et al., 2015). This point addresses the previously noted need for a universal database of carbon labels of materials based on a standard assessment model.

Systems Thinking (Integrated Design)

Beyond looking at a building on an individual scale, designers must take into consideration the environmental context of a given project. A single all-encompassing prescriptive approach for building design and construction is not the solution for reducing the overall carbon footprint of buildings everywhere. Depending on the location of a building site, a variety of different strategies can be utilized for improving a building. As observed by Lugaric et al. (2016), local natural and technological resources are the basis for local low carbon development; a building's construction and development cannot be primarily based on resources and technologies that are imported from elsewhere. Buildings should be considered in the context of the region where they are being built, in order to develop an overall smart low carbon community and not just an optimized, isolated site (Lugaric & Krajcar, 2016). Research has looked at opportunities to incorporate local materials based on a building's surrounding landscape that can utilize environmental practices that already take place in those respective regions (Abd Rashid & Yusoff, 2015). For example, in tropical climates, products made from clay are identified as a better alternative to products made from cement (Abd Rashid & Yusoff, 2015). In a study on residential building in Indonesia, clay bricks and roofing have a lower life cycle energy than bricks made from cement and roof tiles because the clay material provides less thermal heat transfer, causing a cooling effect that would otherwise have to be conducted through air conditioning (Abd Rashid & Yusoff, 2015).

Lugaric et al. emphasized an "emergy" theory that uses three separate concepts – energy, economy and the environment – to deliver a model where future effects of decisions made in the present can help to gain insight on the transformation of an entire city toward a low-carbon energy system (Lugaric & Krajcar, 2016).

Procurement

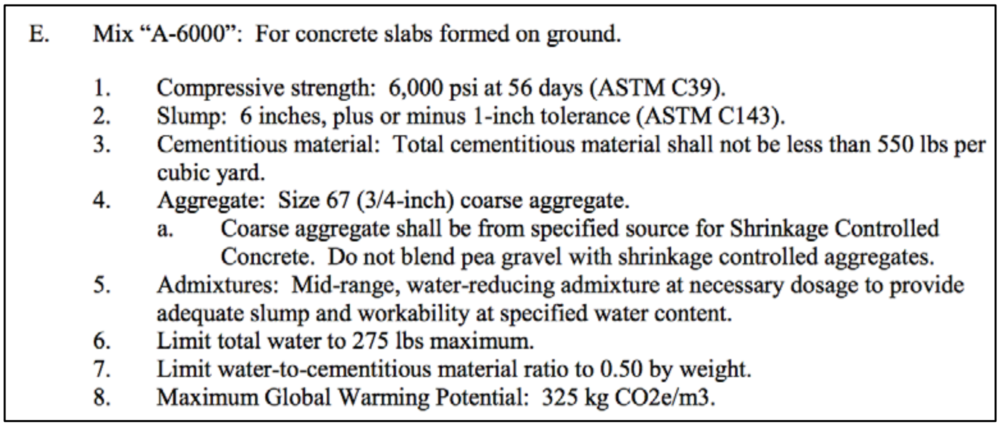
As mentioned before, on a large construction project, the general contractor often bids out scopes of work, known as procurement, to specialty subcontractors, who each play a role in completing different aspects of the project, known as bid packages. Examples of bid packages include concrete, structural steel, plumbing, electrical systems, mechanical systems, and more. During procurement, subcontractors present proposals to the general contractor which include the subcontractor's qualifications for the job, the scope of work intended to be provided, and most importantly, the total cost estimate for the subcontractor to complete the requested bid package (Gould, 2005). Bid package cost estimates generally includes the total cost of materials, labor, and profit margins, and most often, bid packages are awarded to the lowest qualified bidder (Gould, 2005). This is important to note, because the embodied carbon footprint of materials is not currently a factor in the cost estimating or procurement process in construction. The following sections identify opportunities to incorporate embodied carbon considerations during the procurement process that could compromise or potentially enhance a subcontractor's chances of being awarded a bid package based on the embodied carbon footprint of the materials they propose.

Preferential Procurement

During the procurement process, the general contractor has the authority to address the circumstances in which a subcontractor can be qualified to bid for a given package. Additionally, a general contractor can identify inclusions within a subcontractor's proposal that can make the proposal more favorable for consideration, known as preferential procurement (Liu & Cui, 2016). These are not necessarily requirements that are obligatory, but they are factors that if included in a bid package, would make a compliant subcontractor a more favorable choice for being awarded the package. In a study conducted by Liu and Cui (2016) focused on preferential procurement as a strategy for low-carbon building, a model was designed to help owners determine a discount rate for scope bids based on bidders achieving a given carbon reduction goal. This discount rate would be applied to the final bid of prospective bidders that meet a low embodied carbon value for the given scope of work in order to make the subcontractor's bid more appealing to the general contractor, while reducing the overall carbon footprint of the project (Liu & Cui, 2016). The rate would reduce the perceived value for the scope of work, as it incorporates carbon reduction strategies as a discount factor, though the total cost of the work would still be paid out on the original bid price and not the discounted value presented. The study revealed that utilizing a discount rate of .6 of the total price of a bid for low carbon materials use would achieve a 28.2% reduction in greenhouse gas emissions due to materials while increasing procurement costs by 3.87% relative to no intervention (i.e. no discount) (Liu & Cui, 2016). Using a low carbon discount rate would limit the emissions of the awarded contract to a desired level and drive tenders to consider carbon reduction efforts as an investment where the returns would be in the form of an increased opportunity at winning a given job. This study revealed that when bidding out their scopes of work, project developers can incorporate preferential procurement strategies that favor embodied carbon reduction considerations with a cost premium under 4% of the total scope of work. Preferential procurement could serve as a viable option for embodied carbon reduction within a building at a low cost premium.

Specifications

If a project team is adamant on having certain embodied carbon limitations for a given material, they can incorporate these restrictions into the specifications for the relevant bid packages. Specifications are the construction documents for each scope of work that are written requirements for a given material, equipment, system, workmanship, or performance used in the construction of a building (O'Sullivan, 2017). These specifications can identify a set of required criteria, such as performance or material type to be used. For example, concrete mixes need to have a certain level of performance strength based on their application, and these performance requirements can be identified within the concrete specifications of the construction documents (Campbell, 2017). Projects aiming for low embodied carbon footprints can identify maximum requirements within the material specifications in order to ensure that the given materials comply with carbon emission requirements (Campbell, 2017). This strategy has been incorporated into the procurement process at the San Francisco International Airport Boarding Area B project (SFO T1 BAB), where limited total carbon footprints have been established by the project team, Austin-Webcor Join Venture, for key building materials. Figure 14 below is an excerpt from the SFO T1 BAB's concrete specifications. For the referenced concrete mix, "A-6000", there are a number of criteria that the mix must comply with, including strength and water ratio, and the final line states that the mix cannot have a global warming potential greater than 325kg CO_2eq/m^3, meaning that for every cubic meter of this mix, no more than 325 kg of CO_2 equivalent (total greenhouse gas emission potential quantified in carbon equivalent) can be emitted per cubic foot (Rutherford+Chekene, 2016). By establishing these restrictions in the product specifications, the subcontractors are obligated to comply with the maximum emission requirements, reducing the carbon footprint of the building overall.



E. Mix "A-6000": For concrete slabs formed on ground.

1. Compressive strength: 6,000 psi at 56 days (ASTM C39).
2. Slump: 6 inches, plus or minus 1-inch tolerance (ASTM C143).
3. Cementitious material: Total cementitious material shall not be less than 550 lbs per cubic yard.
4. Aggregate: Size 67 (3/4-inch) coarse aggregate.
    a. Coarse aggregate shall be from specified source for Shrinkage Controlled Concrete. Do not blend pea gravel with shrinkage controlled aggregates.
5. Admixtures: Mid-range, water-reducing admixture at necessary dosage to provide adequate slump and workability at specified water content.
6. Limit total water to 275 lbs maximum.
7. Limit water-to-cementitious material ratio to 0.50 by weight.
8. Maximum Global Warming Potential: 325 kg CO2e/m3.

Figure 14 Concrete Specifications for SFO Terminal 1 Boarding Area B (Rutherford +Chekene, 2016)

Establishing Best Practice Requirements from the Top

The previous sections address ways in which a design and construction team can optimize embodied carbon reduction within the buildings they build. One key aspect in regards to these implementation strategies is the motivation behind making such changes within the industry practice. Adding additional requirements within the project specifications require additional time, resources and ultimately increase the total cost of constructing the project. Given that time and budget are often the limiting resources in a project, the general contractor is not likely to change the way it writes its specifications unless instructed to do so, either by the owner/client or from greater forces such as policy. Zhao et al note that the shift toward zero carbon in addition to design and technological considerations, requires changes in business norms and beliefs, existing institutions, and society at large (2016). Therefore, if policy enforcement is not in place, owner/client buy-in, advocacy, and support is essential to ensure implementation and execution of embodied carbon calculation and reduction strategies as mentioned above. The following section of this paper will address what policy is in place to date and the direction of policy development in the future for incorporating considerations for embodied carbon emissions in the building industry.

Transitioning Policy

All of the previously mentioned strategies are valuable approaches to change the way that buildings and materials are approached in a manner that considers their embodied carbon and aims to reduce their total lifecycle carbon footprint. As previously mentioned, many of these practices are not likely to be implemented unless pressured to do so comes from the top down.

This can come from either the market demanding such strategies or policy enforcing it (Alvarez & Rubio, 2015). Alvarez and Rubio (2015) explain that the first steps in government restructure could involve future legislation that regulates tenders by requiring reports and verification of carbon footprint assessments, followed by intensity-related requirements, such as limited greenhouse gas emissions per dollar spent on a given project. Oversight could be implemented by government authorities, who can regularly evaluate carbon offset programs and draw up specific recommendations for improved construction practices i.e. a federally established department structured around continuous improvement in carbon reduction strategies for buildings (Alvarez & Rubio, 2015). These regulations should be issued on a national and potentially global level to reduce region-specific regulations (Alvarez & Rubio, 2015). In the private sector, carbon offset programs could be promoted to reinforce proposed green initiatives and stimulate sustainable behavior (Alvarez & Rubio, 2015).

In a U.S. survey assessing how much respondents supported or opposed a range of different climate and energy-related policies, overall, respondents strongly supported renewable energy focused policies, shown in Figure 15 below (Smith & Leiserowitz, 2014). Renewable energy research received the most support, with over 85% of respondent approving such policies, CO2 regulation received support from 71% of respondents, 61% supported the signing of an international treaty to cut emissions 90% by 2050, and building efficiency funding achieved support from over half of respondents, 55% (Smith & Leiserowitz, 2014). Public support for renewable energy policies can manifest low carbon building materials and products in response, as the energy sources feeding into the manufacturing facilities for these materials can turn to renewable sourcing and lower the total carbon footprint of the final product. With public support for such policies, there exists an opportunity for establishing these policies on a state and federal level, which can then trickle down to impact the business and manufacturing processes of the construction industries within these jurisdictions.

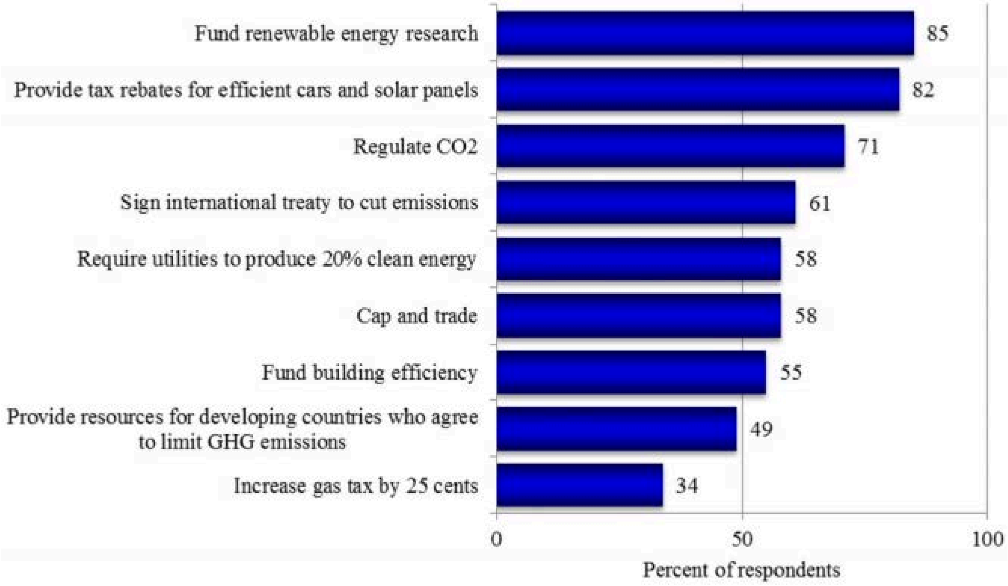


Figure 15 U.S. Support for Green Policies (Smith & Leiserowitz, 2014)

Currently, such types of policy are already being developed or is in talks of being implemented in the near future. The UK government has established joint goals to reduce emissions associated with the construction industry by 50% by 2025, and in response has released WRAP (Waste & Resources Action Program) for building professionals to benchmark designs and compare data (Schofield, 2014). In the United States, the current federal administration has opened up support for all sources of energy production, including the use of carbon emitting resources, such as coal and oil, and makes no mentions carbon emissions or climate mitigation strategies in its policy goals for the future (Trump, 2017). Where federal encouragement is not present for carbon reduction strategies, policies can be implemented at the state and regional scale to push local communities to address carbon reduction strategies on a local scale. Such an approach could best benefit local communities, as the policy makers would know the needs of the community and therefore would know the optimal means to achieve climate mitigation goals that best benefit the context of the local region. In California, there is currently an assembly bill under review, Assembly Bill 262, which would require project bidders on California State University projects to provide “a standard form that states the cumulative amount of specified greenhouse gas emissions that were produced in the material extraction and processing, transport to the manufacturing site, and the manufacturing of eligible materials, as defined, to be used on the project” (Chiu & Steinforth, 2017). This bill would enforce the disclosure of the carbon footprint of materials, and by doing so push manufacturing facilities to have to disclose such information as well as require contractors to implement such considerations into their procurement processes.

Green Public Procurement

The public sector serves a valuable role in leading the market toward innovative and sustainable practices within the industry. Rainville notes that public purchasers play a critical role in stimulating or impeding private sector innovation activities, shaping competition and establishing early markets of sufficient size (2016). This point emphasizes that the likelihood of adopting a strategy for reducing embodied carbon emissions may be most effective when first implemented in the public sector. Green Public Procurement (GPP) is seen as a purchasing strategy for the public sector which reduces the environmental impact across a building's life cycle (Rainville, 2016). It requires the use of environmental criteria, including eco-labels and standards for energy efficiency and emissions in order to make well-informed decisions on materials sourcing (Rainville, 2016).

Developed countries spend over 10% of their gross domestic product on public procurement. In Europe, this Figure is 19%, representing a total expenditure of over 2 trillion euros each year (Alvarez & Rubio, 2015). This offers a major opportunity for the public sector to foster sustainable consumption and production within its industry. Currently, there is limited uptake in GPP due to limited well established environmental criteria or their insufficient publication, as well as uncertainty regarding the legality of different methods of incorporating environmental criteria in calls for bidders (Rainville, 2016). By establishing standards for tenders to comply with, GPP can stimulate competition among suppliers to meet (or exceed) such requirements, which can ultimately result in a wider range of solutions or delivery processes (Rainville, 2016). Standards can be determined through the development of technical specifications based on the consensus of key interested parties, including industry professionals, relevant interest groups and public authorities (Rainville, 2016). By incorporating carbon disclosure standards, GPP would stimulate the private sector to innovate new, lower impact technologies and materials in order stay ahead of the market in regards to anticipated building requirements (Rainville, 2016). Ultimately, GPP could serve as a catalyst in driving the industry toward more comprehensive carbon emission considerations and drive down the impact of the construction industry as a whole. This section address involuntary means of achieving carbon reduction goals in the building industry through legal oversight. The following section addressees the current state of embodied carbon consideration among green building certification programs and opportunities for integration within the market of green building certifications.

Restructuring Green Building Rating Systems

Limitations to Current Rating Systems

Green Building Rating (GBR) Systems have continued to be valuable opportunities for spreading new sustainable building considerations and strategies and pushing the envelope for sustainable building best practices. GBR systems have the potential to incorporate embodied carbon considerations among their assessment criteria and in turn, pushing the construction industry to accommodate these demands (Y. Chen & Ng, 2015). As mentioned earlier in this paper, the LEED Version 4 (v4) rating system was only recently enforced as of October 31, 2017 (Long, 2014). The new LEED v4 rating system allocates three possible credits toward a project's LEED certification score for conducting a whole building lifecycle assessment. To achieve these credits, not only does a WBLCA need to be conducted for the project, but the building must also demonstrate a minimum of 10% reduction, compared with industry baseline building values under the same category, for at least three of the six environmental impact categories identified (USGBC, 2017a). Global warming potential (GWP) is listed as one of the six impact categories listed, but does not need to necessarily be one of the impact categories reduced for the project to be awarded the three credits. Additionally, the LEED v4 scoring system awards one credit for collecting a minimum of 20 EPDs for materials used in the building and an additional credit if 25% of the total building materials, by cost, are shown to have better performance for at least three of the six environmental impact categories identified (USGBC, 2017a). It should be noted, however, these credits are optional credits, meaning that a project team is not obligated to pursue them. These credits comprise 5 points total out of a possible110 point score. A project team could achieve LEED platinum certification, 80 points or above, for their project without any consideration for the carbon footprint of the materials used or the total carbon footprint of their building.

Opportunities for More Embodied Carbon Emphasis

When reviewing four different GBR systems, Chen & Ng noted that the evaluation of materials' embodied GHG emissions is covered to some extent, but their weightings are relatively small (2016). Given that the current structure of GBR systems gives little priority for embodied carbon within their building certification scoring, GBR systems could reconsider their scoring approach to better account for embodied carbon, pushing project teams to better prioritize carbon considerations during building design and material procurement (Yuan Chen & Thomas Ng, 2016). By conducting a survey of building stakeholders' perceptions of current GBR systems and preference on an embodied GHG consideration model for buildings, Chen & Ng proposed the integration of an additional assessment model into existing GBR systems that included three elements: product categories, a GHG auditing framework, and benchmarking materials based on a universal database of materials' GHG emissions (2016). By incorporating mandatory elements of carbon footprint considerations into their scoring systems, GBR systems would be able to drive the building industry toward more comprehensive data regarding embodied carbon emissions in building materials and ultimately to reduce these emissions in response to the newfound information.

Discussion

Stakeholder Roles

This paper has managed to address tools, business strategies, and potential policies and programs that can push the building industry to better incorporate embodied carbon considerations and ultimately reduce the level in which buildings contribute to global anthropogenic GHG emissions. What has not been explicitly noted, but is critical for successful implementation of such strategies is the active participation of all players involved in the design and construction of the building to integrate these optimization strategies. The client must demand such requirements, the contractor must implement such requirements, and the manufacturer must comply accordingly. For successful carbon reduction within a project, all stakeholders need to be properly educated on the expectations involved.

Reduction strategies can only be successful if all stakeholders understand the goals intended from these strategies, follow their direction and execute them properly, making proper communication critical among all participants involved in executing a project through completion. Without project teams understanding the ultimate goal intended from project requirements in regards to embodied carbon reduction strategies, they will not be motivated to truly follow the strategies presented, particularly where a practice is newly implemented and has not been practiced before. It can be easy to follow a 'business-as-usual' approach to construction rather than changing practices (Campbell, 2017). This has been observed in the case study of San Francisco International Airport Terminal 1 Boarding Area B (SFO T1 BAB), which is currently in the process of procurement for several of its largest scopes, including concrete and structural steel (Campbell, 2017). While the steel contractor had submitted product data sheets revealing that the steel they were procuring complied with performance requirements, the supplementary sustainability documentation required for disclosing the GWP of the steel was not submitted (Campbell, 2017). The steel subcontractor was used to providing sustainability product data at the close out of the project, and since the project manager did not understand the role that global warming potential played in reducing the total carbon footprint of the building, this criteria was disregarded in the procurement process (Campbell, 2017). By the time that this oversight was acknowledged, the steel had already been purchased and was on a ship for delivery to the project site (Campbell, 2017). Additionally, information may not currently available and challenges exist in identifying how to report materials that have not been assessed for their carbon footprint. Part of the steel used in the project at SFO T1 BAB was sourced from the subcontractor's back stock warehouse, where steel subcontractor had procured the same type of steel from multiple manufacturers, unsure of the sourcing or manufacturing location (Campbell, 2017). Issues like these could be frequent as the new practice enters into the industry. However, as carbon labelling criteria become more commonplace in the construction industry, further research and information sharing will push manufacturers and construction professionals to become more aware of the expectations and the number of incidents where information is missing would subside over time.

The Untouched Footprint of Embodied Carbon from Construction

This paper focuses on reducing the embodied carbon footprint of a building through optimized building design and careful material selection. Most of these embodied carbon reduction strategies address reducing embodied carbon of the building up until the materials are delivered to the project site. Carbon emissions that take place during the construction phase of a building, which contribute to the total embodied carbon footprint of the building's lifecycle, have not been addressed in this research paper. The construction industry generates the third highest GHG emissions among U.S. industrial sectors (Ahn et al., 2010). Construction activity optimization on the jobsite can serve as a major opportunity for reducing total anthropogenic GHG emissions.

The U.S. Environmental Protection Agency (EPA) has aimed to reduce the impact that construction activity can have on GHG emissions by establishing emission limits for construction equipment (Ahn et al., 2010). GHG emissions from construction can be reduced through multiple strategies such as reduced idling time for equipment, utilizing energy efficient equipment for operation , and minimizing on site transportation of equipment (Akbarnezhad & Xiao, 2017). In order to truly assess the level of impact that construction activity has on total GHG emissions, actual site data must be reported for such metrics as equipment used, equipment run times, total fuel consumption, electricity used, and more (Hamblett, 2017). To date, very little information has been collected from actual construction sites, limiting how much is truly understood regarding the contribution that the construction stage can have on a building's total embodied carbon footprint (Akbarnezhad & Xiao, 2017). Gathering construction activity data is largely dependent on the laborers working on the site to track their activity on a daily basis, which can be time consuming and is not prioritized among other tasks on the job (Campbell, 2017). Additionally, if this activity data is available, there also needs to be accurate conversation factors available for calculating total GHG emissions based on equipment type and run time. Such conversion factors are limited and do not account for all variables in calculating GHG emissions of different types of equipment. This issue has been observed at SFO T1 BAB, where the AWJV has incorporated daily equipment activity reporting into its requirements for subcontractors, but implementation of this requirement has been limited because subcontractors are not used to reporting such information (Hamblett, 2017). Often logs are submitted retroactively based on memory, compromising the accuracy of information being reported (Hamblett, 2017).

The significance of construction activity and the role it plays in contributing to the carbon footprint of a building's lifecycle is not unnoticed, however limitations exist in influencing laborer behavior to reduce total emissions during the construction phase. There is potential to incorporate widespread education programs for all stakeholders on construction teams to understand the impact that construction activity has on contributing to GHG emissions and ultimately climate change. AWJV has used a construction GHG Emissions acknowledgement form (see Appendix B) at SFO T1 BAB for all subcontractors to fill out during preconstruction meetings. This form provides a high level overview to project subcontractor teams of the impact that construction emissions have on GHG emissions, encouraging self-reflection of construction activity on the jobsite, and identifying opportunities where the construction team can reduce emissions through their decisions when operating equipment. In this form, subcontractors are required to pledge a strategy in with their team will reduce GHG emissions from construction activity on the jobsite while performing their scope of work. Acknowledgement forms like the one used at SFO T1 BAB serve as valuable opportunities to educate project teams on the impact their jobs have on GHG emissions and mobilize voluntary behavioral changes to mitigate those emissions.

The Role of Existing Structures

Looking at global building stock in the future and opportunities for reducing the building industry’s impact on climate change, the paper focuses primarily on improvement opportunities in the construction of new buildings. This paper is written on the pretense that new construction is necessary for a given construction project, yet when approaching a construction project, there must be consideration as to whether constructing an entirely new building is required at all. Given the significant value that embodied carbon has on a building, serious considerations must be made in determining whether a building must be built up from scratch or whether there is a current building available that may serve the needs of a project through renovations. This extends the life of an existing building and reduces the total emissions that can result from building up fresh. It must also be noted that 90% of the global building stock in 2050 has already been constructed *today* (Ritchie, 2017). This is an important Figure to consider because this means that the 90% of the constructed landscape of 2050 has already accumulated the majority of its embodied carbon footprint and established a consistent rate of emissions during its operational stage. Therefore, there exists a pressing need to address the current landscape of completed construction projects from an efficiency perspective to ensure that their operations are optimized and that consideration for their end of use is prioritized in order to further extend the lifecycle of the buildings and limit the accumulation of unnecessary embodied carbon due to new construction. If the building industry wants to reduce its role in energy consumption and GHG emissions, it needs to seriously invest in optimizing its current building stock. Building renovations will be pivotal in reducing the building industry’s contribution to climate change.

Conclusion

This paper conducted an integrated assessment of the design and construction industry to see what the current state of the industry is with regard to embodied carbon footprint considerations in buildings and opportunities to reduce the amount of embodied carbon in buildings as a means to reduce the built environment's role in contributing to climate change. The industry is currently facing significant challenges with regard to accurate data for creating user-friendly carbon labels to help with material procurement. While many material carbon footprint databases exist across the globe, a universal database with a consistent set of standards for all building materials has yet to be developed. There are several opportunities within design and construction business models to better incorporate considerations for and ultimately reduce embodied carbon at both the material procurement level as well as from the whole building scale from a design perspective. Business practices can be restructured in order to favor subcontractors and manufacturers that show embodied carbon reduction strategies in their practices. From a top down perspective, owners and clients can hold the most influence by explicitly demanding the construction of a building with a low embodied carbon footprint. From a different top down aspect, public policy shows promise for integrating carbon requirements into public building codes and research has shown that the general public supports the implementation of such policies. The public sector has the power to sway the private sector in response, so integrating embodied carbon considerations for buildings can lead to a trickle-down effect on the building practices as a whole. Green building rating systems also serve as possible influencers for driving change the construction industry, particularly as carbon reduction strategies can be seen as a green building practice. There are currently some considerations for embodied carbon in buildings in the LEED v4 rating system, but these requirements are mandatory for certification, and surveys of industry professionals reveal an interest in restructuring rating systems to better prioritize the value of embodied carbon.

Overall, the success of implementing more embodied carbon reduction strategies is likely to come from collaboration between all stakeholders involved in the process. Communication will be essential for educating all players involved in the design and construction of buildings to ensure that everyone understands the significance that embodied carbon emissions have in the lifecycle of a building and the roles that all can play in reducing the overall lifecycle carbon footprint of a building. In time, the amount of missing information needed for proper embodied carbon assessment of buildings will go down, and with it, the total footprint of buildings will reduce. The construction industry is on the cusp of a construction revolution, aimed at better accounting for and reducing all impacts of building design and construction. Greenhouse gas emissions reduction is just one aspect of many in mitigating the impact of the built environment, but it is a crucial requirement if humanity aims to continue thriving and coexisting with the rest of the natural world.

Works Cited

Abd Rashid, A. F., & Yusoff, S. (2015). A review of life cycle assessment method for building industry. *Renewable and Sustainable Energy Reviews*, *45*, 244–248. https://doi.org/10.1016/j.rser.2015.01.043

Adams, E., Connor, J., & Ochsendorf, J. (2006). *Embodied energy and operating energy for buildings: cumulative energy over time. Design for sustainability*. *Civil and Environmental Engineering*. Cambridge, MA: Massachusetts Institute of Technology.

Ahn, C., Lee, S., Peña-Mora, F., & Abourizk, S. (2010). Toward environmentally sustainable construction processes: The U.S. and Canada's perspective on energy consumption and GHG/CAP emissions. *Sustainability*, *2*(1), 354–370. https://doi.org/10.3390/su2010354

Akbarnezhad, A., & Xiao, J. (2017). Estimation and Minimization of Embodied Carbon of Buildings: A Review. *Buildings*, *7*(1), 5. https://doi.org/10.3390/buildings7010005

Alvarez, S., & Rubio, A. (2015). Carbon footprint in green public procurement: Policy evaluation from a case study in the food sector. *Journal of Cleaner Production*, *93*, 159–166. https://doi.org/10.1016/j.jclepro.2015.01.048

Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, *4*, 1–17. https://doi.org/10.1016/j.susmat.2015.05.002

Besel, R. D., Burke, K., & Christos, V. (2015). A life history approach to perceptions of global climate change risk: young adults' experiences about impacts, causes, and solutions. *Journal of Risk Research*, *9877*(April). https://doi.org/10.1080/13669877.2015.1017830

Bojarski, A. D., Laínez, J. M., Espuña, A., & Puigjaner, L. (2009). Incorporating environmental impacts and regulations in a holistic supply chains modeling: An LCA approach. *Computers and Chemical Engineering*, *33*(10), 1747–1759. https://doi.org/10.1016/j.compchemeng.2009.04.009

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews*, *26*, 379–388. https://doi.org/10.1016/j.rser.2013.05.001

Campbell, W. (2017, March 15). Discussion on Procurement at SFO Boarding Area B. (N. Wheating, Interviewer) San Francisco, CA.

CBPA. (2016). *Carbon Footprint of Commercial New Construction*. Sacramento: California Business Properties Association.

Chen, Y., & Ng, S. T. (2015). Integrate an Embodied GHG Emissions Assessment Model into Building Environmental Assessment Tools. *Procedia Engineering*, *118*, 318–325. https://doi.org/10.1016/j.proeng.2015.08.433

Chen, Y., & Thomas Ng, S. (2016). Factoring in embodied GHG emissions when assessing the environmental performance of building. *Sustainable Cities and Society*, *27*, 244–252. https://doi.org/10.1016/j.scs.2016.03.015

Chiu, & Steinforth. AB-262 Public contracts: lowest responsible bidder: eligible materials. (2017). Retrieved from http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB262

Constantz, B. (2015). *Blue Planet: Economically Sustainable Carbon Captur*. Los Gatos, CA. Retrieved from http://www.blueplanet-ltd.com/#technology

Copiello, S. (2016). Economic implications of the energy issue: Evidence for a positive non-linear relation between embodied energy and construction cost. *Energy and Buildings*, *123*, 59–70. https://doi.org/10.1016/j.enbuild.2016.04.054

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, *140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, *42*(8), 1238–1247. https://doi.org/10.1016/j.enbuild.2010.02.016

DOE. (2017). How energy efficient light bulbs compare with traditional incandescents. Retrieved January 3, 2017, from https://energy.gov/energysaver/how-energy-efficient-light-bulbs-compare-traditional-incandescents

EIA. (2015). Average size of new commercial buildings in United States continues to grow. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=21152

Eleftheriadis, S., Mumovic, D., & Greening, P. (2017). Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renewable and Sustainable Energy Reviews*, *67*, 811–825. https://doi.org/10.1016/j.rser.2016.09.028

Erlich, B. (2017, May). Better Steel, Lower Impacts. *Building Green*. Retrieved from https://www.buildinggreen.com/feature/better-steel-lower-impacts?utm_source=BuildingGreen.com+Mailing+List&utm_campaign=c2595ebd5e-BGB_17_02_14_M2_14_2017&utm_medium=email&utm_term=0_d558b0594a-c2595ebd5e-157537501&mc_cid=c2595ebd5e&mc_eid=649f4a5ca2

Ewe-Modrich, R. (2017, April 12). Discussion on Building Information Modeling. (N. Wheating, Interviewer) San Francisco, CA.

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., … Woloszyn, M. (2015). Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Building and Environment*, *90*, 51–59. https://doi.org/10.1016/j.buildenv.2015.03.022

Franzoni, E. (2011). Materials selection for green buildings: Which tools for engineers and architects? *Procedia Engineering*, *21*, 883–890. https://doi.org/10.1016/j.proeng.2011.11.2090

Frondel, M., Simora, M., & Sommer, S. (2016). Risk perception of climate change: Empirical evidence for Germany, *137*(10), 173–183. https://doi.org/10.1016/j.ecolecon.2017.02.019

Gan, V. J. L., Cheng, J. C. P., Lo, I. M. C., & Chan, C. M. (2016). Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. *Journal of Cleaner Production*, *141*, 825–836. https://doi.org/10.1016/j.jclepro.2016.09.126

Gould, F. (2005). *Managing the Construction Process: Estimating, Exchulding, and Project Control*. Upper Saddle River, New Jersey: Pearson Education, Inc.

Hamblett, T. (2017, February 14). Discussion on Construction Activity Reporting at San Francisco International Airport Terminal One, Boarding Area B. (N. Wheating, Interviewer) San Francisco, CA, United States of America.

Häkkinen, T., Kuittinen, M., Ruuska, A., & Jung, N. (2015). Reducing embodied carbon during the design process of buildings. *Journal of Building Engineering*, *4*, 1–13.

Higuchi, T., Morioka, M., Yoshioka, I., & Yokozeki, K. (2014). Development of a new ecological concrete with CO2 emissions below zero. *Construction and Building Materials*, *67*(PART C), 338–343. https://doi.org/10.1016/j.conbuildmat.2014.01.029

Hitchcock, D., Schenk, R., & Gordy, T. (2011). *Directory of Sustainability Life Cycle Assessment Tools*. *International Society of Sustainability Professionals*. Retrieved from https://www.sustainabilityprofessionals.org/system/files/ISSP_Life_Cycle_Assessment_Tools_Directory.pdf

Ibáñez-Forés, V., Pacheco-Blanco, B., Capuz-Rizo, S. F., & Bovea, M. D. (2016). Environmental Product Declarations: Exploring their evolution and the factors affecting their demand in Europe. *Journal of Cleaner Production*, *116*, 157–169. https://doi.org/10.1016/j.jclepro.2015.12.078

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. https://doi.org/10.1016/j.enbuild.2013.07.026

Imbabi, M. S., Carrigan, C., & Mckenna, S. (2013). Trends and developments in green cement and concrete technology. *International Journal of Sustainable Built Environment*, *1*(2012), 194–216. https://doi.org/10.1016/j.ijsbe.2013.05.001

Ingrao, C., Lo Giudice, A., Bacenetti, J., Tricase, C., Dotelli, G., Fiala, M., … Mbohwa, C. (2015). Energy and environmental assessment of industrial hemp for building applications: A review. *Renewable & Sustainable Energy Reviews*, *51*, 29–42. https://doi.org/10.1016/j.rser.2015.06.002

IPCC. (2007). *Climate Change 2007: Impacts, Adaptation ad Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK.

IPCC. (2014). *Climate Change 2014: Synthesis Report Summary Chapter for Policymakers. Climate Change 2014: Synthesis Report. Contributiong of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/CBO9781107415324

Issa, R. R. A., & Olbina, S. (2015). *Building Information Modeling : Applications and Practices*. American Society of Civil Engineers.

Iwaro, J., & Mwasha, A. (2014). The impact of sustainable building envelope design on building sustainability using Integrated Performance Model. *International Journal of Sustainable Built Environment*, *2*(2), 153–171. https://doi.org/10.1016/j.ijsbe.2014.03.002

Jones, C. (2016, December). The Impact of Embodied Carbon in Real Estate: CLS Holdings plc

Explore the Issue. *The Better Building Partnership*. Retrieved from http://www.betterbuildingspartnership.co.uk/impact-embodied-carbon-real-estate-cls-holdings-plc-explore-issue

Kiss, G., Jansen, H., Castaldo, V. L., & Orsi, L. (2015). The 2050 City. *Procedia Engineering*, *118*, 326–355. https://doi.org/10.1016/j.proeng.2015.08.434

Lee, B., Trcka, M., & Hensen, J. L. M. (2011). Embodied energy of building materials and green building rating systems - A case study for industrial halls. *Sustainable Cities and Society*, *1*(2), 67–71. https://doi.org/10.1016/j.scs.2011.02.002

Liu, X., & Cui, Q. (2016). Assessing the impacts of preferential procurement on low-carbon building. *Journal of Cleaner Production*, *112*, 863–871. https://doi.org/10.1016/j.jclepro.2015.06.015

Long, M. (2014). USGBC Announces Extension of LEED 2009. *USGBC*. Retrieved from http://www.usgbc.org/articles/usgbc-announces-extension-leed-2009

Lugaric, L., & Krajcar, S. (2016). Transforming cities towards sustainable low-carbon energy systems using emergy synthesis for support in decision making. *Energy Policy*, *98*, 471–482. https://doi.org/10.1016/j.enpol.2016.09.028

Madurwar, M., Ralegaonkar, R. V, & Mandavgane, S. (2012). Application of agro-waste for sustainable construction materials : A Review, *38*, 872–878. https://doi.org/10.1016/j.conbuildmat.2012.09.011

McCadden, L. (2016). USGBC Announces International Ranking of Top 10 Countries for LEED. US Green Building Council. Retrieved from http://www.usgbc.org/articles/usgbc-announces-international-ranking-top-10-countries-leed

NASA. (2017). Global Climate Change, Vital Signs of the Planet. Retrieved from www.climate.nasa.gov

Ng, W. Y., & Chau, C. K. (2015). New Life of the Building Materials-Recycle, Reuse and Recovery. *Energy Procedia*, *75*, 2884–2891. https://doi.org/10.1016/j.egypro.2015.07.581

O’Sullivan, L. (2017). Answers from a Spec Writer.

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, *23*(1), 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Pacheco-Torgal, F. (2014). Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. *Construction and Building Materials*, *51*, 151–162. https://doi.org/10.1016/j.conbuildmat.2013.10.058

Rainville, A. (2016). Standards in Green Public Procurement – A framework to enhance innovation. *Journal of Cleaner Production*, 1–9. https://doi.org/10.1016/j.jclepro.2016.10.088

Ritchie, K. (2017, February 12). Discussion on Embodied Carbon Emissions in the Building Industry. (N. Wheating, Interviewer)

Rutherford+Chekene. (2016). Materials Specification: 03 30 00 -Cast-In-Place Concrete. San Francisco: Rutherford + Chekene, San Francisco International Airport Terminal One, Boarding Area B.

Saghafi, M. D., & Hosseini Teshnizi, Z. S. (2011). Recycling value of building materials in building assessment systems. *Energy and Buildings*, *43*(11), 3181–3188. https://doi.org/10.1016/j.enbuild.2011.08.016

Salazar, J., & Meil, J. (2009). Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. *Journal of Cleaner Production*, *17*(17), 1563–1571. https://doi.org/10.1016/j.jclepro.2009.06.006

Samson, J., Berteaux, D., Mcgill, B. J., & Humphries, M. M. (2011). Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. *Global Ecology and Biogeography*, *20*(4), 532–544. https://doi.org/10.1111/j.1466-8238.2010.00632.x

Schinabeck, J., & Wiedmann, T. (2014). The long road to zero – embodied carbon in the built environment. Retrieved from http://www.thefifthestate.com.au/columns/spinifex/the-long-road-to-zero-embodied-carbon-in-the-built-environment/69464

Schofield, C. (2014). UK’s first publically available embodied carbon database for buildings launches. Retrieved from http://www.arup.com/news/2014_04_april/10_april_uks_first_publically_available_embodied_carbon_database_for_buildings_launches

Smith, N., & Leiserowitz, A. (2014). The role of emotion in global warming policy support and opposition. *Risk Analysis*, *34*(5), 937–948. https://doi.org/10.1111/risa.12140

Strain, L., Simonen, K., Yang, F., & Webster, M. (2017). Whole Building Life Cycle Assessment: Promises and Pitfalls. San Francisco: Building Green. Retrieved from https://www.buildinggreen.com/webcast/whole-building-life-cycle-assessment-promises-and-pitfalls?mc_cid=bbd4c16e9a

Ternberth, K., Meehl, J., Masters, J., & Somerville, R. (2017). Overview: Current Extreme Weather & Climate Change.

The Marble Institute. (2017). Green Building: History of Green Building. Retrieved December 4, 2017, from http://www.marble-institute.com/default/assets/File/consumers/historystoneingreenbuilding.pdf

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment*, *37*(4), 429–435. https://doi.org/10.1016/S0360-1323(01)00033-6

Thormark, C. (2006). The effect of material choice on the total energy need and recycling potential of a building. *Building and Environment*, *41*(8), 1019–1026. https://doi.org/10.1016/j.buildenv.2005.04.026

Trump, D. (2017). An America First Energy Plan. Retrieved May 5, 2017, from https://www.whitehouse.gov/america-first-energy

USGBC. (2017a). Building life-cycle impact reduction. Retrieved from www.usgbc.org

USGBC. (2017b). LEED v4. Retrieved from http://www.usgbc.org/leed-v4

USGBC. (2017c). Projects. US Green Building Council. Retrieved from http://www.usgbc.org/projects

Van Den Heede, P., & De Belie, N. (2012). Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. *Cement and Concrete Composites*, *34*(4), 431–442. https://doi.org/10.1016/j.cemconcomp.2012.01.004

Vyas, G. S., & Jha, K. N. (2017). Benchmarking green building attributes to achieve cost effectiveness using a data envelopment analysis. *Sustainable Cities and Society*. https://doi.org/10.1016/j.scs.2016.08.028

Wilson, A. (2011, June). Avoiding the Global Warming Impact of Insulation. *Building Green*.

Wu, J. (2014). Urban ecology and sustainability: The state-of-the-science and future directions. *Landscape and Urban Planning*, *125*, 209–221. https://doi.org/10.1016/j.landurbplan.2014.01.018

Wu, P., Feng, Y., Pienaar, J., & Xia, B. (2014). A review of benchmarking in carbon labelling schemes for building materials. *Journal of Cleaner Production*, *109*, 108–117. https://doi.org/10.1016/j.jclepro.2015.07.067

Zhao, D. X., He, B. J., Johnson, C., & Mou, B. (2015). Social problems of green buildings: From the humanistic needs to social acceptance. *Renewable and Sustainable Energy Reviews*, *51*, 1594–1609. https://doi.org/10.1016/j.rser.2015.07.072

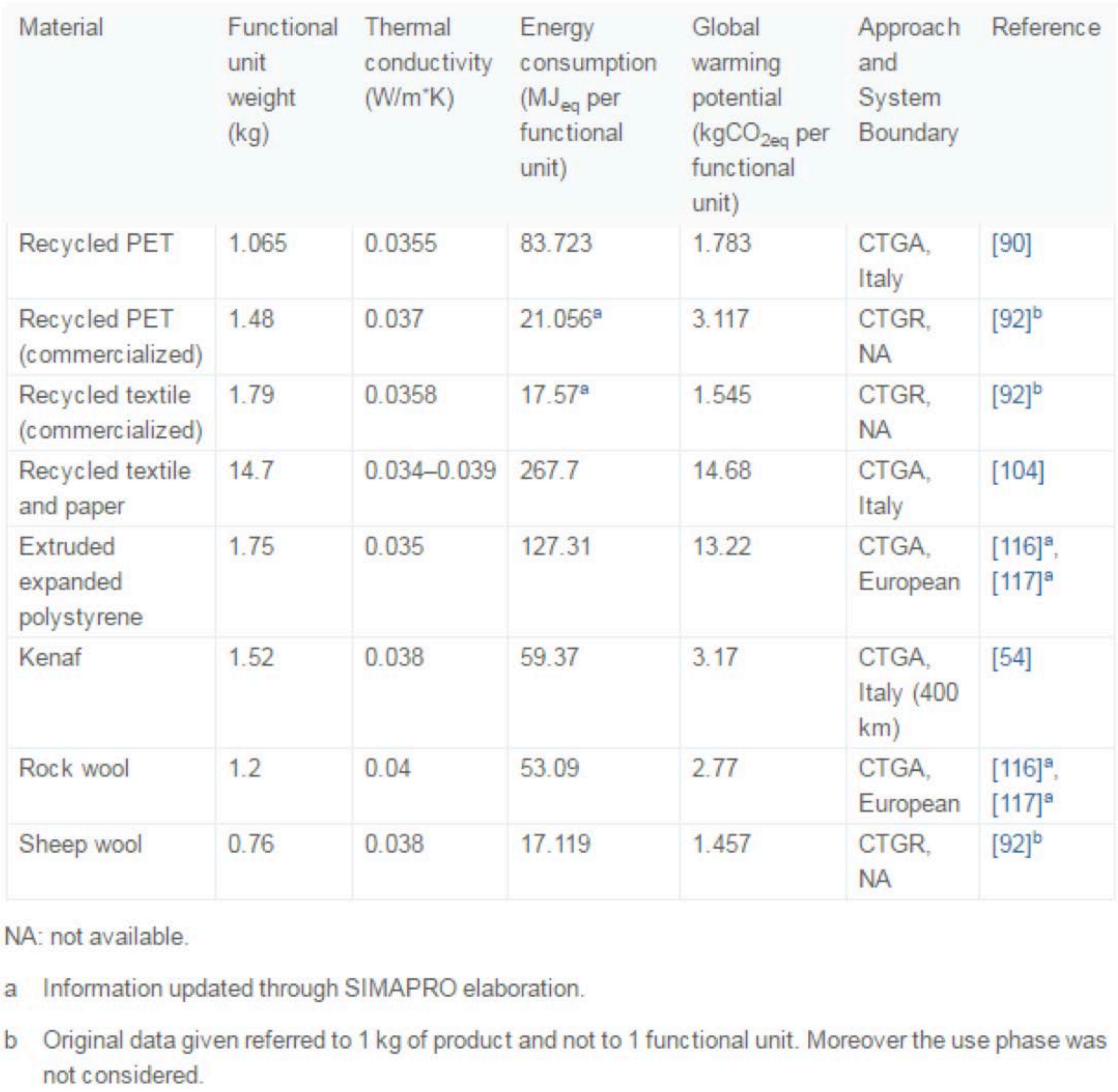
Zhao, X., & Pan, W. (2015). Delivering Zero Carbon Buildings: The Role of Innovative Business Models. *Procedia Engineering*, *118*, 404–411. https://doi.org/10.1016/j.proeng.2015.08.440

Zhao, X., Pan, W., & Lu, W. (2016). Business Model Innovation for Delivering Zero Carbon Buildings. *Sustainable Cities and Society*, *27*, 253–262. https://doi.org/10.1016/j.scs.2016.03.013

Zhong, Y., & Wu, P. (2015). Economic sustainability, environmental sustainability and constructability indicators related to concrete- and steel-projects. *Journal of Cleaner Production*, *108*, 1–9. https://doi.org/10.1016/j.jclepro.2015.05.095

Appendix A

Comparative analysis of the LCA of thermal insulation materials



Material	Functional unit weight (kg)	Thermal conductivity (W/m*K)	Energy consumption (MJ_{eq} per functional unit)	Global warming potential ($kgCO_{2eq}$ per functional unit)	Approach and System Boundary	Reference
Recycled PET	1.065	0.0355	83.723	1.783	CTGA, Italy	[90]
Recycled PET (commercialized)	1.48	0.037	21.056[a]	3.117	CTGR, NA	[92][b]
Recycled textile (commercialized)	1.79	0.0358	17.57[a]	1.545	CTGR, NA	[92][b]
Recycled textile and paper	14.7	0.034–0.039	267.7	14.68	CTGA, Italy	[104]
Extruded expanded polystyrene	1.75	0.035	127.31	13.22	CTGA, European	[116][a], [117][a]
Kenaf	1.52	0.038	59.37	3.17	CTGA, Italy (400 km)	[54]
Rock wool	1.2	0.04	53.09	2.77	CTGA, European	[116][a], [117][a]
Sheep wool	0.76	0.038	17.119	1.457	CTGR, NA	[92][b]

NA: not available.

a Information updated through SIMAPRO elaboration.

b Original data given referred to 1 kg of product and not to 1 functional unit. Moreover the use phase was not considered.

(Asdrubali et al., 2015)

Appendix B

Construction Activity and GHG Emission Reduction Acknowledgement Form

Date of Field 360 Training: ____________________

I confirm that I have been trained in Field 360 and understand the requirements set forth regarding daily log of equipment tracking during construction.

In an effort to reduce greenhouse gas emissions during construction, my team proposes to implement, at a minimum, two of the following practices. Check all boxes that apply, and provide implementation approach details for each:

Activity

- ☐ Energy efficient trailers
- ☐ Onsite energy data measurement and monitoring
- ☐ Fuel efficient transport of delivered materials
- ☐ Low emission vehicles for worker commute
- ☐ Low emission construction equipment (ex. electric power)

Activity

- ☐ Limit packaging of all delivered materials
- ☐ Limit unnecessary ordering of material
- ☐ Provide just in time delivery of fully loaded vehicles
- ☐ Minimize business travel to site
- ☐ Other

Describe the approach details to meet activity reductions selected above:

Explain how the above approaches exceed standard industry practice:

For additional suggestions, reference the following report:
http://web.archive.org/web/20150424002814/http:/www.strategicforum.org.uk/pdf/06carbonreducingfootprint.pdf

If I have questions about tracking and documentation, I understand it is my responsibility to seek clarification from the Austin-Webcor JV (AWJV) Project Team. Furthermore, I understand that my failure to comply with the policies and procedures of the plan may result in financial penalties for me or my employer.

Employee Signature: ___________________________
Print Name: __________________________________
Company: ____________________________________