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## Think outside the box: 'Churn' and the Environmental Impact of Office Fit-Out Retrofit

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### Abstract

Office building interiors undergo frequent replacement of Fixtures, Fittings and Furniture (FFF) as a result of organisational 'Churn' and the 'Make Good' process. This study examines the relative Recurring Embodied Energy (REE) magnitude of FFF retrofit installed in a UK notional office building over various lifespans. It also includes the Life Cycle Assessment (LCA) of four floor finishes in terms of their REE and related CO<sub>2e</sub> emissions. FFF was found to have a higher REE content than other elements and should be especially considered in the case of lower consumption office design. Some of the LCA CO<sub>2e</sub> results were found to vary significantly although the corresponding Embodied Energy values were similar. 'Churn' and the 'Make Good' process warrant further investigation, while it is suggested that building stakeholders be alerted to rethink material choices.

**Keywords:** 'Churn', Retrofit, Recurring Embodied Energy (REE), Life Cycle Assessment (LCA)

### Introduction

One of the key challenges that the modern world is faced with today is climate change and the reduction of greenhouse gas emissions (1). Moreover, the topics of energy security and long-term sustainability have emerged and the existing building stock is being considered as a key player in combating these challenges (2).

In the UK 87% of the national building stock that will exist in 2050 has already been built (3). This consists of almost 30 million buildings, both domestic and non-domestic, where the latter account for approximately 1.8 million and are responsible for 18% of the UK's total carbon dioxide (CO<sub>2</sub>) emissions (4).

Buildings are constructed using long-life energy intensive materials, forming a legacy which is passed to future generations (5). Retaining and reusing the existing building stock prevents that energy from being wasted and increases resource productivity (6: p.8). The benefits resulting from reduced energy consumption and the corresponding emissions of the built environment have been

considered in previous studies while the EU has developed multiple strategies for reducing energy use and the reliance on conventional types of fossil fuels (7). However, a lack of research exists around retrofit procedures and their effect on Embodied Energy (EE) (8). Total embodied energy must be viewed as the sum of 'initial' and 'recurring' EE. While the initial EE has been the core in many LCA studies, recurring EE effect appears under-reported (9). This study aims to investigate the rather unexplored field of EE due to office retrofit activities associated with the 'Make Good' process, as a result of 'Churn' in commercial settings, over a building's life-cycle. Specifically, this study includes an analytical literature review of two studies in order to provide an indication of the relative importance of recurring EE due to retrofit interior fit-outs, including fixtures, fittings and furniture (FFF). This is compared to the initial embodied energy of a UK notional office building (with its finishes and services) and to its operational energy over 25, 50, 60, 70 and 100 years. Further, the study includes an EE and carbon analysis of four floor finishes for

the same building over 50 years in order to give an indication of the relative importance of these finishes in terms of Recurring Embodied Energy (REE) and carbon footprint.

### **Life Cycle Assessment (LCA) concept**

In order to construct a building, energy is required for the raw material extraction, the building product manufacture and the on-site construction. Energy is also needed for meeting the operational needs of a building including lighting, heating, cooling, and maintenance and at its End-of-Life (EoL) in terms of demolition and disposal. It is usually produced through fossil fuel combustion and generally measured in joules (J) or mega joules (MJ). This activity produces by-products, CO<sub>2</sub> and gaseous emissions, with CO<sub>2</sub> being a major contributor to climate change. Therefore, the total life-cycle energy of a building consists of the sum of the embodied energy, operational energy and EoL energy (10).

A boundary is drawn around a building's life-cycle: the inputs and outputs that cross this boundary undergo an assessment which is termed Life Cycle Assessment or Life Cycle Analysis (LCA). This comprises a product's, or a system's whole life-cycle from raw material extraction and processing, manufacturing, transportation, use, maintenance, reuse, recycling and disposal at its EoL (10).

In the late 1970's, the concept of Life Cycle Energy Analysis (LCEA) was developed to specifically measure energy as the only adverse effect of buildings or products. It focuses on an in-depth analysis of this energy and did not emerge in order to replace LCA. Rather, it is used for assessing and comparing both the embodied and operational energy of buildings' or systems' materials and components. Also, the energy used at the EoL stage i.e., for material recycling or disposal is considered. Life Cycle Carbon Assessment (LCCA) is likened to LCEA and is based on energy structures to convert MJ of energy to kilograms (kg) or tonnes (t) of CO<sub>2</sub> (10). Total carbon footprint consists of the sum of embodied CO<sub>2</sub> related

to a building's construction, operational CO<sub>2</sub> due to building use and EoL CO<sub>2</sub>. LCAs can be conducted for a 'full' life cycle, from extraction of raw materials to disposal or recycling of the end product after use. Partial LCAs can also be performed to focus on particular lifecycle phases (10).

### **Operational energy (OE)**

The amount of energy that is consumed in order for building occupants to meet their needs depends on the type and size of the building (11) and is by far the largest component of life-cycle energy in offices (12). Therefore, a prestigious headquarters office can have higher energy consumption per square meter compared to a small, local office. During the last years, energy consumption in offices has been increasing due to air-conditioning, information technology and use intensity. The size of open-plan offices is typically in the range of 500 m<sup>2</sup> to 4000 m<sup>2</sup>. They have higher illuminance levels, lighting power densities and hours of use. They contain more office equipment, vending machines etc., and equipment is used more routinely. Lights and equipment tend to stay on for longer and are switched in larger groups (11). Annual energy consumption for a 'Typical and 'Good Practice' naturally ventilated open-plan office is 0.85 GJ/m<sup>2</sup> and 0.47 GJ/m<sup>2</sup> of treated floor area (TFA), respectively, including gas or oil, and electricity (13).

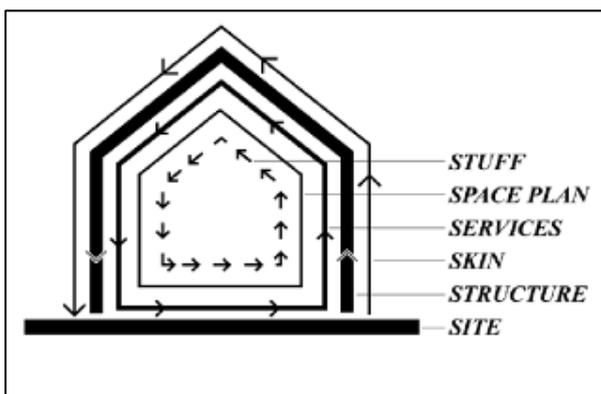
### **Embodied Energy (EE)**

Total EE consists of direct and indirect energy. This can be energy used on-site or off-site for any prefabrication, construction, transportation and administration. Direct energy is used to support these processes and is clearly defined and measured. Indirect energy mainly relates to the energy that is embodied into the building materials and is known as the Initial Embodied Energy (IEE) of buildings. Throughout a building's lifecycle periodic maintenance and refurbishment requirements incur additional embodied energy of replacement goods and materials,

and this amount of energy is known as Recurring Embodied Energy (REE). It is modelled based on assumptions of typical replacement rates of various building components (14). IEE is determined by the source and type of building materials used, while REE is influenced by building material durability and maintenance, installed systems, and the building lifespan. (15).

### Recurring Embodied Energy (REE)

Most IEE is comprised of the building structure and envelope, which are not being replaced regularly (16). However, internal partitions, doors, services, finishes, fixtures, fittings and furniture are being replaced, refurbished and maintained more frequently. European and North American building structures have typical lifespans of 50-70 years (17), while other elements can have much shorter lifespans. For instance, services have a life expectancy of 15-20 years, spatial divisions and fittings 5-10 years and workstation equipment and furniture have lifespans shorter than 5 years (17). The average office building lifespan is 73 years (18). Figure 1 illustrates the different 'layers' that constitute an office building and the diminishing duration of their service lives (17: p.199).



**Figure 1 – Office building 'layers' and their lifespans** (Brand cited by 17: p.199)

### Operational vs Embodied Energy

While some studies have focused on waste reduction and recycling related to demolition the majority of them have focused on the operational energy in academic and government driven initiatives (8). Moreover, due to the fact that Building Regulations have become stricter in terms of operational efficiency this has led to the increase of EE content in relative terms (19). The closer the achievement of zero carbon building design, the greater the component of EE becomes in terms of total lifecycle energy (10). According to Treloar et al. (16) the embodied energy of material manufacture and assembly can be almost equal to the operational energy of a building located in a temperate climate during its useful lifetime. The embodied energy of complex UK commercial buildings might be equal to 30 years of operational use (19) and for some well insulated ones it could be as much as 50% of the OE over 25 years of building life (20). UK Building Regulations have focused on OE to date with EE being omitted from legislation (19).

### IEE existing estimates in office buildings

Yohanis and Norton (20) estimated the IEE of a UK office to be 10.5 GJ/m<sup>2</sup> with finishes and heating system accounting for 13% and 10% of this energy, respectively. Another study by Atkinson et al. (21) estimated that finishes account for 12.5% of the total EE of the whole building. Dimoudi and Tompa (22) found that the EE of offices represented 13.05-19.24% of the total energy, while a Thailand based study (23) estimated this energy to be 17%. In a study by Cole and Kernan (12) typical values of the IEE of offices are presented in the range between 4 and 12 GJ/m<sup>2</sup> with a high figure of 18.6 GJ/m<sup>2</sup> due to differences in building performance and material production efficiencies at the time the study was undertaken. The same study revealed that the EE of building services (HVAC, conveyance, etc.) is the second most significant part in the total EE after the structure and envelope, and represents almost 20-25% of the total IEE. Internal finishes appeared to account for 12-15% of

the total IEE (12). EE values can differ significantly due to material production efficiency and the location of the study (9).

### **Office fit-out, retrofitting and REE existing estimates in absolute and percentage terms**

Office fit-out comprises internal finishes, fixtures, fittings and furniture (16) while retrofit includes the replacement of these elements and that of equipment (8).

An important factor to consider is the grade of fit-out that will determine a building's embodied energy, depending on the replacement frequency (8). Howard and Sutcliffe as cited by Cole and Kernan (12) have estimated EE values related to basic, medium and top-grade office fit-out replacement, assuming annualised frequent replacements over 60 years to be 0.17, 0.23 and 0.34 GJ/m<sup>2</sup>/year. Corresponding values for infrequent retrofit were 0.10, 0.13 and 0.17 GJ/m<sup>2</sup>/year while the IEE of the office was 0.08, 0.09 and 0.1 GJ/m<sup>2</sup>/year for the three accommodation grades. These values indicate REE is always larger than the IEE and for very frequent replacements it can be three-fold (12). The same work (12) stated that over 50 years of building life the REE is almost the same as the IEE. For short life-cycles REE is less than the IEE and for long-life-spans (i.e., 100 years) REE is two and three times larger (12).

While the refurbishment cycle of office buildings is between 25 and 30 years (8), fit-out contains elements which are being replaced more frequently (12). Therefore, as services and internal finishes are the most frequently replaced elements of a building over its life-cycle, they finally outweigh the EE of the structure and dominate the REE – almost 1.3, 3.2 and 7.3 times their initial values for 25, 50 and 100 years of building lifespans (12)

### **'Churn' and the 'Make Good' process**

Office fit-out retrofits are being carried out due to requirements to reduce obsolescence and vacancy rates, upgrade assets, improve rental income and meet organisational needs (8). 'Churn' is defined as the number of office moves during a given period and is expressed as a percentage of the total number of offices occupied (24: p.1). It includes companywide restructuring, co-locations of employees and formation of project teams. Its intensity levels vary from box moves to reconfiguration of the existing furniture, and even to construction moves and additional furniture. Historical figures suggest churn rates of 25% for institutions (i.e., religious, governmental) 44% for services (i.e., financial, energy) with office headquarters facilities reaching the highest churn rate of all, at 45% (24). Brittain et al. as cited by (9) found a high annual churn rate of 30% of building occupants to be normal in the UK and is responsible for a high rate of 'Make Good'. This refers to the hand back process at the end of office leases along with the outgoing tenant's fit-out demolition comprising the removal of finishes, furniture, partitions and building services. The next step is the reinstatement of the pre-lease fit-out. This process is responsible for wasted EE repetitions and increases in REE values (25). Treloar et al. (16) estimated a fit-out retrofit (fittings, fixtures and furniture), rate of 5.6 replacements over 40 years of building life, corresponding to an average 7 year period, with fashion being the main reason. Roussac et al. (26) indicated a 10 year fit-out retrofit cycle. However, this result is based on a property management portfolio, considering particular sustainability objectives and appears larger than the norm. It should be noted that materials from demolished buildings could provide EE reductions of 35-40%, if recycled (9). Fit-out 'churn rate' is defined as the number of times an item is replaced over a facility's life (16: p.405). So, a 0% churn rate corresponds to an item that has never been replaced while 100% churn rate indicates a single replacement of an item over the building's life (16).

Table 1 presents the assumed churn rates of various building elements that were reported in the study by Treloar et al. (16) over 40 years of building lifespan.

Building element	Churn rate (%)
Upper floors	0
External walls	10
Internal walls	10
Columns	0
Substructure	0
Floor finishes	200
Wall finishes	400
Ceiling finishes	100
Fixtures, fittings and furniture	560
Electrical	20
Air-conditioning	20
Fire protection	20
Plumbing	20
Other	20

**Table 1 – Various building elements’ ‘churn rates’** (16: p.406)

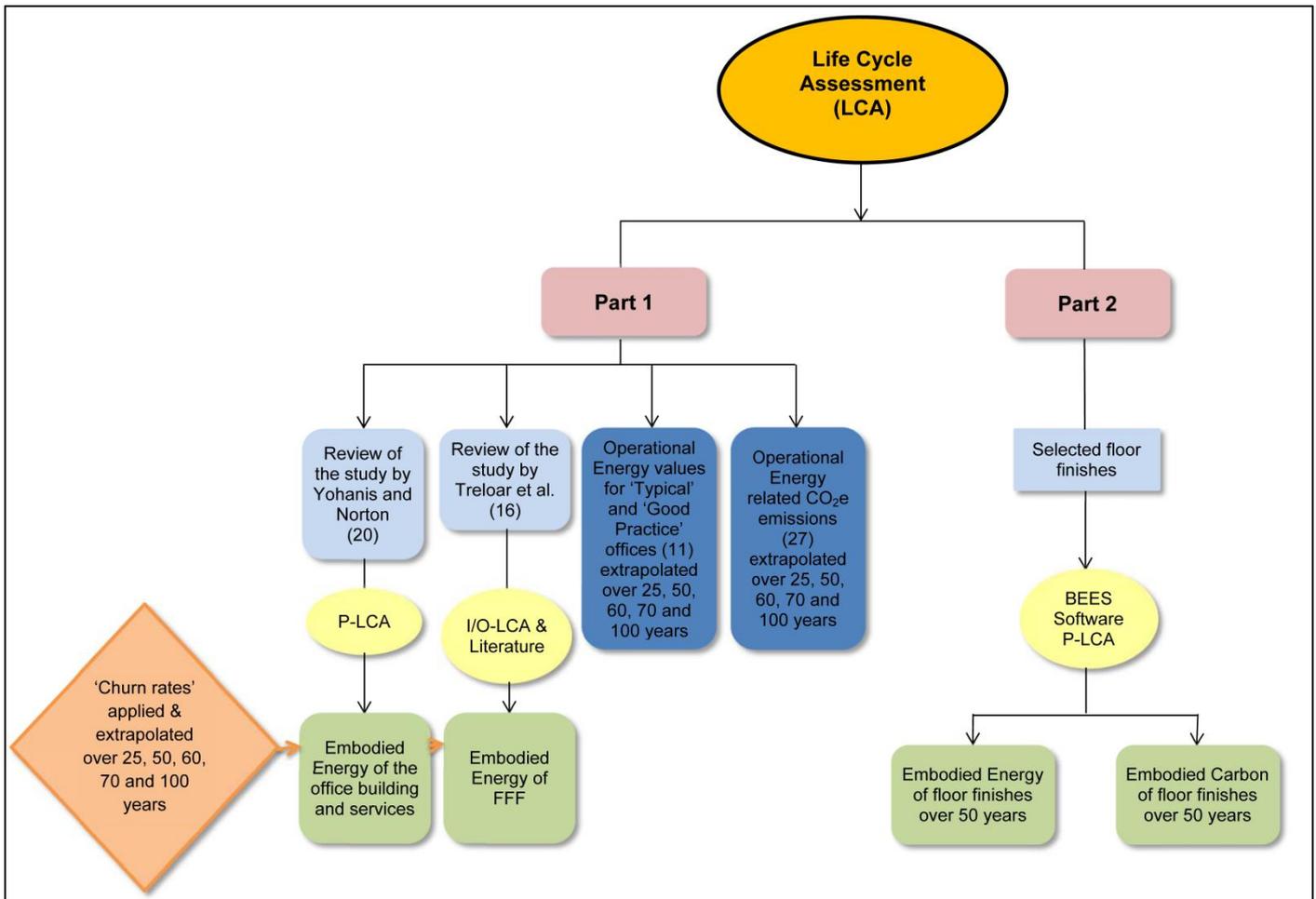
## Methodology

A variety of LCA approaches exist, including process analysis (P-LCA), input-output analysis (I/O-LCA), hybrid analysis and other more simplistic ones (10). The data used in this study was collected through the review of two studies (16, 20). Data on the EE of the office building was derived using P-LCA (20) while data on the EE of interior finishes, fixtures and furniture was obtained using I/O-LCA, with other information taken from literature (16). P-LCA evaluates both the direct and indirect energy inputs involved in a product’s life and usually begins with the final product and works backwards to the point of raw material extraction (an ISO 14040 requirement). I/O-LCA is based on the use of tables containing monetary flows between sectors and can be transformed to physical

flows to gain environmental fluxes between economic sectors (10).

The direct manufacturing energy of the FFF was estimated using ‘assumed manufacturing coefficients’ (16: p.405). OE consumption values were taken from the Association for the Conservation of Energy (13) report. ‘Typical’ and ‘Good Practice’ values were considered and the same fuel mix, and production processes and consumption trends were assumed over 25, 50, 60, 70 and 100 years of building use. OE related CO<sub>2</sub>e emissions were derived using Defra’s carbon conversion factors (27).

The LCA of four floor finishes were conducted using the BEES web application software (28). This uses the P-LCA method. Embodied energy results are classified a) by fuel and feedstock energy and b) by fuel renewability. Fuel energy is that energy used as fuel (i.e., oil or gas burning) and feedstock is that energy used as a material input to manufacture products such as plastic and rubber. Renewable energy is produced via e.g., hydropower, wind, biomass, etc., while non-renewable is derived via fossil fuels such as petroleum, gas, etc. (28). During the second part of this study a building lifespan of 50 years was assumed as this is the duration considered in all BEES calculations. Moreover, equal weight factors were assumed over all environmental impacts and transportation distance from the manufacturing plant to the building site was set to zero since the notional building has no fixed location. Demolition energy is not reported in BEES for individual material profiles and thus was assumed to be very minor. It should be noted that BEES analysis derives US average results, not applicable in other countries with different manufacturing methods, fuel mix, etc., and was used to acquire indicative values only. Figure 2 illustrates the steps of the method of this study.



**Figure 2 – Study method and steps**

It should be noted that the outcome of this study should not focus on the absolute values obtained, rather on the magnitude and importance of the REE of FFF with reference to other major building elements and building lifespans. The mixing of methodologies is unorthodox but is performed here to establish a need and rationale for extended research. The mix of LCA approaches used to derive indicative values is representative of the information available at the time of writing, and warrants further research.

### Functional Unit

The IEE of the building structure, substructure and envelope and heating service was expressed in  $\text{GJ/m}^2$  of total floor area (TFA). This is the area inside the building envelope, including the external walls, and excluding the roof (29). The EE of

FFF was expressed in  $\text{GJ/unit}$  which was the item itself. This energy was afterwards calculated in  $\text{GJ/m}^2$  of TFA.

Further, the OE energy estimates taken from the Association for Conservation of Energy (13) report were expressed in annual  $\text{GJ/m}^2$  of treated floor area (TFA). This refers to the gross area less plant rooms and other areas such as roof spaces, covered car parking, etc., not directly heated (11: p.21) and was assumed to be approximately equal to total floor area as definitions vary globally. BEES results were expressed in  $\text{GJ/m}^2$  and  $\text{kgCO}_2\text{e/m}^2$  ( $\text{CO}_2$  equivalent) of the floor surface over 50 years, considering replacement numbers based on product lifespans. OE related  $\text{CO}_2\text{e}$  emissions were expressed in  $\text{kgCO}_2\text{e/m}^2$  TFA over 50 years.

## A UK notional office building

An open-plan, single-storey, steel frame, UK notional building plan was adopted by a study carried out by Yohanis and Norton (20). The office building envelope, structure, substructure, finishes and heating service IEE was estimated to be 10.5 GJ/m<sup>2</sup> TFA (20). In this paper a total floor area of 716.7 m<sup>2</sup> (including office area, reception hall and excluding toilets) was considered. External wall finishes were considered in this study (20) and were assumed to be equal to internal ones. Further, authors had not encountered construction energy and therefore a 10% factor related to direct construction energy (30) was applied, resulting in a (non-FFF) IEE of 11.55 GJ/m<sup>2</sup>. Regarding building services only heating was considered (20), yielding a much lower value compared to other studies.

## Fittings, fixtures and furniture (FFF)

Average EE values of the FFF were taken from a study conducted by Treloar et al. (16). Product material and volume/dimension descriptions were not available. For the estimation of element quantities a mean open-plan office density of 10.9 m<sup>2</sup>/ desk was assumed (31). 50 desks were considered, two medium-sized meeting rooms (17m<sup>2</sup> each), enclosed with full-height (3m) partitions and three small-sized group-work tables divided with panels of 21.4m total length and 1.5m height. These quantities were multiplied by the corresponding average element energy intensity in order to derive the EE values for the fit-out of the notional building.

The assumed churn rates reported previously were extrapolated over 25, 50, 60, 70 and 100 years of use of the notional building, considering an identical retrofit trend through time. It was also assumed that the envelope and heating experience churn rates similar to that of external walls and air-conditioning, respectively. Assuming that all the materials used in the retrofits and their energy intensities will remain the same without improvements in the manufacturing

processes, results will appear larger than in reality (12).

Further, reused and recycled fittings, fixtures and furniture were not considered in order to achieve a more precise indication of the EE loads. Similarly, demolition energy was not considered in this study (16). An important limitation to be mentioned is that the EE estimates taken from the study of Treloar et al. (16) are Australia average values, used as an indication of the EE magnitude of FFF. Table 2 presents the quantities of the FFF of the notional building along with the corresponding average EE values taken by Treloar et al. (16: p.405).

Element	Quantity	Average IEE (GJ/item)	Total (GJ)
Workstation	50	6.14	307
Desk/table	50	2.7	135
Reception hutches	3	7.6	22.8
Pedestal table	3	2	6
Conference table	2	6.5	13
Credenza	3	3.8	11.4
Cupboards	1	2.8	2.8
Drawer/file storage	52	2.1	109.2
Shelving	10	3.2	32
Desk-chairs	79	1.6	126.4
Pull-up chairs <sup>1</sup>	55	0.48	26.4
Partition (m <sup>2</sup> )	93.6	2.74	256.46
'Compactus' <sup>2</sup>	2	19.6	39.2

**Table 2 – Embodied energy of the notional building's fittings, fixtures and furniture**

<sup>1</sup> Pull-up chairs were assumed to be used by visitors

<sup>2</sup> 'Compactus' are i.e., large volume document storage units on tracks (15)

## Selected floor coverings

In a broader study aimed at environmental sustainability in relation to office retrofits, four natural, renewable, potentially recyclable and biodegradable floor coverings were selected in order to acquire an indication of their EE content and carbon footprint.

a) Carpets fall into the category of the most energy intensive flooring type as they mainly rely on fossil fuels (32). Synthetic carpets are usually made from non-renewable petroleum products. However, some of them contain recycled material (i.e., recycled bottles) (33). Polyamide or nylon carpet face fibres are durable and resilient and use nylon 6 (single and more easily recycled polymer) or 6.6. (34). Wool carpet fibres are natural as they are made with sheep wool and are considered to be renewable and durable (33). Wool has a higher EE than nylon (35). At their EoL they are usually disposed of in landfill, taking up useful space and consuming resources that could either be reused or recycled (33, 36). 0.7% of synthetic broadloom carpet is recycled (28).

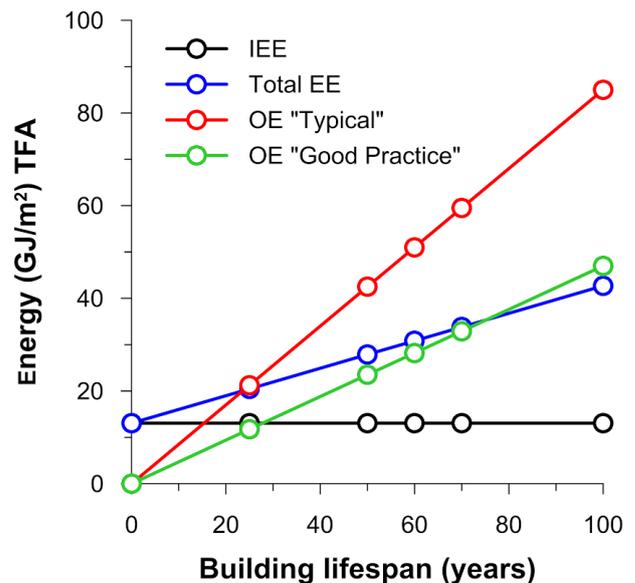
b) Natural cork tiles (NCT) are made of cork which is a natural, resilient and renewable material, harvested from the bark of the oak tree. It is a local material in Western Mediterranean areas and could be used as a substitute of other non-renewable materials (37, 38). Its manufacturing does not consume a large amount of energy by contrast with its shipping (39). Cork flooring is completely biodegradable. It is sometimes considered to be a natural alternative to carpet as it has most of its advantages without its liabilities, and a more sustainable alternative to vinyl composite tiles (33, 40). At its EoL it ends up in landfill (28) or may be compostable depending upon the finish type (39).

c) Vinyl Composite Tiles (VCT) are limestone-based flooring tiles together with a polyvinyl chloride (PVC) binder. With regards to primary energy consumption, raw material extraction is the most energy intensive phase during their life-cycle while the least energy intensive is their EoL phase. 94% of non-renewable resources are consumed during their manufacturing (41). At the EoL stage

around 300 tonnes of material are currently being recycled. The remainder is disposed of in landfill or incinerated (42, 28).

## Results and discussion

Figure 3 shows the IIE and total EE of the building including its finishes, services, direct construction energy and FFF along with the OE of a 'Typical' and 'Good Practice' office building over 25, 50, 60, 70 and 100 years.



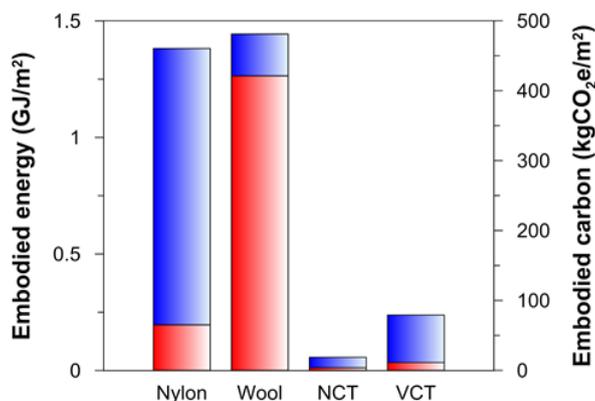
**Figure 3 – IEE and Total EE values of the building and related elements along with the OE of a 'Typical' and 'Good Practice' office over various building lifespans**

The IEE of the building, with its finishes, services and direct construction energy alone was 11.55 GJ/m<sup>2</sup> while FFF added an extra IEE of 1.52 GJ/m<sup>2</sup>. However, the effect of the 'Make Good' process became more and more obvious over extended building lifespans because this recurs at quite high rates for some elements with the highest one regarding FFF. The FFF REE was 5.32, 10.64, 12.77, 14.89 and 21.28 (GJ/m<sup>2</sup>) over the considered building lifespans, respectively.

In particular, over 60 years the FFF REE was very close to the IEE of the building and related elements (13.07 GJ/m<sup>2</sup>), while over 100 years was 1.62 times this value. More importantly, the REE of FFF appeared to range between 26 and 49% of the building's

total embodied energy considering 25, 50, 60, 70 and 100 year-long lifespans.

Further, over 25 years the REE of FFF 5.32 GJ/m<sup>2</sup> was almost half the OE of a 'Good Practice' office with a consumption of 11.75 GJ/m<sup>2</sup>. Over 25 years, the OE of a 'Typical' office was quite similar to the sum of the IEE and REE. Over the consecutive lifespans the OE of 'Typical' offices appeared much higher. Another important point was that the total EE appeared slightly higher than the OE of a 'Good Practice' office during the first 70 years with a small drop over 100 years and exceeded the total IEE by 226.7% over a century. This indicates that as focus has been on OE consumption, designers tend to improve the performance of buildings in terms of this, while the REE contribution of interior fit-out retrofit is still unconsidered. Thus, it would not be surprising if REE related to interior fit-out was well exceeding the OE of 'Good Practice' offices, in the future. Fittings, fixtures and furniture appear to impose an important environmental impact over office building lifespans. Figure 4 presents the results of BEES analysis regarding the EE (blue) and CO<sub>2</sub>e (red) of the selected floor finishes over 50 years.



**Figure 4 – EE and CO<sub>2</sub>e emissions of four floor finishes over 50 years**

The REE analysis of the floor finishes showed that wool carpet is the most energy intensive (1.443700 GJ/m<sup>2</sup> over 50 years) due to its manufacturing process (scouring, drying, tufting, etc.), and the long distance transportation of raw materials, including the combustion of both gas and electricity. Nylon carpet appeared to be closely following the performance of wool containing 1.381 800

GJ/m<sup>2</sup> of EE, having much higher feedstock energy content as it is a synthetic material (11 years lifespan). It is also replaced more frequently than wool carpet (25 years lifespan) over 50 years. The 50-year lifespan NCT covering had negative feedstock energy (-0.002400 GJ/m<sup>2</sup>) content as it is made from a natural material and in particular contains recycled cork waste. Further, the fuel requirement was low because the harvesting and manufacturing do not consume a lot of energy compared to its shipping. However, cork shipping is considered to be artificially low because it is a low density material. Shipping is quantified in MJ per km per kg, where low mass, high volume materials can appear erroneously low. VCT analysis' results showed that during manufacture large amounts of non-renewable fuel energy are required, resulting in a total of 0.238 000 GJ/m<sup>2</sup> over 50 years. Therefore, the REE of each of the floor finishes regarding the total floor area (716.7 m<sup>2</sup>) of the notional office over 50 years would be 990.3, 1 034.7, 40.71 and 170.57 GJ for the nylon, wool, NCT and VCT finishes, respectively. These values remained much lower than the REE of the FFF over the same lifespan.

Regarding emissions, wool finishing appeared among the highest (421.235 kgCO<sub>2</sub>e/m<sup>2</sup>) due to livestock emissions (methane, CH<sub>4</sub>), related to raw materials. Nylon carpet arrived second with its carbon emissions being mainly related to raw material production used to make the carpet and was followed by VCT (40 years lifespan) with only 11.229 kgCO<sub>2</sub>e/m<sup>2</sup> due to its recycled content and manufacturing over 50 years. NCT contained cork waste product and the analysis did not contain environmental burdens from virgin cork production. Therefore, it had unsurprisingly very low emissions (3.746 kgCO<sub>2</sub>e/m<sup>2</sup>) along with the ability to sequester carbon (which has not been factored into the analysis at this stage). Regarding OE related CO<sub>2</sub>e emissions, only wool carpet emissions appeared significant in comparison, accounting for 25% and 14.3% of these for a 'Good Practice' (1 976.5 kgCO<sub>2</sub>e/m<sup>2</sup>) and 'Typical' (3 357 kgCO<sub>2</sub>e/m<sup>2</sup>) office, respectively. The CO<sub>2</sub>e emissions of other finishes appeared negligible in comparison.

## Conclusions and recommendations

- The amount of recurring energy embodied in fixtures, fittings and furniture was found to hold a significant percentage of the total embodied energy content of an office building, as a result of 'Churn' and the 'Make Good' process, over different office building lifespans. Their role was further empowered through a comparison with corresponding operational energy consumption values. The study showed that the REE relative magnitude of FFF is more important in the case of 'Good Practice' offices than in that of the 'Typical' ones. This raises the importance of REE as awareness of lifecycle energy and carbon rises in response to zero and near zero energy building designs.
- This work also revealed that although the REE related to interior finishes and services have been considered in a number of studies, they have a much lesser REE effect compared to fixtures, fittings and furniture due to the 'Make Good' process over extended building life-cycles.
- The embodied energy analysis of four floor coverings further supports the abovementioned statement as their REE values over 50 years were quite low in comparison.
- Further, the BEES analysis of four floor finishes showed that wool carpet was the most energy and carbon intensive one followed by nylon carpet, VCT and NCT. An important highlight is the comparison of nylon and wool carpet, having similar EE intensities, which revealed that this similarity cannot be assumed regarding CO<sub>2</sub>e results due to a number of reasons explained before.
- However, the effects of 'Churn' and the 'Make Good' process both in regards to REE and embodied carbon of fixtures, fittings and furniture have been rather unexplored to date. Therefore, further detailed research is needed in order to quantify the impact which fit-out choices and their frequency have; and to what extent these impede green fit-out.
- Also, questions around the social, financial, fashion and functional drives of the quick cycle obsolescence observed in office buildings are raised and warrant further investigation.
- Designers, facilities managers (FMs), practitioners and owners need to rethink their design choices in conjunction with the 'Make Good' process and possibly design for shorter cycles as retrofit often takes place before materials are worn out. They could also avoid highly energy intensive materials of unnecessary high longevity and turn to more natural, local, renewable and recyclable material choices, while considering their embodied carbon. However, in order for designers, FMs and practitioners to understand the impact of their choices they have to be educated towards this direction and to be fully aware of the environmental impact of different interior materials.
- Therefore, the longevity of the existing office building stock in the UK, can be fostered via the careful choice of finishes, fittings, fixtures, furniture and building services together, while minimising resource depletion, carbon footprint and securing a better 'home' for future generations.

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