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An Overview of Building Lifecycle Embodied Carbon Emissions Research

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Abstract: The building and construction industry is a sector that is heavily tied to natural resources and contributes to a large discharge of greenhouse gas emissions. It is therewith critical for the entire industry to work towards sustainable design and construction with which environmental impacts could be utmost reduced. An overview of research reveals that the primary emission type, throughout a building lifecycle, constitutes emissions at the construction stage (a.k.a. upstream embodied carbon), as well as emissions at the operational stage. While there has been a significant research interest on mitigation strategies for curbing operational emissions, embodied emissions are generally overlooked. However, recent studies have revealed that reducing operating carbon is accompanied with a little increase in embodied carbon. Therefore, this study posits that both aspects, when tackling the global carbon emissions challenge, are equally important and need to be collectively examined, and a potential resolution would be identifying the interplay between embodied and operational carbon. According to the comprehensive review on the state-of-the-art literature pertaining to lifecycle carbon issues, this study reiterates the increasing significance of embodied carbon, urges that accurate assessment approaches for embodied carbon should be formulated, and recommends that the future research focus should be placed on holistic carbon assessment standard that could calibrate both embodied and operational carbon impacts.

Keywords: Buildings; Embodied and operational carbon emissions; Environmental impacts; Climate change.

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1 Introduction

The building and construction sector is crucial as it contributes greatly in the economic growth of a nation. Such a sector, which is heavily tied to natural resources, has been long plagued as one of the major contributors of climate change^[1]. According to Chau et al. (2015), the building sector accounted for 40% of the world's energy consumption, 30% of raw materials use, 25% of solid waste, 12% of land utilisation, and 33% of greenhouse gas emissions^[2]. Moreover, the annual usage of concrete in the construction industry continues to increase by 23 billion tons^[3], and the cement industry solely contributes 5% to the global manmade CO₂ emissions^[4]. It is therefore urgent for the construction sector to formulate effective solutions and techniques to accommodate sustainable development strategies.

Basically, the building's lifecycle carbon emissions consist of two main components: embodied and operational emissions. Due to the largest share of energy-related in-use emissions^[5], embodied carbon is presently not a consideration when the building is designed, specified and constructed. However, recently, there have been solid evidences that embodied impacts of buildings also serve as the main contributor to the global emissions. Based on the types and functions of buildings, geographic and climatic conditions, applied construction methods, etc., they can occupy for more than 50%^[6] and up to 74%-100%^[7] of the building's lifecycle carbon emissions. Moreover, Ibn-Mohammed et al. (2013) claimed that the increasing proportion of embodied emissions was actually one consequence of efforts to reduce the operating emissions^[8], thereby shifting the environmental pressures from one life cycle stage to the others. This implies that there is a certain limit for the overall emission savings through reduction in operating energy; hence, sustainable design now should target towards the impacts embodied in the remaining phases of the building's life cycle.

In response, this paper aims to provide a comprehensive overview of the building's lifecycle embodied carbon emissions and the current trend concerning embodied versus operational carbon in the building's lifetime. Additionally, the paper emphasises the importance of embodied carbon along with the need for an internationally-accepted assessment framework to calibrate both embodied and operational carbon in the building performance analysis.

2 Building's Life Cycle Carbon Emissions

The whole-life carbon emissions can be categorized as Embodied Carbon (EC) and Operational Carbon (OC). While embodied carbon is defined as the carbon emitted from the extraction, manufacturing, transportation of the final material to onsite assembly, OC is the carbon expended to maintain the desired indoor environment of a building, encompassing all activities relevant to the function of the building, including HVAC system, domestic hot water, lighting and appliances^[9]. However, in practice, there are various definitions of embodied carbon, relying on the boundary of the studies and EC's different forms. Based on the chosen system boundary, there are three common definitions: cradle-to-gate; cradle-to-site; and cradle-to-grave EC (see Figure 1).

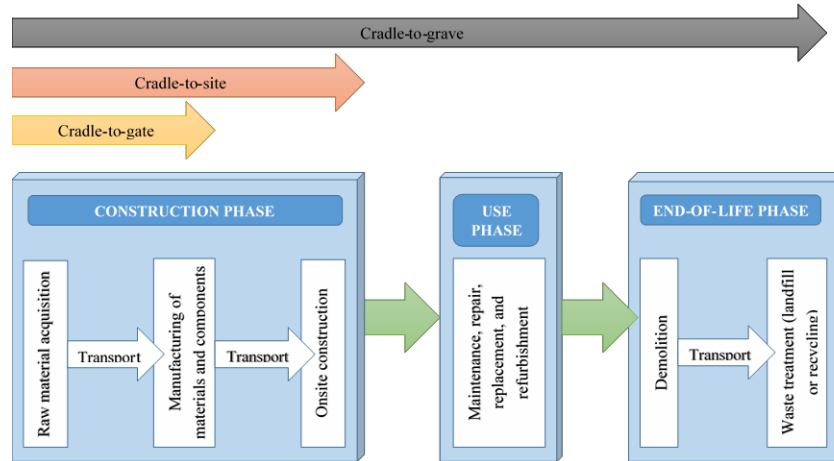


Figure 1. Building's lifecycle embodied carbon emissions (cradle-to-gate; cradle-to-site, and cradle-to-grave)

According to Li et al. (2014), embodied carbon composes of two forms: direct emissions from the assembly activities and indirect emissions, incurred in the extraction of feedstock, and the production and transportation of final building materials to the construction site^[10]. Further, embodied carbon can be defined as the summation of fuel-related carbon emissions, discharged from the production plants and equipment, and process-related carbon emissions, for example, the calcination of limestone occurring in the cement manufacture^[11]. Moreover, in the same manner of Embodied Energy (EE), embodied emissions can also be classified into: Initial Embodied Emissions, ranging from the materials production to the jobsite erection phase and Recurring Embodied Emissions, referring to repair and replacement when the material's lifespan is shorter than the building operation years^[12]. Besides, the sequestration of carbon within constructive materials, such as timber and wood components and the lifetime use of materials, namely the carbonation of concrete, should be taken into consideration as well to obtain the most accurate value of the overall embodied carbon emissions.

2.1 Embodied carbon versus operational carbon in buildings

In the past, many researchers believed that embodied impacts of a building are insignificant compared with the operational ones. For instance, Suzuki and Oka (1998) estimated that the embodied energy and carbon emissions of all office buildings in Japan accounted for 18% and 21%, respectively^[13]. Recently, Ramesh et al. (2010) have conducted a critical overview of the lifecycle energy assessment of 73 case studies across 13 countries^[12]. Results revealed that operating and embodied phases, amounting to 80-90% and 10-20%, respectively, were the main contributors of the building's lifecycle energy demand. In like manner, many other studies also found a smaller share of embodied carbon (less than 20%) in comparison with operating carbon^[1,5,14]. Consequently, reducing the operation energy consumption and carbon emissions has been long believed as being utmost importance and far more effective than tackling the embodied impacts.

However, lately, several studies have indicated that embodied carbon percentage can be higher. Based upon the type and the function of a building, along with other factors including geographic and climatic conditions, building's orientation and structural system, building's lifespan, etc. embodied carbon can vary from less than 20% for conventional buildings to as high

as 80% for low-energy buildings^[9] and almost 100% for zero-energy buildings^[15]. For example, Islam et al. (2015) asserted that emissions embodied in the construction and maintenance phases respectively amounted to 47% and 42% of the total energy demand and Greenhouse Gas (GHG) emissions^[16]. From a post-occupancy lifecycle analysis of a newly-built residential house, Crawford (2014) affirmed the significance of embodied energy and GHG emissions in the building's lifecycle^[17]. Specifically, the author figured out that EE and EC (including initial and recurrent) could respectively account for 59% and 54%, exceeding those of the operation stage.

In addition, with respect to the moderate and cooling regions, embodied energy could represent from 25% to 35% of the total lifecycle energy^[18], due to the lower operation energy demand. On the contrary, in heating dominated regions, embodied emissions only accounted for 10% of the whole building's carbon emissions^[8]. This observation indicates a sensitive manner of embodied impacts in terms of geographic and climatic conditions. Furthermore, the relative share of embodied carbon and operating carbon are dependent on the building's lifespan. To illustrate, Rauf and Crawford (2015) investigated the building's functional life and its effects on the lifecycle embodied energy of buildings^[19]. For a building's service life of 100 and 150 years, EE respectively amounted to 54% and 52% of the entire lifecycle energy. A small decline in the latter embodied energy percentage was attributed to an increase demand for maintenance and replacement during the extended time.

In case of low energy buildings, Thormark (2007) affirmed that embodied energy ranged 40%-60% of the total energy consumption^[20]. Chastas et al. (2016) undertook a literature review of embodied energy in 90 residential buildings^[7]. The results disclosed an increasing share of embodied energy in the trend towards passive, low-energy, and nearly zero-energy buildings, which were 11%-33%, 26%-57%, and 74%-100%, respectively. The gradual increase proportion from 33% to 100% of the lifecycle energy stems from the fact that reduction in operating energy could be accompanied with a little increase in embodied energy due to the application of energy efficient instruments. These findings put a question on the actual relative relationship between embodied and operational impacts and challenges the common belief of the trivial contribution of embodied carbon in a building's performance. In summary, Figure 2 illustrates a wide range of embodied impacts (EE and EC) reported in some frequently cited studies.

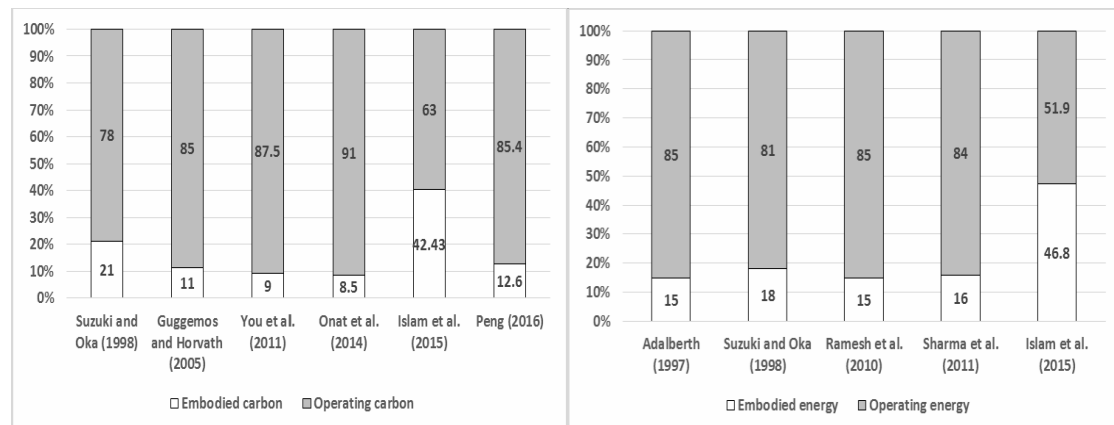


Figure 2. Embodied vs. operational impacts in the building life cycle

2.2 Embodied carbon and its variation

Despite the increasing awareness and development of computation models, there is currently no

internationally-accepted analysis framework and design standard covering the embodied environmental impacts in the building performance assessment. Thus, there is a great amount of quantification analysis studies derived for estimating embodied emissions of different building types, leading to a wide range of findings in the body knowledge. According to Eaton and Amato (1998), depending on different kinds of structures, which were steel, composite, reinforced and precast concrete, the embodied carbon of office buildings was 600-850 kgCO₂-eq/m²^[221]. On the other hand, Clark (2013) reported that the embodied carbon of office buildings varied from 300 to 1650 kgCO₂-eq/m², depending on different methodologies applied in academic and industry assessments^[222]. Likewise, Ding (2004) reviewed embodied energy obtained from previous researches for residential and commercial buildings with a wide range of 3.6-19 GJ/m²^[223]. Recently, Dixit et al. (2012) reported several parameters causing the variability of EE values, which were system boundaries, EE measurement methods, the building's geographic location, data resources' ages and completeness, technology of manufacturing processes, and so forth^[224]. Therefore, the authors emphasised the urgent need of a holistic and globally-accepted measurement protocol to evaluate the embodied environmental impacts of the building's lifecycle.

3 The significance of embodied carbon

Since the use phase is generally believed as the biggest contributor in the building's lifecycle environmental impacts, recent decades have witnessed the rapid advancement in the field of green technologies, such as energy-saving HVAC systems and the employment of advanced constructive materials and renewable energy^[225], along with the world-wide stringent regulations of sustainable policies^[226]. As a result, OC is substantially decreasing and no longer the driving force in the building sustainable performance. The massive decline of in-use emissions has consequentially led to the growing relative proportion of embodied carbon. Certainly, the application of energy-efficient measures requires sophisticated installation techniques, thereby resulting in higher material consumption and embodied emissions. Moreover, a passive design with improper material selection as well as inappropriate construction methods and waste management could further intensify the severe issue. For illustration, Wang et al. (2016) investigated the lifetime GHG emissions of two state-of-the-art commercial green buildings to disclose the relationship between low GHG buildings and green buildings^[15]. The authors recognised that the employment of exterior shadings could reduce the energy consumption of air-conditioning in the use phase, but may induce more embodied carbon emissions. Furthermore, depending on the material used for the shading system, namely, lower carbon-intensive steel versus aluminum, the growing EC of two green buildings were different. On the other hand, Sartori and Hestnes (2007) acknowledged that some self-sufficient buildings possessed extremely high embodied energy, surpassing the lifecycle energy of several low-energy versions^[227]. This indicates that there is a limitation for energy-saving in the occupancy phase and the sustainable analysis now should focus on the embodied impacts incurred in the rest of the building's lifecycle.

Besides, some recent studies highlighted the critical influence of the construction carbon emissions, when the carbon footprint accounting is scrutinised from the temporal point of view. In fact, 'the carbon spike' occurred in the early short-term lifecycle phases is more detrimental than the decades-long operation emissions, owing to the cumulative volume of GHGs trapped in the atmosphere^[14]. Furthermore, from macro-level analysis, the construction phase actually

constituted more than 60% of the lifecycle carbon and energy of the whole building sector, due to numerous construction projects being erected every year^[28]. Additionally, the annual carbon footprint per working area of the pre-occupancy stages are far higher than those of the use phase. According to Crawford and Treloar (2003), the annual operational energy of most of Australian buildings was only equal to 2-5% of their corresponding embodied energy^[29]. Hence, as the world population and the immense demand for newly-built buildings are growing, the relevant embodied environmental impacts cannot be overlooked.

4 Conclusion

While a great amount of efforts has been put into tackling the operational emissions, little attention is paid to embodied emissions occurred in the upstream processes. This prompted an overview of the lifecycle embodied carbon emission to disclose the interplay between embodied and operating carbon and verify the significance of embodied impacts in the sustainable performance of a building. Owing to the advent of energy efficiency technologies and the regulation of stringent sustainable policies, the potential for curbing operational carbon has increased. As the operating carbon is continuously reduced to approach zero energy or zero carbon buildings, the contribution of embodied carbon is on the increase. Since the increasing percentage of embodied carbon is one outcome of efforts to reduce in-use emissions, excluding the embodied impacts of the building's construction in sustainable design and assessment may cause bias in decision-making and lead to counterproductive reduction schemes. As there are several definitions and quantification analysis studies of embodied carbon, the contemporary state of research is plagued by a wide variation of EC values. Due to the increasing significance of embodied carbon and the current trend towards low-carbon buildings, it is important to develop a robust inventory data and a comprehensive methodology to streamline the EC computation framework. Moreover, the development of a lifetime carbon accounting benchmark in terms of both EC and OC is essential to provide the trade-offs amongst different design options and a better understanding of potentials of GHGs mitigation strategies.

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