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Carbon viability of retrofitting office buildings to residential use

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ABSTRACT

The paper evaluates the carbon viability of office-to-residential retrofits. It aims to determine at what point in time a retrofit becomes more carbon-intensive than a theoretical newbuild scenario (with a similar design in the same location), primarily due to enhanced operational performance of the latter. Comparative Life cycle Assessments (LCAs) showed that despite the high embodied carbon savings of the retrofit, the newbuild scenario has a lesser carbon impact overall when considering a typical lifespan of 60–100 years. This was due to the newbuild outperforming the retrofit with regards to lower operational carbon emissions, annulling the initial embodied carbon advantage after 22 years. Considering that LCA is typically conducted for 60–80 years, and that on average a buildings' lifespan in the UK is 60–100 years, it can be concluded that the retrofit would present a significantly higher carbon footprint over the entire life cycle, when compared to demolition and reconstruction. To address this, the paper also presents recommendations for minimal energy standards for retrofits, which aims to result in significant carbon savings.

1. Introduction

Recently, there has been an emerging discussion regarding underutilised buildings in city centres, especially of that in London, UK [1–5]. Here, over 34,000 domestic properties were classed as vacant in 2022, and only 55 % of office space [6,7] is currently occupied (compared to 70 % observed pre-pandemic) [8]. This latter figure is roughly equivalent to 68 million square feet [9] of office space being unoccupied. This represents a significant economic impact (accredited to Covid-19 and changes in work patterns), and as such it is important to restore these levels to their former positions [10].

To help resolve this, the adaptive reuse of offices is of particular interest, which helps avoid wasted land space and resources (a premium in the city centre). This refers to building renovation that favourably transmutes a building to a different use type [11]. This presents a significant opportunity, with £1.3bn of Central London office stock already purchased with the intention of converting after 2022, with an additional £635 m under offer [12]. Adaptive reuse commonly involves the improvement of building performance and/or efficiency in order to meet the required standards of the new function. An alternative to this practice is the demolishment and rebuild strategy (described as newbuild in this paper), which usually involves the demolishment of part/all of the existing structure and rebuilding. Both of these strategies seek to result in an improvement of the building fabric and consequently its performance.

With regards to which holds more merit for the building stock in general, this is subject to a multifaceted discussion. For those that promote retrofit, campaigns such as RetroFirst highlight the need for a larger degree of circularity within construction, through the reuse of existing materials and structure. This is to realise higher embodied carbon savings by reducing raw material consumption, in comparison to newbuild. This is also recognised by literature, which stress the need to account and optimise both operational and embodied carbon during building renovation [13–17]. However, there are certain sociotechnical challenges which challenge the viability of retrofitting, such as the reduced taxation for new builds compared to retrofitting, and a required shift in policy [13,15]. Another commonly discussed advantage of retrofitting is that the financial cost is often lower than newbuild, especially for commercial buildings; it is estimated that the former only represents 3.3 % of the cost of the latter, not including the benefits from reduced relocation [18]. This comparative ratio is particularly apparent for retail (0.5 %) and office buildings (1 %), with similar merits also experienced for domestic buildings [19–24]. In further support for retrofit practices [2,25], RICS has found that by the practical completion stage, 35 % of the whole-life carbon of a typical office development will already have been emitted, while the figure for residential is 51 % [26].

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This indicates that an office-to-residential conversion would result in less embodied carbon, compared to demolishing the existing office and rebuilding a residential property in its place.

Various academic studies also demonstrate the effectiveness of retrofitting. Rabani et. al. utilised both an LCC and LCA model [27] to determine the effectiveness of a retrofit case study in Norway and found that the reduction of CO_2 emissions from operational energy use outweighed the embodied CO_2 emissions from retrofitting the structure. Aste and Pero provide similar findings for an office case study in Italy, with a reduced primary energy demand by 40 % after various retrofitting measures [28]. Koinakis and Sakelaris investigate energy retrofits for two different case studies in Greece, and conclude improvements in thermal comfort and energy management (optimised heating and cooling periods [29]).

Concerning demolition and rebuild (referred to as newbuild in this paper), the main advantages may include i) design flexibility, ii) updated safety and resilience within the building fabric [30], iii) reducing obsoletism and incompatibility of old and new building systems, iv) extended design life of entire building, v) enhanced operational efficiency, and/or vi) expansion or growth of the existing structure. This is beneficial, when considering the ageing stock and inconsistency of many office buildings in the UK, which are unviable to retain their use from an energy efficiency perspective [2,21,31–36].

Due to the various unique merits presented by both strategies, it is important to consider which is most appropriate for a building to improve its performance, since both options are often available. Whilst such a comparison is crucial to best improve the building stock, this is seldom completed for studies that quantify the effectiveness of either a retrofit or newbuild scenario. This paucity of comparisons is especially true for high-rise structures, of which the significance of this is discussed below [31,32,37–42]. Currently, for new residential properties Energy Performance Certificate (EPC) Band C Standard by 2035 [43] is required, and for commercial buildings (both existing and new), there is an enforcement of a Minimum Energy Efficiency Standard (MEES) from EPC E to EPC B likely by 2030 [44,45]. Overall, this represents a significant upgrade to the existing building stock. Therefore, if this assessment is not made, this directly impacts the source and amount of carbon emitted by the building. This is important to quantify, as once either process has been completed, it is impossible to recover this carbon. As a result, this may challenge the overall carbon output of the building, and will undermine any improvements in operational efficiency created. This means it is crucial for literature to juxtapose and quantitively compare multiple action scenarios. This will also help form a repository of case studies that represent multiple building typologies for future consultation and decision making.

Next, the upgradation decision will significantly impact the building fabric and associated design decisions. Here, retrofitting has different design considerations and restrictions compared to newbuild, which can affect the operational performance of the improved structure (e.g., WWR, façade compatibility with existing superstructure). This is significant, since it actually may be more carbon viable to rebuild rather than retrofit over the typical lifespan of a building. As such, it is important to not only weigh the options in terms of initial resource savings and expenditure, but also the latent impacts and considerations for each. There is limited research which discusses this carbon relationship for retrofit and newbuild (building replacement) alternatives.

Third, with the scale of buildings requiring retrofit, the urgent push towards Net Zero, and the significant potential to improve an aging building stock, the investigation to which upgradation solutions holds more merit is mandatory. This lack of studies is also recognised by Goldstein, who notes the lack of research that uses LCAs for retrofit vs newbuild [21]. If the less than optimal solution is pursued, means that retrofitting of these buildings will be required again sooner (due to falling below increasingly stringent regulations), and the carbon will be 'locked in' the building [46].

To help contribute to these gaps in research, as well as help shift the discussion towards more holistic analyses for the upgradation of the building stock, this research aims to quantitatively compare retrofit and newbuild options for an office case study in London, UK. Here, the study aims to provide a framework that can determine the conditions in which a typical high-rise would favour newbuild (with regards to life-cycle carbon) than traditional retrofit. In simple terms, this can be described at what point in time the retrofit becomes 'inefficient' compared to a newbuild (i.e., the initial carbon advantage of the former is annulled), to assess whether this exists outside the expected life span of a building (defined by RICS as 60 years). Currently, typical established frameworks do not address this [47]. The study also seeks to demonstrate that the decision to retrofit or newbuild should not only be dependent cost or convenience, but also the carbon payback achieved by both strategies.

Only a few studies could be found that possesses a similar methodology to the one in this paper. First, a study examines of the factors of housing quality through the office to residential conversion process are assessed, for both the UK and Italy from a policy perspective [25]. The study concludes that the conversion of office to residential is the 'greener option' than demolition and newbuild, due to the carbon reduction, but that the conversion should be based on applicability. However, this study has the main limitation of providing conclusions for independent cases rather than evaluating specific scenarios for the same site, meaning that the option of a retrofit is compared with a new building elsewhere. Second, a study by McGrath et al. conducts a similar comparison between a newbuild and retrofit, and concludes that the lifespan of the newbuild is likely to be greater than a retrofit [48]. This is due to the quicker obsolescence and reduced durability of the existing components of the latter (the study concludes a maximum building lifespan difference of 176 years). As such, the environmental/carbon impact of the retrofit is likely to be worse. However, this paper does not focus on a direct comparison between a newbuild and a retrofit scenario, in terms of which has lower life cycle carbon emissions. It is also unclear whether demolition emissions of the existing building are included within calculations. There are also few studies into the viability of retrofitting offices [1,27,31,32,42]. With these, the ones that present a comparative analysis tend to focus on the cost factors associated with retrofit, rather than the carbon emission through quantitative comparison [1,32,42].

As such, this study will investigate whether newbuild (demolition and reconstruction) practices can present a carbon viable alternative to retrofitting (over a typical building lifespan), which is perhaps contrary to conventional presumptions. Here, retrofitting is not being discouraged as a viable strategy, but the authors are suggesting that its environmental impact should be investigated in each case. With regards to which scenario is likely to be more carbon viable, this is difficult to hypothesise. On one hand, retrofitting enjoys a reduced embodied carbon due to less substantial changes being required, but on the other, newbuilds can receive a higher degree of operational performance improvement (with respect to having less limitations). In essence, this means that at the beginning of the project a retrofit would emit less carbon than a newbuild, but this advantage will diminish over time due to the higher operational carbon consumption. This concept will be further discussed in the consequent chapters.

2. Methodology

The paper presents a Whole Life Carbon Assessment (WLCA) assessment, to inform a comparative analysis between retrofit and newbuild scenarios for the same building. The case study chosen is the Delta Point Development in London (UK), which utilised a retrofit approach. This will be compared against a theoretical newbuild scenario. In essence, this study will identify the point in time at which the retrofit scenario becomes more carbon intensive than a theoretical newbuild. If this point is within the typical life cycle of the building, then the newbuild should have been pursued, when assessed through a carbon lens. Whilst the authors understand the various other performance metrics that dictate the degree of success of a building improvement, carbon is becoming ever-more crucial to consider, yet currently suffers from a lack of coverage in similar studies.

In terms of similar methodological approaches to this paper (comparative analysis between retrofit vs replacement to determine carbon payback), a single study could be found. Here, the authors investigated an LCA for retrofit versus newbuild for a domestic building, with a consideration for End-of-life emissions [48]. The study concluded that retrofit was more favourable than newbuild. Whilst this research has several merits, the retrofit was completed to Passivhaus standard, which in practical terms is difficult (both practically and financially for retrofits) to achieve, and thus the findings are only applicable to a small proportion of building stock. This comparison did not account for demolition of the existing building either (completed before constructing the newbuild). Therefore, this study will build on this, and conduct an analysis on a high-rise building, with an assessment to current standards. The relevance of such will be discussed in the next sections.

2.1. Location considerations

This study is based on an existing high-rise building in the UK. This is due to several reasons, including i) the lack of research surrounding such buildings and their carbon impact especially within a holistic whole life cycle framework, ii) a lack of research (that is UK based), that analyses retrofit scenarios from an LCA perspective, and none of which compares it to a theoretical newbuild scenario, and iii) London was chosen due to the current discussion surrounding its prevailing skyline and the future of London's office stock. Here, the city of London Corporation has pledged to develop at least 1,500 new homes by 2030 within the city centre called Square Mile, by repurposing existing vacant buildings and offices in a movement toward redeveloping the district after the Covid-19 pandemic [4]. As such, this research will provide a viability assessment that helps to support industrial decision making.

Out of the building stock in London, high rise buildings that are over 11 stories were prioritised when selecting the case study, due to the prevalence of buildings of this type being considered for conversion. Buildings greater than 100 m tall are generally described as skyscrapers and therefore are not relevant to this research [49–51]. With these criteria in mind, the Delta Point development was selected as the case study [52]. It is one of the largest conversions of office space to residential living in London. Situated just outside of the Square Mile, the building was converted in 2015, with 404 residential units ranging from 1 to 3 bed flats. The building was originally constructed in 1985 [53]. Fig. 1 below shows the development. This can be regarded as representative for office to residential conversions.

To model the energy consumption and carbon emissions of this building, this was done via the use of existing available documentation for the retrofit (such as EPC data), and simulation data (validated through similar studies) for the newbuild. These are discussed in detail below.

2.2. Building model considerations

It was possible to obtain most of the required information through submitted planning applications, accessed through the local authority digital portal [53]. However, it should be noted that these are planning drawings, and as such there may be an inherent element of inaccuracy when compared to the as-built construction. Nonetheless, the majority of carbon impacts are often determined at the planning stage (e.g., form, purpose, materials, overall structure), and as such these documents were deemed suitable to use.

For this study, two scenarios were modelled, and are as follows. The first will evaluate the current decision to complete a residential retrofit for the Delta Point Development. As such, this will largely be based on existing data and design decisions. The second scenario will offer a theoretical alternative, whereby the existing office building was instead demolished in 2015, and rebuilt into a residential development with the same building volume and floor area. The specifications of this latter scenario will be based on building standards and existing building stock data. With regards to modelling the building for both scenarios, it was deemed sufficient to design a single exemplar floor. This is because of the inherent modularity of office buildings; each floor is often repeated for ease of construction. After a preliminary analysis of the drawings, the third-floor level was chosen to proceed with, due to its regularity in plan.

For the retrofit, the planning drawings were exported into AutoCAD

Fig. 1. Delta Point Development Case Study (London, UK).

to obtain quantitative estimates of each material used. If any information was not provided within these documents, typical building data was assumed. Alternatively, for the newbuild scenario, the third floor was modelled in Sketch-up, and then assessed through the Sefaira plugin (dynamic energy simulation software) to obtain the operational energy usage [54]. The building model was orientated and linked to the true location to obtain accurate information, with the surrounding urban form also modelled to fully represent the daylighting conditions. An important consideration when modelling the building was ensuring that the model aligns with the required build standards; this will also be discussed later.

Through contacting the architecture practice regarding the information on the Delta Point development, it was found that due to confidentiality agreements there is no access to materiality information, apart from the building permits obtainable through the planning portal. This meant informed assumptions must be made, to quantify the building materials used in the building's construction. For both scenarios, the main body of the structure was concrete, as this is the principal material selected in the UK for this building typology [55]. The external walls/supports, floorplates and columns were assumed to be encompassed under this bracket, with many of the elements being constructed in-situ (columns are assumed to be precast elements). The thickness of the concrete floor plate was estimated to be 0.25 m thick based on an estimated suggestion for a span of this nature [56]. The general construction detailing for the newbuild presents similar material quantities to this, to provide a fair comparative analysis and to reflect the similar construction. Therefore, it is assumed the theoretical newbuild will be largely identical to that of the retrofitted development. As such, the height, footprint, and most of the structure (e.g., load bearing framework external walls, substructure) was assumed to be identical. Shafts are assumed to be kept for the retrofit, due to the similar need for residential buildings. For Delta Point, the building has no basement, and the carbon of the foundation has been divided across 8–14 floors, comparable to ~ 3.5 cm concrete slab per floor. The newbuild scenario was assumed to be built without basement as well, which aligns with the typical practice in London and would assure a fair comparison between retrofit and newbuild.

The main building elements for the newbuild considered include the windows, masonry walls, cladding, concrete floor slabs and columns, and external walls. Any minor components such as finishes and interior furnishings have not been considered, due to their insignificance towards the overall carbon output of the building, and lack of available information. These would also be similar for both the newbuild and retrofit, and is an acceptable cut-off to implement within such a comparative analysis. Due to the theoretical newbuild having less design restrictions and considerations than the retrofit, there would be some differences concerning the overall operational energy efficiency of the building. These are discussed later. With regards to the glazing for each scenario, this is as follows. Here, although unspecified within the planning documentation, the retrofit scenario was assumed to have double glazed aluminium framed windows. This is because this glazing configuration is typical of the typology and age of the building, as well as the building standard at the time of retrofit. Such a window design was reported to be implemented in a ratio of 5:7 (retained: replaced with high performance glazing). For these older windows not being replaced, a U-value of 1.6 W/m^2K was assumed, as this would meet the building standard at the time. Similarly, the newbuild was assumed to have the same glazing and window-to-wall ratio. This is because the required building standards would be the same as the retrofit, at the time of building upgrade. The difference is that no original windows were retained for this latter scenario (since it is a newbuild). The potential implications of keeping the same WWR used in the office are explained later in the text.

For the retrofit, the following u-values were achieved through upgradation: walls (1.09 W/m2K), older windows (1.6 W/m2K) upgraded into high-performance new windows (1.3 W/m2K), and roof and ceiling construction detailing were improved (0.35 W/m2K). These are based on available EPC data, combined with assumptions based on the planning documents. The heating system was also changed to implement a district scheme, with a charging system linked with programmers and TRVs (Thermostatic Radiator Valves). Low energy lighting was also provided in all fixed outlets. For the newbuild, EPC B performance was assumed as 85 % of new residential homes built in England and Wales fall within this category. The U-values are shown in Table 1 (Chapter 3.3.3.).

2.3. LCA considerations

The life cycle carbon emissions of a building, according to RICS Guidance, are commonly divided into four main phases: Product Phase (A1-A3), Construction Process Phase (A4-A5), Use Phase (B1-B7) and End of Life phase (C1-C4) [57]. This framework can be seen in Fig. 2 below. It is noteworthy that the official RICS guidance was recently updated and revised, effective July 2024.

This study utilises a cradle-to-grave framework (A1-C4) to assess the total carbon emissions ($kgCO_2e$) emitted, rather than cradle-to-cradle. Due to the comparative nature of the research, the additional D section would not impact the results, as the information is relative to the built fabric. Overall, the section was deemed unnecessary to quantify in this study.

The Reference Study Period (RSP) for this project was selected as 60 years, as this is based on the typical life expectancy of a Building [47]. Most of the building elements, for example the main structure, matches the expected lifespan of the building, and therefore are not assumed to be replaced during the RSP. Ones that are replaced are detailed in Section 3.3.2.

The framework and the calculations are similar for both retrofit and newbuild scenarios with a small exception: A0* is introduced as an additional module, that represents the demolishment of whole or part of the existing structure on site (applicable to both retrofit and newbuild) [57]. This is referred to as 'preparation emissions' in this paper. With the latest update of the RICS guidance, this is now quantified as A5.1 (preconstruction demolition) for the first time. Here, the guidance states that "actual figures should be used where possible" to calculate emissions, or alternatively an assumption of 35 $kgCO_2e/m^2$ should be used. For this study, the actual demolition emissions are calculated for both the retrofit and theoretical newbuild scenarios. This is referred to as A0* in this paper (instead of A5.1), to isolate the significance of the stage (rather than including it into the overall Stage A5).

For the operational phase of the LCA (B6 and B7), this was calculated in a unique way for each scenario. For the retrofit, the current Delta Point EPCs were used to calculate the overall operational energy per year. It is noteworthy that EPCs are based on Standard Assessment Procedure (SAP) assessments, which consider how much primary energy a structure will consume, when delivering a defined level of comfort and service provision. This enables a like-for-like comparison of dwelling performance. To calculate an average consumption that would best reflect the overall building, the median of the data was used. Since this data is not available for a theoretical newbuild, it was assumed that an EPC Grade B was achieved for this scenario. This is further developed within Sefaira, an energy simulation software which is compliant to ASHRAE 290, and LEED and BREEAM v4 Early-Stage Energy Analysis.

Table 1
Element U-values.

Element	U-Value [W/m^2K]
Walls	0.26
Floor	0.22
Roof	0.18
Glazing	1.6

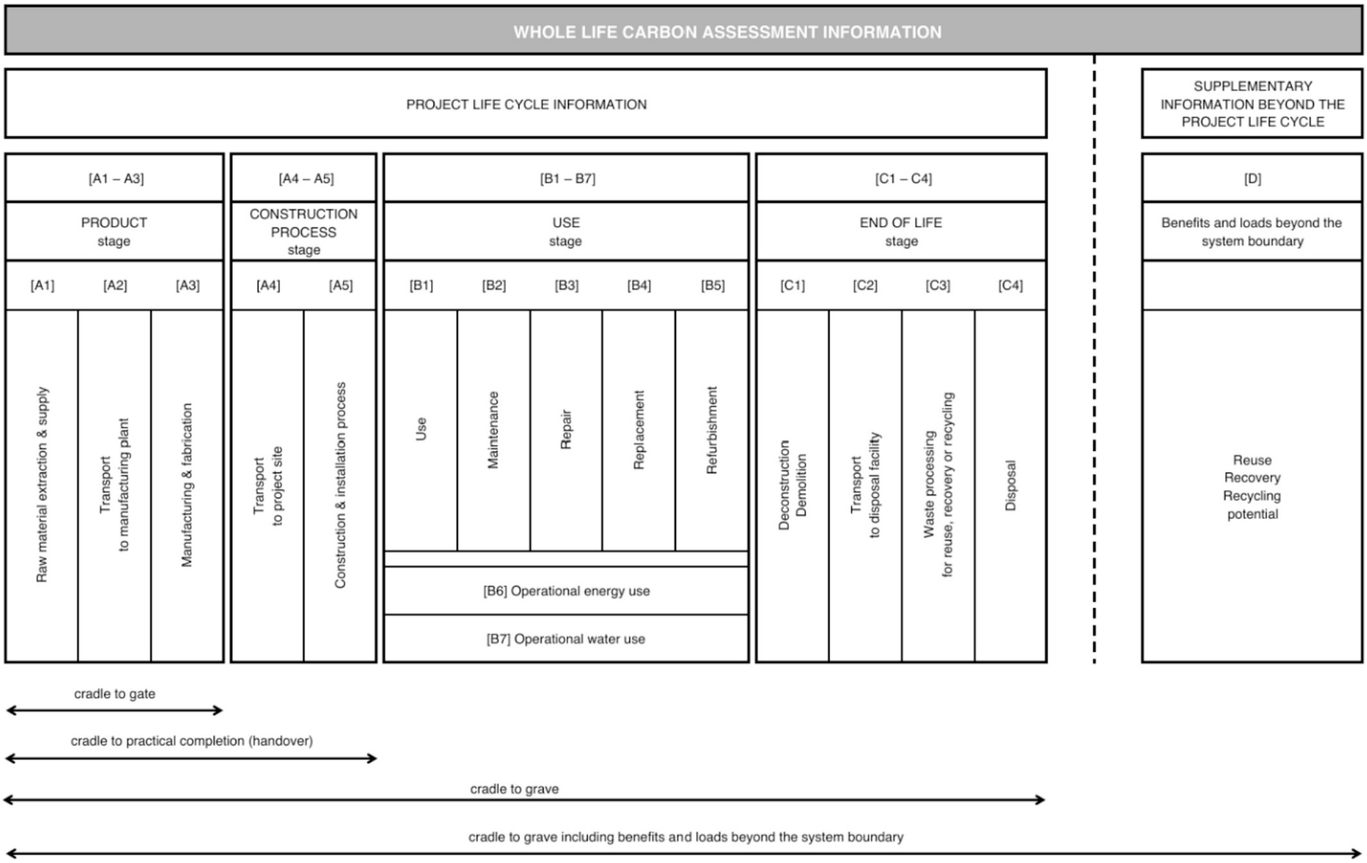

Fig. 2. RICS Project LCA Stages [57].

3. Results

For all the following sections, supplementary data and calculations can be found in the Repository [58]. This is to encourage transparency and accessibility of the study. Cut-offs for quantifying emissions were incorporated strategically for all stages of the LCA.

3.1. *A0*: Site preparation emissions*

As previously mentioned, this stage is integral to such investigations, albeit it is not currently widely adopted in LCA assessments, nor within the comparison of newbuild and retrofit scenarios. Defined as Stage A0* (represented by A5.1 within new RICS guidance), it accounts for emissions produced before the Product Stage (A1-A3), in particular the demolition of redundant structures on site. This is relevant for both the newbuild and retrofit, as both require preparation of the existing structure. For the newbuild, this would involve removing the entire former building.

For the retrofit, A0* accounts for the demolishment, removal, transportation, and recycling (where relevant) of the existing stud walls, cladding, and windows (framing and glass). Here, the emissions can be assumed to be equivalent to that produced in the End-of-Life Stages C1-C4 (as per RICS guidance). The breakdown of this is explained below. For C1, demolition processes for the stud walls, windows, and cladding were calculated and used, each with a demolishment carbon intensity factor of 3.4. For C2, the recycling of concrete, glass, windows, cladding, and stud walls were quantified. Here, domestic travel distances were assumed for all these materials. The distance to nearby landfills was also calculated, and an average taken for these sites (3.4 km). Due to the geographical location of the case study, these were relatively close to the Delta Point Development. A large proportion of the collected materials were assumed to be recycled, to represent the likely case for such a flagship project. For C3 (waste processing) a percentage of the (A1-A3) embodied carbon was taken as per RICS guidance. For C4 (disposal), the waste was assumed to be non-organic, with an intensity factor of 0.013 $kgCO_2e/kWh$. The full detailed calculation set for this, and all other calculations can be found in the Repository.

Retrofit (A0*) Embodied Carbon Total = $\underline{3171.14\ kgCO_2e}$.

New build (A0*) Embodied Carbon Total = $\underline{71{,}685.66\ kgCO_2e}$.

As expected, the carbon emission value for the retrofit scenario is considerably lower than the newbuild scenario. For the former, the largest proportion of emissions are calculated to be from the waste processing. If the two scenarios are compared, 90 % more embodied carbon is produced for the newbuild scenario. This disparity between the two scenarios is significant, and provides some justification to why assessments such as this should implement such a calculation.

3.1.1. *A1 – A3: Product stage*

Stages A1-A3 represents the embodied carbon within the building caused by the excavation of the raw materials, the transport to the plant for manufacture, and the manufacturing of specific products. It also accounts for the additional materials wasted during the erection of the building.

Overall, the retrofit would likely have a lower contribution within the Product Stage, since less of the structure would need to be replaced. Here, the superstructure is maintained, including the main concrete elements. The interior stud walls of the building were replaced with brick to meet the necessary building regulations (e.g., BS EN1996-1–1). This was quantified using floor plans and elevation drawings. Next, the windows were replaced at a pre-defined ratio. This equated to 100 window units on the exemplar third floor being maintained, with 140 replaced (due to building regulation demands for operable windows in domestic settings). The aluminium cladding was also replaced for the entire façade. Minor components such as finishes and interior furnishings have not been considered, due to their insignificance towards the overall carbon output of the building. As such, the emissions created from the brick walls, glazing, and cladding were considered within these calculations for the retrofit.

The general calculation for material contributions and the results can be seen below in Equation (1):

$$A1 - A3(KgCO_2e) = MassofMaterial(Kg)*SiteWasteFactor *CarbonFactor(KgCO_2e/Kg) \tag{1}$$

Retrofit (A1-A3) Embodied Carbon Total = 227,540 $kgCO_2e$.

New build (A1-A3) Embodied Carbon Total = 880,854 $kgCO_2e$.

Comparatively, the retrofit emitted 74 % less embodied carbon than the newbuild scenario for the Product Stage.

3.1.2. A4: Transport emissions

For the transport emissions, these were mainly accredited to the bricks, windows, and cladding for the retrofit. For the theoretical newbuild, other materials such as concrete were included within the calculations. Travel distances were based on the RICS guide, and are not inclusive of the commute of employees as these are not attributable to the project [47]. The concrete was assumed to be sourced locally (50 km). The general equation can be seen below (2).

$$(A4)EmbodiedCarbon = Mass(Kg)xTravelDistance(Km) xCarbonConversionFactor(KgCO_2e/Km) \tag{2}$$

Retrofit (A4) Embodied Carbon Total = 26,925 $kgCO_2e$

New build (A4) Embodied Carbon Total = 53,129 $kgCO_2e$

3.1.3. A5: Installation emissions

Following RICS recommendations, this life-cycle stage is split into A5.1 (pre-construction demolition), A5.2 (construction activities), A5.3 (waste management), and A5.4 (worker transport). As previously mentioned, A5.1 has already been accounted for within A0*. Emissions related to waste management (A5.3) worker transport (A5.4) are also excluded here, the former due to contributing a negligible impact, and the latter as per RICS guidance. The remaining stage A5.2 is discussed below.

RICS guidance states that for the theoretical newbuild, Stage A5.2 can either be taken as 40 $kgCO_2e/m^2$ GIA as a baseline, or site-specific data can be used instead (the latter of which was used in this study). This can be based off the construction cost and multiplied by a carbon coefficient. In the UK, RICS guidance suggests a rate of 1400$kgCO_2e$ per £100,000 construction cost for the whole building [47]. For the newbuild, the cost was estimated to be 2180 £/m^2 across a floor area of 2631 m^2, creating a total value of £5,735,580. This was then multiplied by a carbon coefficient of 1400 kg/£100 k.

In a similar manner, the retrofit cost estimate was based on the Project Value of £35 million [53] which was proportioned to the number of units present on the Third Floor (41 out of a total 404). The cost was quantified this way rather than per floor, due to the differentiation in floorplan types and usages.

Retrofit A5 Embodied Carbon Total = 49,727 $kgCO_2e$.

New build A5 Embodied Carbon Total = 80,298 $kgCO_2e$.

For these installation emissions, the proportional carbon saving of the retrofit compared to the newbuild is similar to previous research studies [27,30,59].

3.2. B1, B2, B3, B5: Maintenance and Refurbishment emissions

Across the lifecycle of a building in general, Stages B1 (in-use), B2 (maintenance), B3 (repair) and B5 (retrofit) for this type of project have a negligible contribution to the total carbon of the project, when compared to other stages (e.g., B6) [60]. To this effect, RICS recommends B2 to be 1 % of A1-A5, and B3 25 % of the B2 maintenance impacts. B5 accounts for planned improvements of assets, such as change of HVAC (heating, ventilation, and air conditioning) systems. In this case however, since no such works are planned (outside to the original upgrades presented by retrofit or theoretical newbuild), this is considered minimal.

Retrofit B1 + B2 + B3 + B5 = 3802 $kgCO_2e$.

New build B1 + B2 + B3 + B5 = 12678 $kgCO_2e$.

3.3. B4: Replacement emissions

For replacement emissions, this is recommended to be divided into B4.1 (replacement of construction products, components and systems) and B4.2 (replacement of industrial systems), albeit the latter is not significant for this study. For the former, the Reference Study Period (RSP) was chosen to be 60 years, as this is based on the standard life expectancy of this building typology [47]. Within the building, each material has a different churn rate and will directly dictate the level of embodied carbon created. In this study, the replacements of the windows and cladding were quantified. For the former, this poses a unique scenario due to the retention of some windows and immediate upgrade of others; this will be discussed below.

With regards to the windows, those that were retained for the retrofit will need to be replaced earlier than those that were already changed during the main building upgrade. This discrepancy was reflected within the B4 calculation, and as such two sets of replacements were considered for the new glazing, and three for the retained (to reflect an earlier replacement).

Retrofit = 157,828 $kgCO_2e$.

New build = 156,279 $kgCO_2e$.

It should also be noted that there may be different replacement needs for reused components in the renovation scenario. For example, it is assumed that elements of the retained superstructure will last the full life of the building (60 years). However, the building has already been in operation for around 30 years at the time of the renovation [53]. As such, there could potentially be a need for a significant retrofit sometime during the present life cycle.

3.4. B6: Operational energy emissions

For this building typology, the operational energy emissions are generally the largest contributor to the total carbon produced over the whole life cycle. With this being said, it is typically dependent on the consumed energy and carbon intensity. The process of evaluating such emissions is described below.

For the retrofit scenario, the current EPC data was used to calculate the overall operational energy per year, as the certificates present a primary energy consumption for numerous flats within the development. Here, the median consumption across all flats was selected as a representative value. This corresponded with an EPC C rating, and an Energy Use Intensity (EUI) of 175 kWh_p/m^2a. Overall, 96 % of the flats in the retrofit development were EPC Grade C, with the highest primary energy consumption being 249 kWh_p/m^2a. The authors are aware that EPCs may present inaccurate representations of emissions and energy usages in some cases, however they were deemed appropriate in this case [61].

Although the exact energy mix is typically required to convert EPC data into emissions, residential properties at this EPC rating are likely to rely solely on electric supply, without the use of gas [62]. Therefore, it is assumed that the Delta Point retrofit would be entirely supplied through the national electric grid. For this, the carbon emission factor at the time of the retrofit would have been around 0.207 $KgCO_2e/kWh$ [63]. Whilst exact data for 2015 could not be found, this was deemed suitable for use, and it was kept consistent across both the retrofit and newbuild.

For the newbuild scenario, the energy consumption benchmark from RIBA for this building typology was used (130 kWh/m^2a), validated through the use of Sefaira (explained below). For the latter, a key consideration was the specifications of the building elements. These were estimated based on the overall energy demand of the building and typical specifications, if EPC Grade B conditions are assumed to be achieved. The U-values of each material have been provided below in Table 1. These were directly integrated within the Sefaira software, to provide an estimation of the overall energy use intensity. Any unknown variables were assumed based on the required build quality (e.g., g-value of the glazing).

The author recognises the limitations of such software, primarily a lack of detailed parameterisation available. However, this software was considered acceptable, as the theoretical building design could be modelled with sufficient accuracy and is typical of what would be produced at Schematic Design stage (RIBA Stage 2). The software is also compliant to various early design stage standards (see Chapter 2.3). The building model can also be seen below in Fig. 3.

Overall, it was calculated that the Energy Use Intensity (EUI) of the building was 128 kWh/m^2a, which as expected is less than the retrofit, and is consistent with the RIBA figure used. This is primarily due to the windows being improved (represented as an improvement in both u- and g-values), and the replacement of the aluminium cladding. The window improvement was directly inputted through parameterisation, whilst the latter was represented by improving the insulation value of the external walls. This EUI corresponds to EPC B [64].

Sefaira was also used to model the assumed retrofit construction detailing, achieving an EUI of 169 kWh_p/m^2a. This was based on the known construction detailing and planning documents provided. Infiltration and ventilation rates were assumed to be consistent with a typical residential building. Overall, it was deemed acceptable to use the value provided by the EPC C classification (175 kWh_p/m^2a).

In terms of the breakdown of energy usage for the exemplar floor, this can be seen below in Table 2 for the newbuild. Here, the majority of primary consumption is from heating (59 %). With regards to lighting, the floor was predominantly well-lit according to residential living standards, which was recommend at 301.4 lx. The Spatial Daylight Autonomy (sDA) was recorded as 86 %, and the Annual Sunlight Exposure (ASE) 46 %. The COP used for heating and cooling services considered the use of Heat Pumps (4.2 and 4.0 respectively). The site-to-source conversion factor used was 3.167kWh_e/kWh_p.

Newbuild EUI = $\underline{128\ kWh/m^2a}$.

Retrofit EUI = $\underline{175\ kWh/m^2a}$.

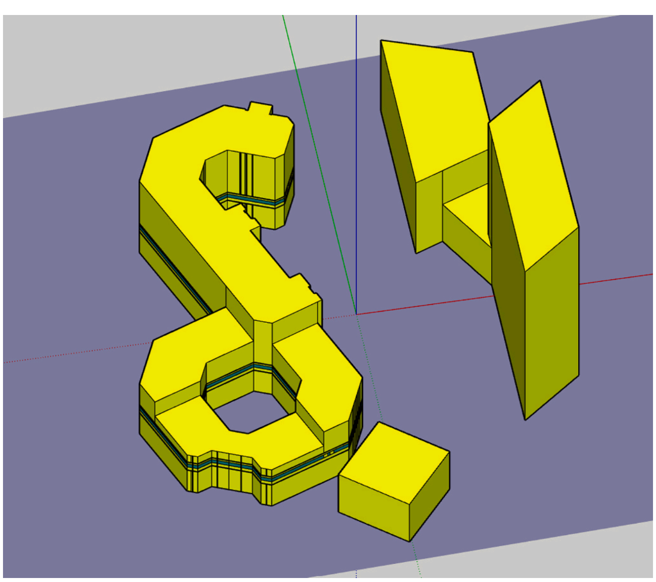

Fig. 3. Delta Point Development modelled in Sefaira, with a single floor highlighted for analysis.

Table 2

Operational Energy Consumption calculation for the newbuild scenario [65,66].

Type	Operational Energy Demand (kWh/a)	Final Energy (kWh/a)	Primary Energy Use (kWh/a)
Heating gas	199,221	47,433	150,220
Cooling	1682	420	1330
Illumination	34,185	34,185	108,264
Equipment	83,909	83,909	265,739
Fans and pumps	18,630	18,630	59,001

3.5. B7 – Operational water consumption emissions

For the emissions created through water consumption within the structure (B7.1, B7.2, and B7.3), this was deemed to be same for both the retrofit and newbuild scenarios. This is because the building demand will be very similar. The daily water demand was calculated on the basis that each person within the property consumes 120 L per day [67]. The number of users was calculated based on the planning documents, calculated to be 114 for the third floor. The water supply carbon coefficient (0.149 $kgCO_2e/l$) and water treatment carbon coefficient (0.272 $kgCO_2e/l$) were also accounted for in calculations.

Operational Water Consumption Emissions = $\underline{1717\ kgCO_2e/a}$.

3.6. B8 – User activities

For other user activities (B8.1, B8.2, and B8.3), these were assumed to be negligible for the project and as such this stage was omitted.

3.7. C1 – C4 End of life emissions

This element of the LCA for both scenarios was deemed to be the same, due to the similar processes that would be required to dismantle and decommission the building. For C1 (Deconstruction and demolition), RICS guidance recommends quantifying this stage as a proportion of A5.2 impacts (3). To account for business as usual, this should be 25 %.

$$C1Emissions(KgCO2e) = A5.2Emissions*0.25 \tag{3}$$

C1 Emissions = $\underline{8945\ kgCO_2e}$

For C2, the distance of travel from the building to the waste management site is dependent on whether the material is recycled or disposed of. This means the mass of waste was separated for the two scenarios. The Transport Carbon Factor used was 0.0001065 $kgCO_2e/kgkm$ [47].

$$\begin{aligned} C2Emissions(kgCO_2e) = {} & MassofWaste(kg) \\ & *TransportCarbonFactor(kgCO_2e/kgkm) \\ & *Distance(km) \end{aligned} \tag{4}$$

C2 Total Transport Emissions = $\underline{53{,}059\ kgCO_2e}$

For C3 (waste processing), this applies to materials which are being recycled and is recommended to be calculated as a percentage of the (A1-A3) embodied carbon value. Due to the materials being recycled, the amount of carbon emitted into the atmosphere is reduced considerably, so the ratio is 98 % [68] less than the materials being disposed of at landfills. Therefore, the C3 Value is calculated as below (5).

$$\begin{aligned} C3Emissions(kgCO_2e) = {} & MassofWaste(kg) \\ & *MaterialCarbonFactor(kgCO_2e/kg)*2\% \end{aligned} \tag{5}$$

C3 Total Waste Processing Emissions = $\underline{12{,}966\ kgCO_2e}$

For C4 (disposal), the waste material masses are all deemed to be 'non-organic' waste. Therefore, the landfill carbon emission factor is recommended to be 0.013 $kgCO_2e/kg$ [47].

C4 = 4113.35 $kgCO_2e$.

Total End of Life Emissions (C1-C4) for Both Scenarios = 79,083 $kgCO_2e$.

4. Discussion

As previously mentioned, the primary objective of this study is to observe whether a newbuild option would have been better from a carbon perspective to pursue for Delta Point, compared to the retrofit which was completed in 2015. The findings can then be extrapolated to similar building typologies and cases, to inform future decision making and policymakers. This study quantifies the emissions released at each life cycle stage, within a cradle-to-grave framework. The results of this are discussed below.

The overall data for both scenarios is presented below in Fig. 4, split into each major life cycle stage. The emissions are displayed as per million $kgCO_2e$ in the graph. For the retrofit and newbuild scenarios, the overall emissions were calculated to be 7.19 and 6.21 million $kgCO_2e$ respectively. As such, from a whole life-cycle carbon perspective, the newbuild would have likely offered a more advantageous scenario. In terms of the carbon intensity of the newbuild, this is equivalent to 2155 $kgCO_2e/m^2$. This is higher than similar scenarios presented by literature (typically up to 1650 $kgCO_2e/m^2$) [64,69]. Possible reasoning for this is i) the inclusion of A0* (discussed later), ii) differences in LCA protocols and methods, iii) extent of modifications, material uses and efficiency enhancements for each scenario, and iv) inaccessibility of information for the theoretical newbuild [70].

For the A0* stage, this accounted to 12 % of the overall carbon produced for the theoretical newbuild scenario. This is significant, as this stage is not normally considered within literature, and as such the overall carbon assessment of a building would be underreported by this amount. This would ultimately challenge the reliability of such assessments and may not provide a true reflection of a building's emissions. As such, the demonstrated influence of A0* may influence the decision to retrofit or newbuild.

The overall carbon of both scenarios is primarily driven by the operational energy usage of the building. This is a sizable contribution and is an expected result which correlates with the general findings of similar buildings typologies and case studies [71,72]. For the retrofit scenario, operational carbon comprises around 92 % of the total emissions, and for the newbuild this was 79 %. This reflects the significant impact of the chosen energy efficiency level of the retrofit on the whole carbon impact; this also aligns with similar studies [73]. Here, the retrofit operational emissions were calculated to be 36 % higher than the newbuild scenario, due to differences in functional efficiencies.

To quantify this impact of the operational efficiency within the decision to newbuild or retrofit, the authors have proposed a sensitivity analysis framework comprised of different energy consumption scenarios. Here, four different retrofit operational efficiencies are investigated for the present case study and compared against the theoretical newbuild. This seeks to indicate in what conditions the retrofit would have been more carbon viable than the newbuild. In addition, through using a timeline approach, it can be identified at what year this happens. If this point in time is within the 60 year RSP, then the retrofit should have been pursued instead, as after this identified year carbon savings would start to accrue. A similar concept can be seen in [74], but instead is applied for window options.

The EPC retrofit scenarios are summarised in Table 3 below. These are comprised of the current retrofit scenario, and two other improved cases.

All retrofit scenarios start from Year 0, which equates to the embodied carbon of the Product and Construction stages (A0*-A5). These are then modelled over a 60 year RSP. To account for the increased operational efficiency of the improved scenarios, the embodied carbon has also been increased. As such, a nominal 15 % increase has been added for the 'Improved EPC C' scenario, and a 30 % increase on the 'EPC B'. This increase mainly results from the need for additional insulation, improved mechanical systems (e.g. floor heating) and renewable energy sources (e.g. solar panels), which are important driving factors in improving EPC ratings.

As shown in Fig. 5, both the current EPC C and Improved EPC C retrofit scenarios both intersect the newbuild EPC B in years 22 and 41 respectively. This means that neither of these scenarios present a more carbon advantageous option when compared to the newbuild, as after

Table 3
Delta Point Retrofit Scenarios.

Retrofit Scenario	*Primary Energy Value (kWh/m^2a)*
Improved EPC B Retrofit	130
Improved EPC C Retrofit	151
Current Retrofit (EPC C)	175
Current Newbuild (EPC B)	128

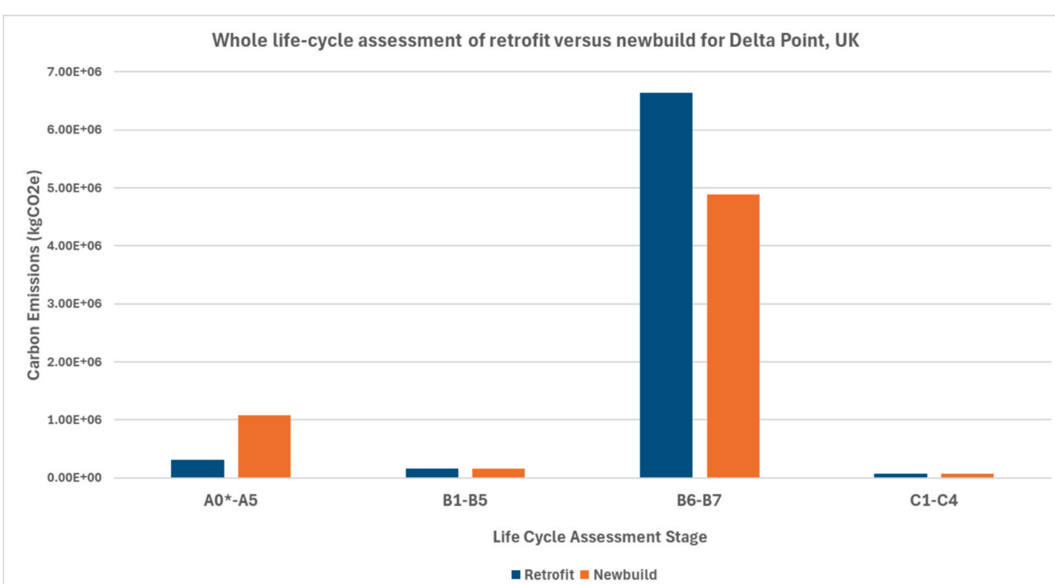

Fig. 4. Whole life-cycle assessment of retrofit versus newbuild for Delta Point, UK.

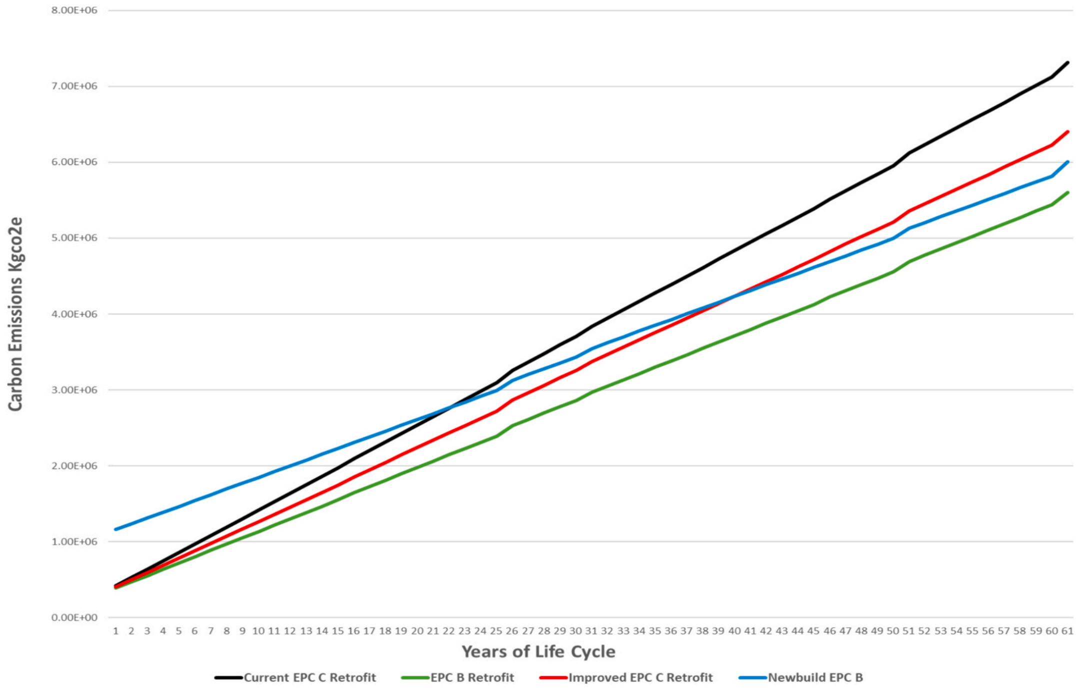

Fig. 5. Operational efficiency scenarios for the Delta Point Development.

this year the carbon becomes comparatively higher. Out of all four scenarios measured, the EPC B retrofit presents the best option, even when compared to the newbuild. This is an expected result, since the improved retrofit would experience similar operational efficiency, but at a lower embodied carbon cost. As such, these results show that unless an EPC B rating (and associated build quality/efficiencies) could have been achieved for the Delta Point retrofit in 2015, then opting for newbuild would have been better with regards to life cycle carbon.

Another useful aspect of such a comparative tool is that the maximum primary energy use of the retrofit can be calculated, such that it produces a carbon advantageous building compared to a theoretical newbuild. For the present study, the retrofit would have to keep primary energy use under 142 kWh/m^2 (instead of the current 175 kWh/m^2).

Fig. 5 also can be interpreted in another way. Since the newbuild scenario has higher initial embodied carbon but lower operational emissions, the former could be seen as an initial investment to lower annual emissions over the lifecycle.

It should be noted that whilst carbon viability is a crucial aspect towards Net Zero, there are other implications that must be considered for such projects, including construction costs and challenges. Whilst studies generally suggest that retrofit projects (for office-to-residential conversions) have lower initial financial and carbon investments (and therefore would be more attractive to investors and funding), this must be offset against the potential design difficulties faced (e.g., more stringent building codes and design limitations). These challenges, combined with the fact that embodied carbon is not widely monetised, may mean a newbuild is considered more attractive, even if this is not the most carbon advantageous solution across the life cycle [70]. This presents a unique problem, that policyholders must address in order to decarbonise the building stock. This is because as the building stock is pushed towards more stringent regulations, the decision whether to retrofit or newbuild will become significantly more apparent.

The proximity and accessibility of the converted building to urban amenities should be considered. For existing office buildings in retail parks and brownfield sites, these would pose unique cases. This is because considerable external works would be required (including the renovation or adaptive reuse of neighbouring buildings), in order to boost user attractiveness and realise demand. As such, it may be more attractive to demolish and reconstruct the building in order to match the rest of the new external constructions.

In terms of regulations for building upgradation, the authors believe that in the UK it is not strict enough for newbuilds or retrofits. For other countries, especially within the EU, regulations are typically stricter. As such, unfortunately retrofits are completed under the illusion of being "green", when in reality they often either are ineffective upgrades, with higher emissions compared to newbuilds. In EPBD Article 2, major renovation refers to more than 25 % of the building envelope being renovated. In the case of Delta point, this classification was achieved, simply through upgrading the windows. Since the EPBD was first implemented in 2003, this means the 2015 retrofit would have been classed as a major renovation. As shown by this paper, the retrofit was largely ineffective in terms of cradle-to-grave carbon, in comparison to an equivalent newbuild. In addition, for retrofitting practices, the life-span of the newbuild is likely to be greater than a retrofit, due to the quicker obsolescence and reduced durability of the existing components of the latter. As such, the environmental/carbon impact of the retrofit is likely to be even worse over time, due to reduced operational efficiency and the need to replace building components. Overall, the authors propose that UK regulations need to be more strict, and conversions should also include significant energy upgrade. This could offer a better or competitive solution to newbuild, as shown by this paper.

Another main point demonstrated by the paper is that whilst a reduced energy consumption can be achieved through better envelope design, improved mechanical systems, and upgraded internal building components, a more effective way may be to reduce the WWR. Since an office building will typically have a high WWR, when retrofitted into a residential use this same WWR is often unsuitable for residential use compared to a newbuild alternative, and causes significant energy demand. Therefore, when this is reduced, the retrofit scenario may be able to achieve an EPC B, and the newbuild an EPC A. This would improve the overall envelope u-value substantially, especially for the retrofit scenario since the facade insulation was not directly improved.

5. Conclusions

The purpose of this study is to provide an objective tool to assist the decision-making process between either retrofitting or newbuild replacement, from a carbon perspective. From a methodological standpoint, this study presents policymakers with an evidence based framework that can help support major decision making of the upgradation of outdated building stock. This is done via offering a comparative analysis between various retrofit and newbuild scenarios, to ascertain which is more carbon viable over the typical lifespan of the building.

With regards to whole life-cycle emissions, Delta Point would have been more carbon advantageous as a newbuild (at an EPC B standard). It was estimated that the current retrofit possesses an EUI of 175 kWh/m^2/year, which would have to be reduced to 142 kWh/m^2/year to pose a more viable scenario than a theoretical newbuild.

Overall, the results suggest that such a high-rise office building retrofit that is unable to achieve a high EPC C rating should be at least investigated for a newbuild scenario, with a framework such as the one outlined in this paper. It is also suggested that any buildings that have been retrofitted to EPC D standard should be reassessed, as they are likely unviable from an operational carbon perspective. In general, it can be concluded that such an office retrofit should achieve at least an EPC B standard to make sure that it remains viable from carbon perspective for its whole life cycle. With this being said, the study recognises the potential variability in required local building codes and energy performance standards, which may influence the viability of choosing an option predominantly based on comparative carbon emissions.

This study shows that whilst retrofitting in general is an effective approach to lower carbon emissions, decision makers must compare the savings achieved by an equivalent newbuild scenario. This is because significant carbon savings could be realised, made possible through conducting such an assessment. Policymakers should aim to incorporate this ideology into urban planning and building management processes, to offer guidance for the upgradation of the building stock.

In terms of future research, a database is required in which a large number of various office-to-residential scenarios are evaluated, with regards to whole life cycle carbon. This would help policymakers with evidence-based decision making, to provide a convincing argument towards either retrofit or newbuild. Decision makers should also seek to incorporate such carbon assessments as the one conducted in this paper within the renovation stage of the building, in addition to cost and practicality assessments. Future research should also seek to provide a more disaggregated quantification of certain building components that may influence the embodied carbon, e.g., foundations and basements, to ensure an accurate representation is created for both newbuild and retrofit scenarios.

CRediT authorship contribution statement

Brandon Mok: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Matyas Gutai:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tara Vincent:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giulio Cavana:** Writing – review & editing, Supervision, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115979.

Data availability

Data will be made available on request.

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