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Carbon Analysis, Life Cycle Assessment, and Prefabrication: A Case Study of a High-Rise Residential Built-to-Rent Development in the UK

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Abstract: Recent research relating to energy use and carbon emissions by buildings has started to move from operational energy carbon impacts to the embodied energy/carbon impacts of buildings, and the methods and approaches used in architectural design to reduce embodied carbon have become more prominent. From a practitioner's perspective, working with an 'in-house' Life Cycle Assessment (LCA) tool has become a growing trend for architects, and one perceived way of improving the LCA outcomes of a proposed building is to consider prefabrication of the construction process. Initiatives such as the Low Energy Transformation Initiative (LETI) and government bodies such as Greater London Authorities (GLA) provide guidance on LCA and upfront carbon emission targets for transitioning to net zero by 2050. The aim of this study was to establish (i) the LCA impacts from prefabricated residential buildings against current benchmarks; (ii) boundaries and opportunities in architectural practice in the UK when conducting an LCA; (iii) the effectiveness of an in-house LCA tool. This study shows that, although the life-cycle emissions of this prefabricated building achieved a low band in the LETI labelling system, with 1076 $kgCO_{2e}/m^2$, it still performs better than the business-as-usual model value of 1200 $kgCO_{2e}/m^2$. The results also reveal that the construction industry is not ready to provide realistic data on the prefabrication process to test its advantages compared to conventional constructional methods. However, having an in-house LCA tool provides a faster and more comprehensive LCA due to the commitment to carbon assessment in the office and saves time compared to manual calculations.

Keywords: prefabrication; LCA; LCA tools

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1. Introduction

It has been widely acknowledged that the climate emergency requires all sectors (residential, commercial, industry, and transport) to take measures to decrease the carbon emissions from energy end-users. The role of reduction policies and strategies for the building sector has become more prominent because buildings emit 23% of the direct and indirect carbon globally among all industries [1,2]. The UK emissions figure is 25%, and up to 42% if the transport emissions are included [3].

In many previous studies of energy use in buildings [4–6], the focus was on a building's operational energy demand and carbon impacts. The reason for this was that buildings were not energy-efficient and required high consumption of operational energy to provide thermally comfortable indoor conditions to their occupants, especially in winter, due to low levels of thermal insulation, thermal bridges, and less airtight building envelopes. Therefore, in the past, operational energy and carbon emissions dominated a building's energy life cycle. This poor performance led to various approaches to increase energy efficiency and decrease Green House Gas (GHG) emissions in use. Examples of these approaches include the German energy standard Passivhaus [7], the Swiss low-energy standard Minergie [8], and Nearly or Net Zero Energy Buildings (NZEB) concepts [9]. These approaches have proven successful in keeping operational energy demands at certain levels and lowering carbon emissions in the in-use stage.

However, recent studies have shown a growing interest in operational and embodied carbon impacts. This is due to the realisation of the significant impacts from the building's construction materials compared to the operational energy demand, particularly in low-energy buildings [10–13]. Figures 1 and 2 show how the balance of operational and embodied energy varies between conventional and low-energy buildings. This is because the quantity of the material used to have an airtight building skin and, therefore, to lower heat losses, especially in the heating season in colder climate regions, is increased in new buildings. In a new building, embodied carbon can be about 40–70% of a building's whole life cycle carbon emissions [14]. The UK Net-Zero approach to decarbonising the electricity from the grid and transitioning to heat pumps shows that by 2050 the only carbon emissions from the building could be from the construction materials' embodied carbon [14].

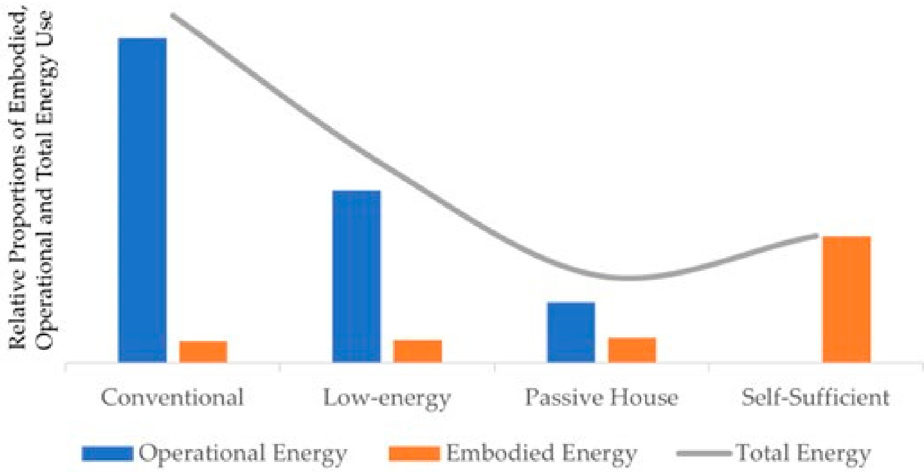


Figure 1. Relative Proportions of Embodied, Operational, and Total Energy Use in Conventional, Low-Energy, and Zero Energy Buildings [13].

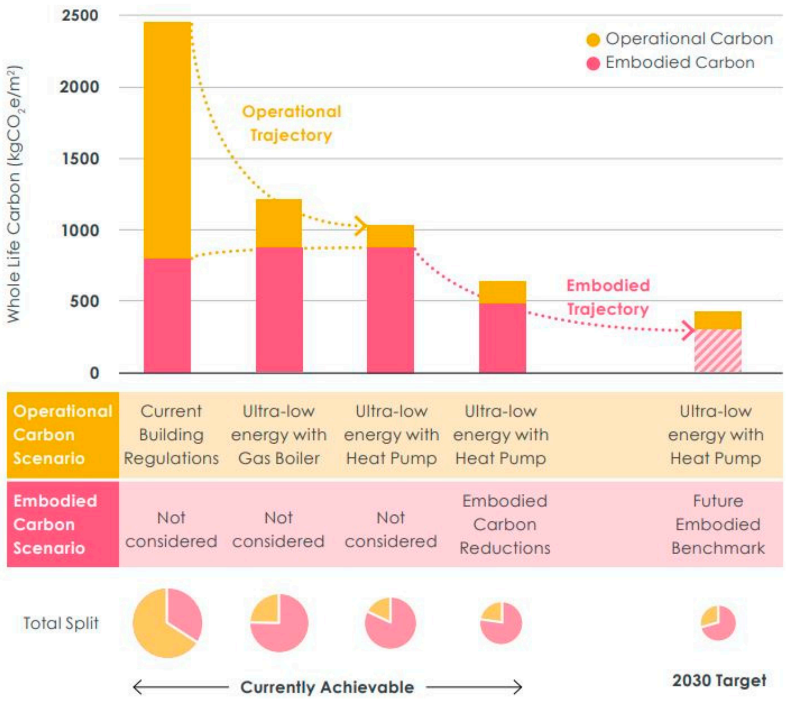


Figure 2. Embodied Carbon Trajectories Based on Different Scenarios and Current Regulations [11].

The growing awareness that both the operational and the embodied energy/carbon of a building were important has led to a range of assessment methods being introduced. These include Life Cycle Assessment (LCA) and standards such as ISO 14044:2006 'Environmental management, life cycle assessment: requirements and guidelines' and EN 15978:2011 'Sustainability of construction work: assessment of environmental performance of buildings'. These are helpful in putting the impact calculations into a standard framework when assessing the environmental impact of construction materials on a building. LCA methodologies categorise the impacts made through a material's life, such as A: manufacturing and construction emissions; B: operational emissions; C: end-of-life emissions; and, finally, D: emissions beyond the life cycle, including reuse, recovery, and recycling potential. These are shown as Modules A to D in Figure 3. Further, based on the methodology, Environmental Product Declarations (EPD) became practical to provide LCA figures for different impact categories, such as ozone depletion, acidification potential, and eutrophication potential, for individual products from manufacturers [15]. The EPD reports are third-party verified and valid for five years, keeping the information updated and reliable.

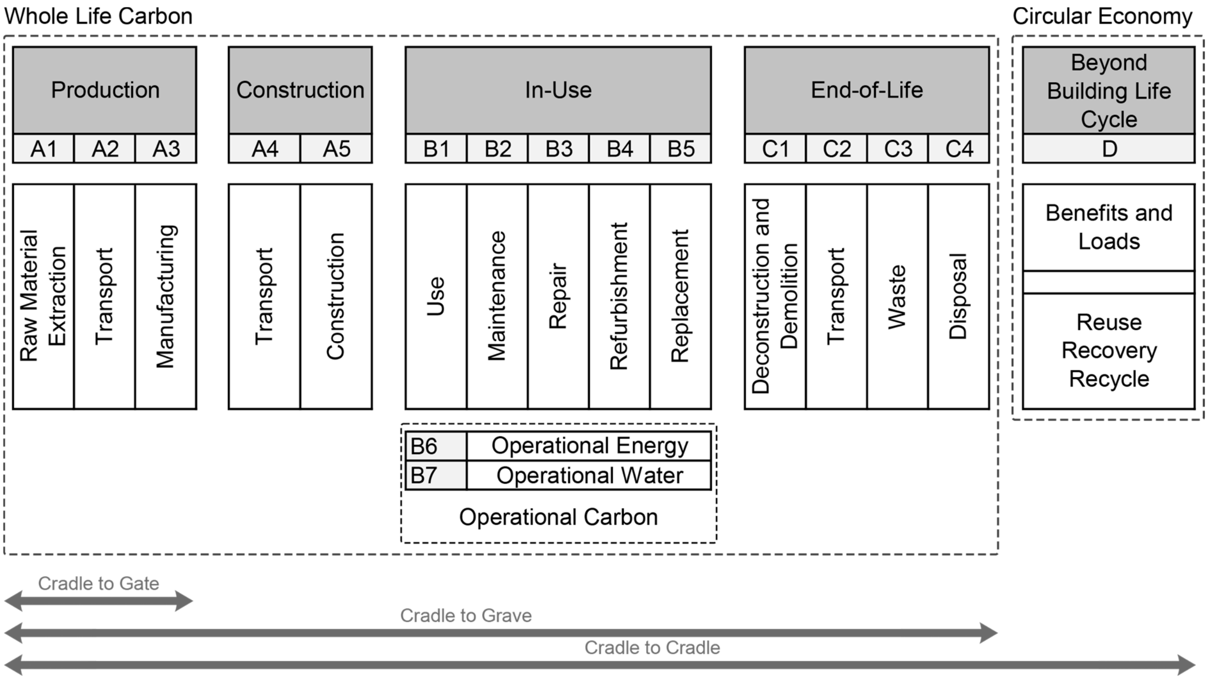


Figure 3. LCA Stages Based on EN 15978:2011.

In recent years, the Building Research Establishment Environmental Assessment Method (BREEAM) and the Greater London Authority (GLA) have started to require LCA reporting for building projects. In the BREEAM NC 2018 [16], a building can achieve up to 7 credits under the Materials heading Mat 01—Environmental impacts from construction products—Building life cycle assessment section to receive outstanding or excellence certificates. The GLA requires analysis of pre-planning and post-completion stages of a project with current carbon figures and future decarbonised scenarios.

Organisations such as the Royal Institute of British Architects (RIBA), the Low Energy Transformation Initiative (LETI), UK Green Building Council (UKGBC), and GLA have also introduced LCA guidelines for lowering embodied carbon emissions by 2050. RIBA, LETI, and GLA also provide benchmark figures and labelling system for different types of buildings to help the comparability of the projects in the building sector (see Figures 4 and 5).

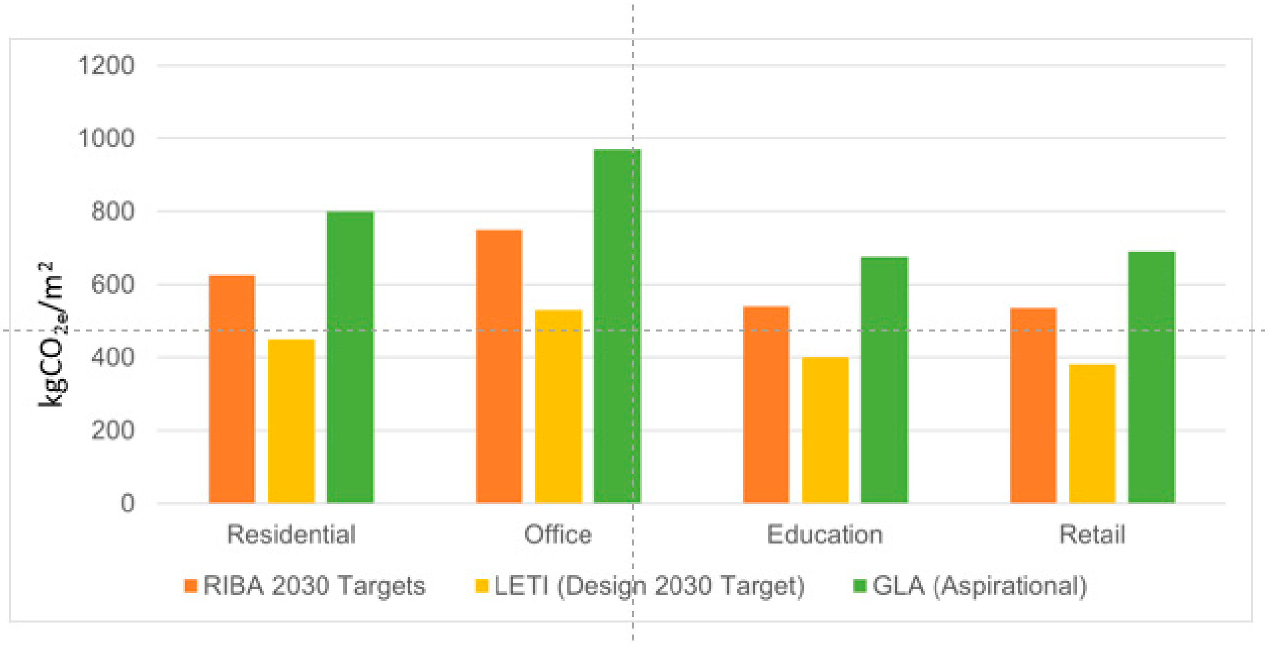


Figure 4. Whole Life Cycle Assessment Benchmarks by Building Type [17–19].

Upfront Embodied Carbon, A1-5 (exc. sequestration)

	Band	Office	Residential (6+ storeys)	Education	Retail
	A++	<100	<100	<100	<100
	A+	<225	<200	<200	<200
LETI 2030 Design Target	A	<350	<300	<300	<300
	B	<475	<400	<400	<425
LETI 2020 Design Target	C	<600	<500	<500	<550
	D	<775	<675	<625	<700
	E	<950	<850	<750	<850
	F	<1100	<1000	<875	<1000
	G	<1300	<1200	<1100	<1200

Life Cycle Embodied Carbon, A1-5, B1-5, C1-4

	Band	Office	Residential (6+ storeys)	Education	Retail
	A++	<150	<150	<125	<125
	A+	<345	<300	<260	<250
	A	<530	<450	<400	<380
RIBA 2030 Design Target	B	<750	<625	<540	<535
	C	<970	<800	<675	<690
	D	<1180	<1000	<835	<870
	E	<1400	<1200	<1000	<1050
	F	<1625	<1400	<1175	<1250
	G	<1900	<1600	<1350	<1450

Figure 5. LETI 2030 Carbon Labelling System and Comparison with LETI 2020 and RIBA 2030 Design Targets ($kgCO_{2e}/m^2$) [18].

Up to this point, the standards and methods were 'voluntary' in transitioning to decarbonised future targets in the building sector. However, in the UK, a new building regulation amendment, called Part Z, has been proposed by some building industry partners. The amendment defines the requirements of a LCA of a building and suggests limiting the GHG from construction materials in large-size projects [20]. The current proposal covers buildings with total floor areas of 1000 m^2 and above and brings the LCA into the policymaker's domain.

Along with the current developments mentioned above, other methods to lower energy and carbon impacts also became prominent in building construction. One way to decrease the carbon footprint of buildings is to reduce material waste and on-site emissions, lowering the labour and machinery hours during construction, by using prefabrication of construction components. In the UK, prefabrication is generally referred to as Modern Methods of Construction (MMC) and the process is called Design for Manufacture and Assembly (DfMA). With standardised components, prefabrication can lower the embodied impact of a building by up to 22% [21] and material usage by 20% [22].

Prefabricated construction provides a higher quality of work and greater on-site safety and is not as affected by weather conditions due to the shorter construction times [23,24]. Although it was less preferred in the past due to the lack of knowledge and experience, there is an increasing trend towards off-site manufacturing and on-site assembly (prefabrication) in the building sector. In addition, it is often addressed as a sustainable construction method in the literature, generating 40–50% less material waste than conventional construction methods [23,25].

Current studies showed that the environmental impact of buildings with prefabrication ranges greatly, depending on the size and the percentage of the prefabrication involved during the construction [26–28]. Although the prefabrication has less impact after the building elements are installed, Wang and Sinha [26] found that the emissions at the production level increase as the work in the factory environment increases. This increase could be up to 57% by simply adding a new layer of insulation to the prefabricated building element [27]. However, the study, conducted with 27 cases from the literature, showed that, overall, about a 16% reduction in embodied carbon emissions is possible with prefabrication [28].

This paper uses the development of a multi-residential project in London as a case study to establish (i) the Life Cycle Assessment (LCA) impacts from prefabricated residential building blocks against current benchmarks, (ii) the boundaries and opportunities in architectural practice in the UK when conducting an LCA, and (iii) the effectiveness of an in-house LCA tool.

2. Methodology

2.1. Case Study Building: Portlands Place, Stratford, London (also Known as the East Village Plot No:6)

Portlands Place was designed by Hawkins\Brown Architects (HBA). It is a multi-residential project with commercial and recreational areas combined on the east side of London, UK. The 57,000 sqm building has 524 apartment units and provides a commercial opportunity for F&B (Food and Beverage) and co-working space at street level. Portlands Place has two towers; one of them is 26 stories high, and the other is 31 stories. These towers are connected by a sky bridge to each other and to a ten stories pavilions (Figure 6).

The essence of this project is having a high level of prefabrication involved during its design and construction. The most important part is that the façade, bathroom pods, service risers and internal wall systems, plants and equipment, and wiring looms were to be fully prefabricated. This gave a 40% reduction in vehicle transport and 60% less people on-site [29], and it raised the pre-manufactured value to over 60% [30] in the project, which constitutes a higher construction time reduction than conventional methods.

The external façade is made of a curtain walling system, including story-height glazing with coloured glasses and Glass Reinforced Concrete (GRC). The U-value of the curtain wall system is 0.89 W/m^{2}K (opaque and glazed elements are combined), and the ratio of transmitted to incident solar radiation, g-value, is 0.33. The air tightness of the building is 3 m^3/h·m^2 @50 Pa, as specified in the Part L specification report of the project. The structural system is an in-situ concrete frame with pile foundations in the pavilions, while the only structural core is in-situ in the towers. All upper-level floor slabs and columns were cast offsite. The building's heating and hot water are connected to the central Combined Heat and Power plant (CHP) energy system, and the ventilation is provided by Mechanical Ventilation with Heath Recovery (MVHR).

Figure 6. East Village Plot No:6 (credit: Hawkins\Brown, 2020).

2.2. Hawkins\Brown Emission Reduction Toolkit (HBERT)

HBERT is an LCA in-house tool based on BS EN 15978:2011, designed for HBA [31]. The tool works as an extension to the Revit software by Autodesk and has an extensive library of construction materials, especially the ones used for HBA projects. HBERT is based on process-based analysis and uses the carbon material profiles derived from the ICE database, EPDs from manufacturers based in the UK and Europe. Alongside the materials profiles, HBERT has some generic hybrid build-ups and building components, such as steel frame structures (SFS) in different sizes, that can be easily applied to the building component layers and make the assessment process less complex and time-consuming (Figure 7). This is in contrast to the findings of Wastiels and Decuypere [32], who highlighted the low level of detail in BIM generated LCA results.

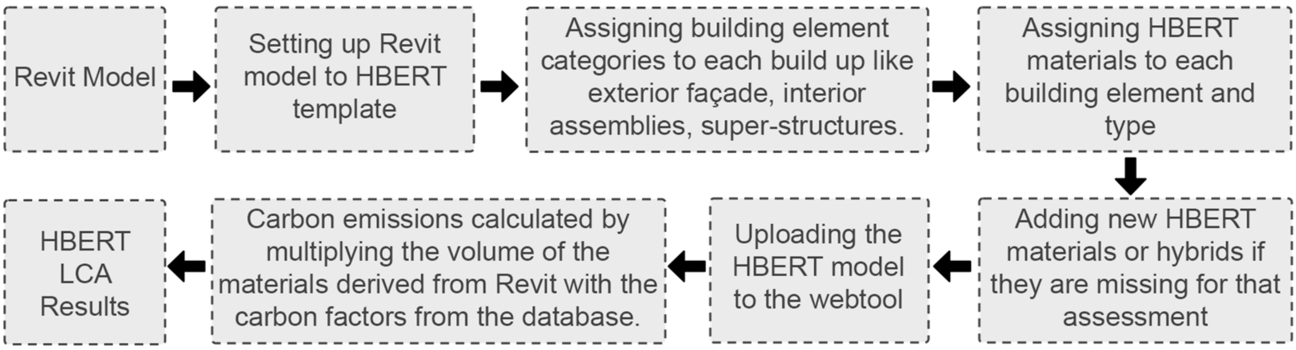


Figure 7. HBERT LCA Calculation Process.

The advantage of HBERT over other building LCA tools, such as One Click LCA, AECB PHribbon, and ATHENA Impact Estimator, is in providing real-time results, availability, and direct compatibility with BIM rather than exporting the model as a gXML file (Table 1). Additionally, HBERT overcomes some of the shortcomings of using EPDs in an LCA [32], because, being an in-house tool, it gives the freedom of verifiability of the EPDs used during the LCA calculations, meaning that the EPD validity and adaptability to different construction sizes (e.g., different size of windows or insulation panel thicknesses) are always checked by the HBA assessor/s. This is not always the case for other programs because they are controlled by their developers.

Table 1. Comparing different building LCA tools.

	HBERT	OneClick LCA	AECB PHribbon	ATHENA Impact Assessor
Database	ICE V3.0 and EPDs	ICE V3.0, EPDs and other databases around the world	ICE V3.0 and EPDs	ATHENA
Geographical Boundary	UK	World	UK	North America
BIM compatibility	+	+	-	-
Benchmark Comparison	+	+	+	-

For the Portlands Place case study, the HBERT tool was used to conduct the LCA. HBERT materials were applied to each build-up layer for each type of building assembly. To provide more granulated and comparable results, each building assembly type was assigned to 'HBERT Categories', such as External Envelope, Internal Assemblies, FF&E, Sub Structure, Super Structure, and Not Applicable. Throughout the material and category assignments process, the correctness of the Revit model was also checked and aligned with the technical drawings (Figure 8).

Figure 8. HBERT web-tool interface.

One of the useful features of the tool is that it shows the material completion percentage and Master Material Schedule. These features act as a third party in the assessment process, ensuring the completeness of the materials assigned in the project model. Therefore, HBERT does not proceed with an assessment if the total of materials assigned is less than 85%. In the Portlands Place project, 100% of the materials were assigned as HBERT materials for the LCA calculations.

2.3. The Assessment

To simplify the assessment process, the building complex was divided into 'towers' and 'pavilions' due to the similarity of the construction approach in these units, and the project was modelled in this way by HBA. Although the units were built with prefabricated components, it was realised that the repetitiveness in the project was low, especially for the façade fixings and panels. There were more than 150 types of steel fixings and 200 types of prefabricated façade modules. All these Revit families needed to be reviewed to add new parameters and to enable material assignments one by one.

Complex building components such as window frames, curtain walling mullions, and SFS, 'hybrid' HBERT materials were created. The hybrid materials are based on the volumetric information per 1 m^2 of a build-up, multiplying the volume with the material density then multiplying that with an embodied carbon figure (from a database or an EPD) of the material's unit value per kg (Figure 9). More than 15 hybrid materials and over 500 connection and fixings were used for this project assessment, which are not available in any public source for an LCA study.

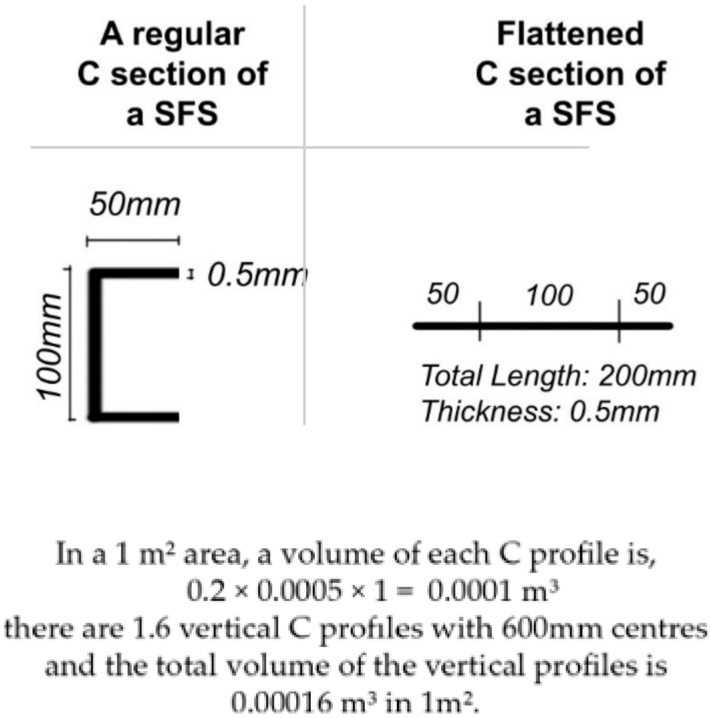


Figure 9. Example of a volume calculation for hybrid method.

Although it is a post-completion analysis, due to the availability of the data, Module A (manufacturing and transportation emissions), B4 (emissions from material replacement), and C1 (deconstruction and demolition emissions) stages are included in the LCA for a 60-year life span MEP (mechanical, electrical, and plumbing) figure, which is also based on the GLA benchmark percentages for residential buildings <1200 kgCO$_{2e}$/m^2, which represents 20% of the total impact of a project [19].

3. Results and Discussion

3.1. LCA Results against the Benchmarks

The total carbon footprint of EVn6 was 1076 kgCO$_{2e}$/m^2. Comparing this with the RIBA 2030 Climate Challenge [17] targets and LETI labelling system [18] (Figure 10), it can be seen that the building's carbon emissions fell under the RIBA 'business as usual' scenario of 1200 kgCO$_{2e}$/m^2 and LETI Band E. If the upfront carbon emissions (emissions from A1 to A5), which was 755 $kgCO_{2e}/m^2$, is benchmarked against the current targets, this falls under the LETI Band D, <775 $kgCO_{2e}/m^2$.

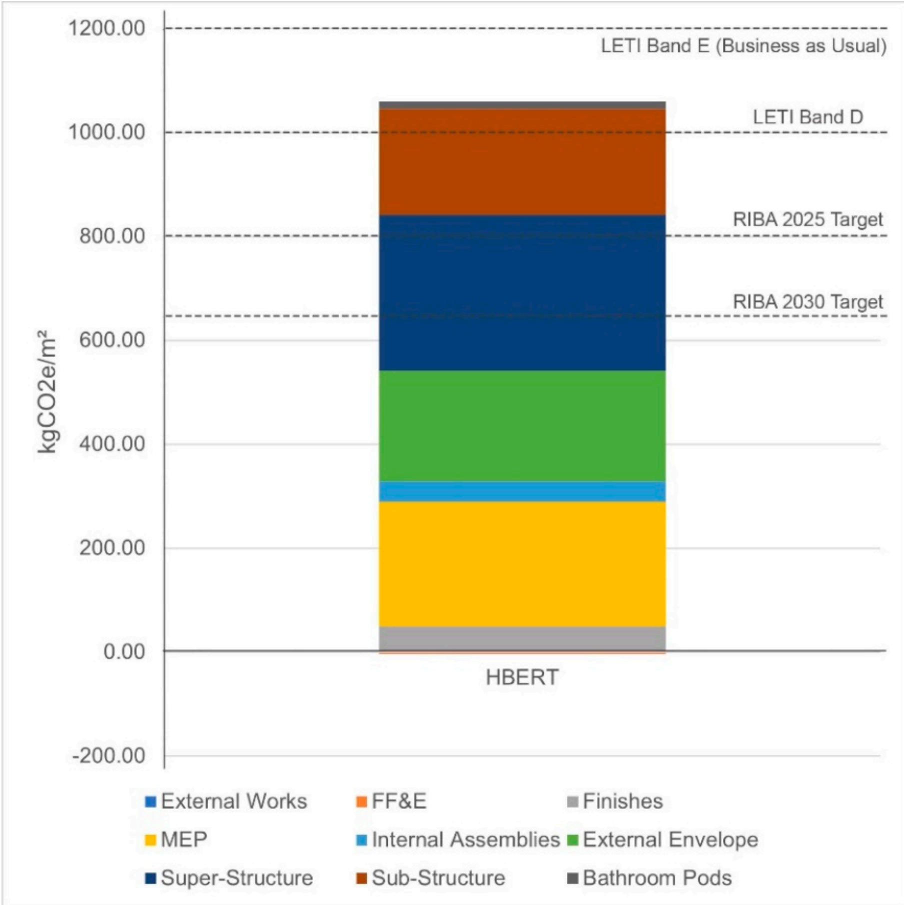


Figure 10. EVn6 LCA results compared against LETI and RIBA targets for residential buildings.

Looking further to the LCA subcategories, most impacts come from the structural elements due to the high levels of concrete and steel usage. While substructure and superstructure emissions cover 42% of the GLA's Whole Life Cycle Assessment (WLCA) benchmark for residential buildings [19], Portlands Place sets a slightly higher trend with 47%. Considering the much more detailed assessment process carried out in the LCA compared to more high-level approaches with a low level of detail in building components in the sector [32], this is acceptable. Another significant contributor is the façade modules, with about 20% 213 $kgCO_{2e}/m^2$, or around 20%, which shares a bigger portion in the GLA WLCA benchmark, 23% (Figure 11). Because the façade panels are produced offsite, with low cut-off materials and less labour, the building, including the prefab methods and the construction, has a lowering impact on carbon emission in the façade category in the LCA. Internal assemblies also draw much lower figures; this may be simply because the bathroom pods are being produced off-site, while bathrooms normally involve a complex installation process in on-site production.

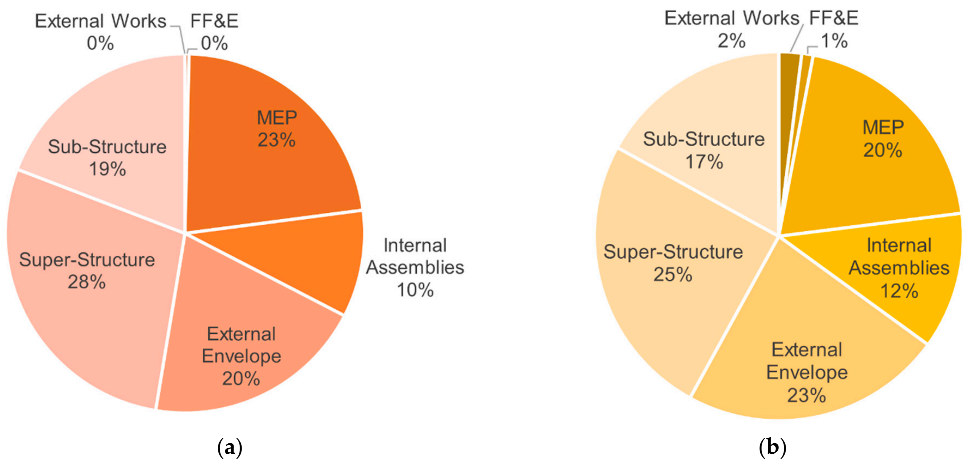


Figure 11. Each building assembly category shares in LCA (Portlands Place on the left and GLA benchmark on the right). (**a**) Portlands Place (total carbon footprint 1076 $kgCO_{2e}/m^2$). (**b**) GLA.

Comparing the results in embodied carbon level gives a different perspective. In the LETI Embodied Carbon Primer [11] for residential buildings, it can be seen that the Furniture, Fixtures & Equipment (FF&E) and External Works categories are excluded. Being very low proportions compared to the other values, they were omitted from this comparison. Structural emissions contribute 53% of the total of module A, while this is projected as 67% in the LETI document. Internal emissions also cover a much lower proportion, with a value of 7% compared with LETI's 16%. The emissions correlated external envelope is slightly higher than the LETI provision, with a 1% difference (Figure 12). However, considering the LETI Carbon Primer report targets medium-size projects and Portlands Place falls under large-size projects and the building envelope has a heavy steel curtain wall system and fixings, the module A carbon emissions of this built-to-rent development show more promising results.

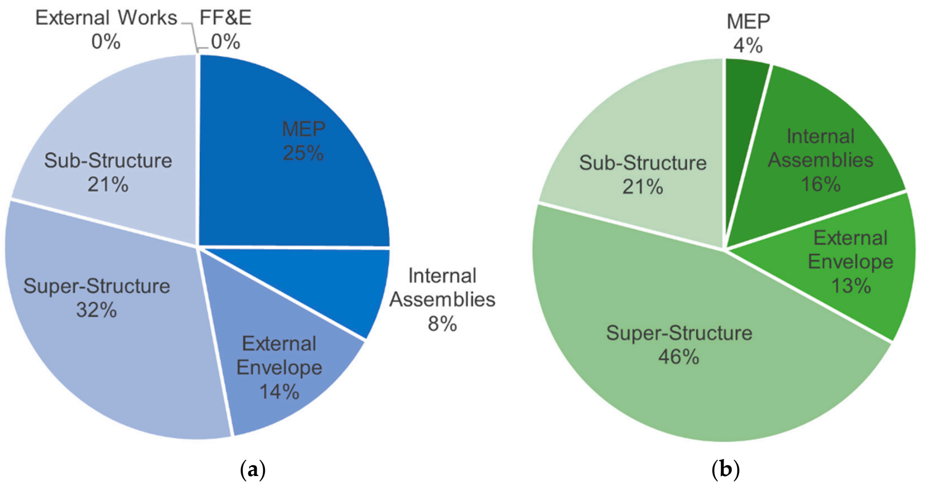


Figure 12. Embodied Carbon shares of building elements (Portlands Place on the left and LETI on the right). (**a**) Portlands Place. (**b**) LETI.

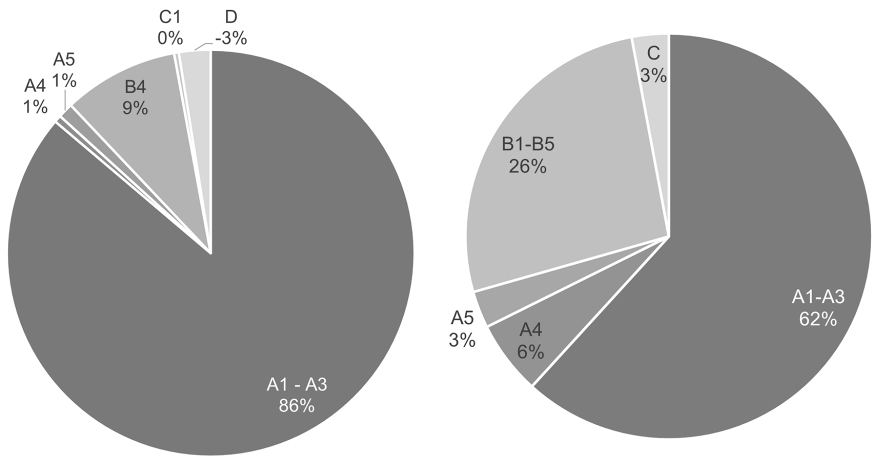
The total carbon emissions were 638 $kgCO_{2e}/m^2$ from the towers and 438 $kgCO_{2e}/m^2$ from the pavilions. Although the towers have more stories and larger GIA, they constitute 60% of the total emissions.

3.2. Prefabrication and Conventional Construction

Although this LCA exercise is essential in providing a real-life experience and sets an example for the literature and practice, care should be taken when considering prefabrication over conventional construction techniques. This brings the prefabrication to a discussion on the effectiveness of lowering the embodied impacts from buildings due to the measurability of the on-site works' emissions (stages A4 and A5).

Current databases and figures for stages A4 and A5 are mainly catering for conventional construction processes, and the emissions from those stages are measured/calculated accordingly. Therefore, when conducting an LCA for a prefabricated building, the calculation is for the same building with the same materials but constructed with conventional methods with industry averages. So, with the current tools and data, it is not always possible to measure actual impacts and establish prefabrication advantages when the main difference comes from A4 and A5 stages. A study conducted with 775 case studies highlighted that A4, A5, and C1-4 stages constitute less than 1% impact, thus omitting them does not have a significant impact on the results [33] However, these stages can be a distinctive factor between conventional and off-site buildings due to additional carbon emissions correlated with module transport and 70% less emissions on-site [34]. This should be a consideration for the next stages of LCA developments.

Another care should be taken when comparing the MMC and conventional methods at the production stage of the building assembly and materials. Unlike LETI projections, it can be seen from Figure 13 that LCA emissions clustered at 86% in A1-A3 because the majority of the construction work was carried out in the factory environment rather than on-site.



(**a**) (**b**)

Figure 13. Embodied Carbon Emissions Portions. (**a**) Portlands Place. (**b**) LETI (reproduced from LETI Embodied Carbon Primer, 2020).

Lastly, previous studies have stated that buildings with prefabricated components have a lower environmental impact compared to conventional systems. This can be between 2 and 5% with semi prefabrication [35] and up to 20–50% with high level of prefabrication involved [34,36,37]. Therefore, although Portlands Place fell below LETI Band E, it still has less impact than the business-as-usual model by around 10%.

3.3. Limitations in LCA in Architectural Practices

There has not been a specific methodology for architectural practitioners to follow or skills defined when measuring a building's carbon emissions. While quantity surveyors suggested conducting LCA studies, owing to their expertise in the bill of quantities [38], a spreadsheet method combined with BIM software is the common methodology applied in the sector due to the complexity of the calculation process [32,39]. In addition, the data being used were not always clear in the calculations, which hinders the quality and reliability of the LCA studies from practice.

The main limitation during the calculation process of this study was the availability of the construction data from the sub-contractors involved. This is because, after a project is completed, sub-contractors are not obligated to provide information regarding LCA studies in practice unless stated in the initial agreement or contracts. Even though more up-to-date information is available from a sub-contractor for a building element, it is not always possible to use those data for the LCA studies in practice due to the contract boundaries. Therefore, this kind of information exchange should be included in contracts as a binding clause.

Another issue revealed by this study is that, although toolkits such as HBERT provides simplified methods for the LCA, the modelling details are not always fit for purpose. For example, window and door frames or curtain wall mullions. Drawing these elements as a void mass in a Revit model is much easier and faster, making the model file less heavy than modelling in detail (Figure 14). This approach hinders the simpleness of a BIM-LCA tool, making the process more complicated by finding a new EPD or creating a new hybrid profile (when an EPD is unavailable for the building element) in the tool. This process would be much faster by assigning material from the database to a well-detailed building element. However, this may bring another dilemma in practice regarding the value of the time spent on LCA or during the modelling process.

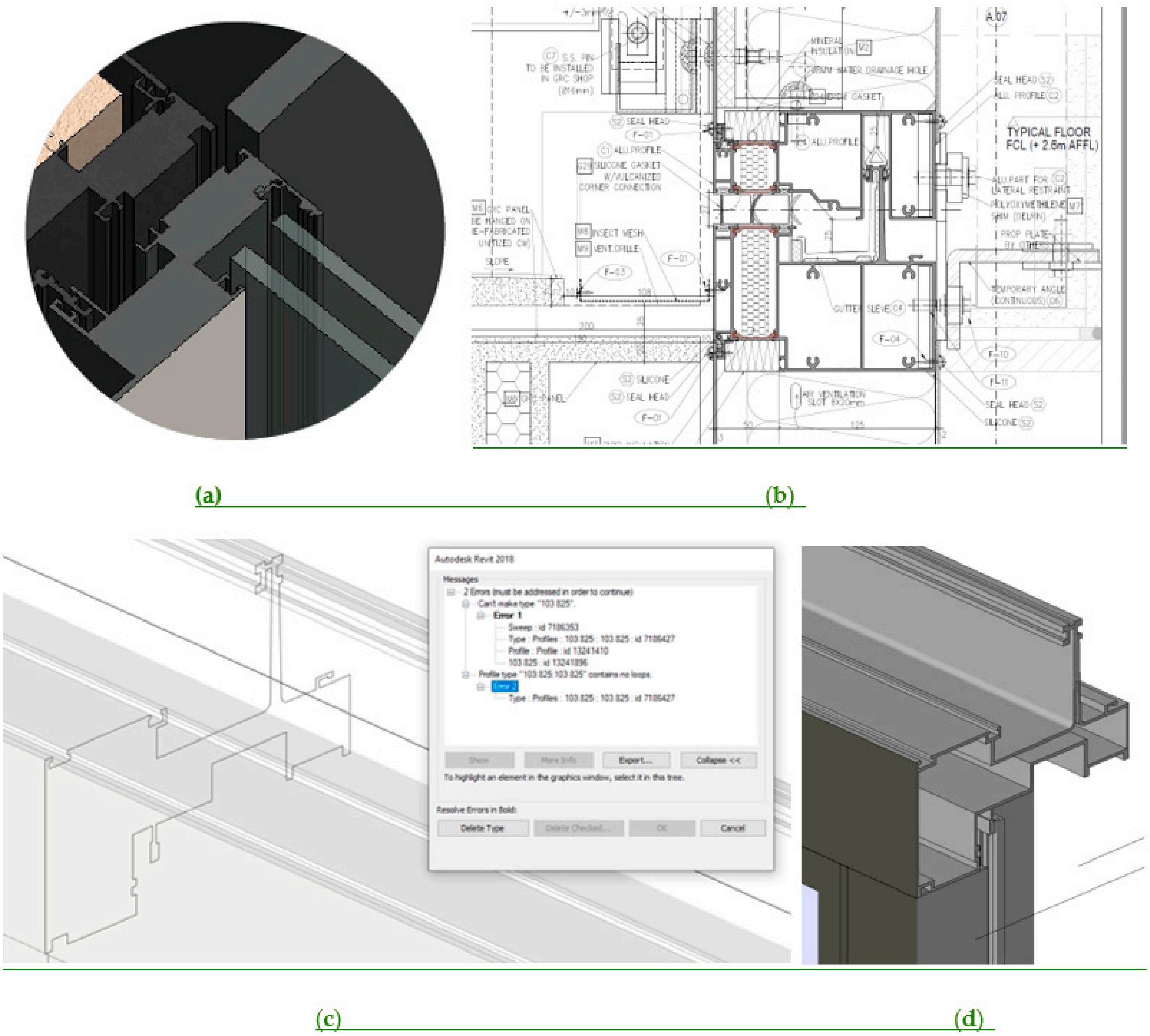


Figure 14. Void curtainwall mullion in the model versus a detailed curtain wall mullion: (**a**) Curtain wall mullion void drawing in Portland Place Revit model. (**b**) Actual drawing of the mullion. (**c**) Error window when converting the void item to a detailed mullion. (**d**) Curtain wall mullion detailed model in Revit.

One recommendation for the practitioners and policymakers would be to define the skills needed to conduct an LCA study of a building because depending on the knowledge and judgments made during the calculation can affect the overall results. In addition, quality benchmarks are needed in the data used in the LCA due to the greenwashing in the sector. Knowing that assessments achieve a certain level of accuracy can help identify the issues in the building sector and thus can help to take much more realistic measurements. Having third-party verification in building assessments, as in EPDs, can help to improve the reliability of the LCA studies. Finally, some steps have already been taken with the UK government's Building Regulation Part L proposal, GLA, and LETI guidelines for measuring the carbon emissions and labelling the buildings; the next step by the governmental bodies should be to put these initiatives in place in the UK, which should not take much longer.

4. Conclusions

This paper aimed to establish an LCA on a building with high prefabrication and compare it against the current targets and benchmarks in the UK. Although the current figures from GLA and LETI provide guidelines, it has been seen that there is still a need for more granulated and detailed benchmarking systems considering different construction systems, such as MMC.

This study also reinstated that, although the life-cycle and up-front emissions of this prefabricated building achieved a low band in the labelling system, with 1076 $kgCO_{2e}/m^2$ and 755 $kgCO_{2e}/m^2$, it still performs better than the business-as-usual models, with 1200 $kgCO_{2e}/m^2$ and 775 $kgCO_{2e}/m^2$, respectively, and other cases [19,26–28]. Therefore, including prefabrication in the construction process of a new build or a refurbishment project is an important step in reducing carbon emissions in buildings by at least 10%, which is promising at this level of prefabrication compared to other studies, which had values of about 16% [28]. In addition, A4, A5, C1-4, and module D in material carbon emission data and in EPDs should not be overlooked as they disperse the construction methods from one to another in the low-carbon design process.

The calculation process also revealed that the building industry is still not ready for a complete LCA study with high accuracy in results due to the lack of EPD and data availability and limitations in information sharing between the companies involved in the construction after completion. Contracts are not binding to support an LCA study knowledge sharing between the companies and clients.

Building methods with low impacts alone are not enough; governments and/or governmental bodies should also take steps to ensure that the practice is designing low-impact buildings and assessing the emissions transparently with labelling and verification systems, as mentioned above.

Lastly, based on the authors' experiences during the LCA process, having an in-house LCA tool was very helpful in terms of freedom and time savings in creating new materials and carbon profiles as well as a 'third-party' verification with material assignment check feature.

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