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Parametric embodied carbon prediction model for early stage estimating

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ABSTRACT

The focus of carbon management is shifting from operational carbon to embodied carbon as a result of the improved operational energy efficiency of buildings. Measuring and managing embodied carbon right from the early stages of projects will unlock a range of opportunities to achieve the highest possible emissions reduction which could not be achieved otherwise during the latter stages. However, measuring embodied carbon during the early stages of design is challenging and highly uncertain due to the unavailability of detailed design information. Therefore, the research presented in this paper addresses this problem in a structured and an objective way. A parametric embodied carbon prediction model was developed using regression analysis to estimate embodied carbon when only minimal design information is available and with less uncertainty. The model was developed by collecting historical data of office buildings in the UK from four different data sources and estimating embodied carbon by combining several estimating techniques. Wall to floor ratio and the number of basements were identified as the model predictors with a model fit of 48.1% (R^2). A five-fold cross-validation ensured that the model predicts within the acceptable accuracy range for new data. The developed model had an accuracy of ±89.35% which is within the acceptable accuracy range for an early stage prediction model. In addition, the need for standardising embodied carbon measurements and to develop embodied carbon benchmarks to facilitate embodied carbon estimating throughout the project lifecycle were emphasised.

1. Introduction

Carbon management of buildings is imperative to achieve the emission reduction targets imposed on the built environment as the global construction industry is responsible for approximately 30% of the Greenhouse Gas (GHG) emissions [27,37]. Carbon management of buildings involves both operational and embodied carbon though embodied carbon is not regulated at present. However, the Green Construction Board [35] of the UK suggests that 21% reduction of embodied carbon by 2025 and 39% reduction by 2050 have to be achieved for the UK to achieve its 50% and 80% of the overall reduction targets by 2025 and 2050 respectively [35]. This echoes the need for regulating embodied carbon of buildings and calls for effective embodied carbon control mechanisms for the built environment.

Controlling embodied carbon requires carbon measurement in the first place. However, embodied carbon estimating is not a mature process as opposed to the operational carbon estimating practices. The work of Dixit et al. [10,11] and De wolf et al. [9] echoes the need for standardising embodied carbon measurement as there is a huge variation in the embodied carbon figures reported in the literature attributable to the variability of the assumptions made in the measurements. Embodied carbon can be calculated from raw material extraction (which is called the ‘cradle’) until the demolition of a building project (which is called the ‘grave’). In some cases, end of life benefits resulting from reuse, recycle and recovery of building materials are accounted in the embodied carbon calculations (which is called as cradle-to-cradle). The scope of the embodied carbon calculation is called the ‘system boundary’. Even though embodied carbon estimating practices are still developing, lessons can be learned from the well-developed cost estimating practices [3,28], as both cost and carbon can be estimated concurrently due to the same determinants (material, labour (only for cost) and plant). Accordingly, it is proven in cost studies that the highest reduction potential can be achieved during the early stages of design [4] and RICS [32] suggests that the same is true in the case of embodied carbon. Tables 1 and 9.

The reduction potential of embodied carbon in buildings have been demonstrated through alternative design solutions in the lit-

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Table 1
A review of embodied carbon estimating practices adopted in past studies.

Study	[30] Stage	System boundary	Source of EC data	Estimating technique
Halcrow Yolles [15]	4 – Technical design	Cradle-to-gate	The UK Building Blackbook	Bottom-up approach
Victoria et al. [39]	4 – Technical design	Cradle-to-gate	The UK Building Blackbook	Bottom-up approach
Sansom and Pope [34]	4 – Technical design	Cradle-to-grave (excl. recurring emissions)	GaBi database	CLEAR life cycle assessment model/ bottom-up approach
Monahan and Powell [26]	4 – Technical design	Cradle-to-site	ICE, ecoinvent, published government sources, US life cycle inventory	Simapro software/ bottom-up approach
Hacker et al.[14]	4 – Technical design	Cradle-to-grave	Published data from Institution of Structural Engineers	Bottom-up approach
Sturgis and Roberts [51]	4 – Technical design	Cradle-to-grave	ICE, conversions factors from Department of Environment, Food and Rural Affairs (DEFRA), BCIS lifespan data	Bottom-up approach
RICS [32]	4 – Technical design	Cradle-to-gate	ICE, SimaPro, GaBi	Bottom-up approach
	5 – Construction 6 – Handover and closeout	Gate-to-construction	DEFRA greenhouse gas conversion factor repository, GHG protocol calculation tools	Bottom-up approach
	7 – In use	Construction-to-grave	BCIS life expectancy of building components (BCIS 2006) + product stage sources	Bottom-up approach
Yeo et al. [42]	3 – Developed design 4 – Technical design	Cradle-to-gate	ICE, ecoinvent, World Steel Association, Franklin, USA, etc.	Probabilistic method
Construction carbon calculator	2 – Concept design	Cradle-to- construction	Web-based resources of embodied carbon intensity ratios of different building materials.	Parametric model (methodology is not transparent)
Steel construction embodied carbon tool (structure only)	3 – Developed design	Cradle-to- grave (excl. recurring emissions)	Environmental Product Declaration (EPD) published by the European Steel Industry	'Auto generated mode' estimate structural material quantities using algorithms. 'Manual input' mode allows to enter the actual material quantities
Embodied CO_2 estimator	3 – Developed design	Cradle-to- construction (excluding transport)		Not explicit though it appears to be underpinned by some form of algorithm
Carbon calculator for construction projects	4 – Technical design	Cradle-to- grave		Bottom-up approach

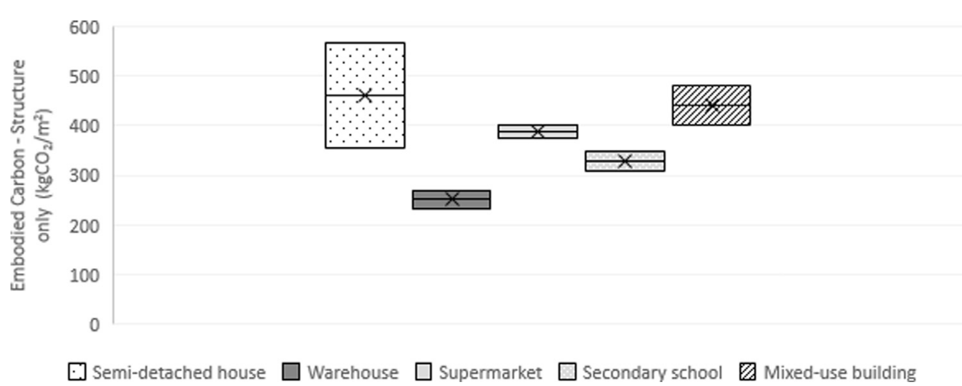

Fig. 1. Embodied carbon values of different types of buildings from the literature.

erature. Fig. 1 summarises the embodied carbon values of different types of buildings obtained from various studies. It should be noted that the values reported only include the embodied carbon of the building structure. The values of semi-detached houses were obtained from Hacker et al. [14] and Monahan and Powell [26]. A two storeyed semi-detached house was studied in both cases and alternative structural options were simulated to analyse the impact of design decisions on the embodied carbon of the building. Studies reported that the EC of the structure of the case study building ranges from 355 $kgCO_2/m^2$ to 569 $kgCO_2/m^2$ and concluded that the embodied carbon can be reduced by 51% from the structure of the building alone. The embodied carbon values of other types of buildings were obtained from the study conducted by Sansom and Pope [34]. Single case studies were employed for each type of building and the impact of alternative structural forms on the embodied carbon of each building was studied. Further, Sansom and Pope [34] adopted a cradle-to-grave system boundary which includes the emissions associated with the raw material extraction up to the demolition of the building (however, the study excluded recurring embodied carbon which covers repair, maintenance and replacement during the use phase of the building). Estimating embodied carbon using a life cycle model is a more holistic approach and desirable as it helps to see the macro picture of the emissions and cost savings achievable during the life cycle of the building. For instance, Kneifel [21] showed that energy efficient technologies can reduce the energy use in commercial buildings of up to 40% at a negative life cycle cost and suggest that initial investments on energy efficient technologies pay back several folds in the long run. However, life cycle assessments are challenging and it is hugely influenced by project specific factors.