

# EMBODIED ENERGY AND OPERATIONAL ENERGY: CASE STUDIES COMPARING DIFFERENT URBAN LAYOUTS

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## ABSTRACT

While significant progress has been made in reducing Operational Energy; Embodied Energy has been largely ignored. However, these topics are strongly linked and should be considered as a “Balance Equation”, where all factors must be carefully measured in order to avoid the excesses of both. A comparative study of urban layout and form utilising VIRVIL plugins (in Sketchup) with HTB2 (Heat Transfer in Buildings) indicates that urban layout have an impact on the Operational and Embodied Energy of buildings. The case studies analysed in this paper suggest that there is an advantage of Mid-rise type of buildings in terms of Operational Energy, however the Embodied Energy scenarios are less clear and seem to depend more on the use of the building.

## INTRODUCTION

Evidence of the overwhelming signs of climate change are now well disseminated (Communities, 2006, COST, 2009), furthermore it is widely accepted that human activity has been largely responsible for this change and therefore policies have been developed aiming to reduce the problem (Commission, 2012, Abanda et al., 2012). The building sector is largely responsible for such negative environmental impact (Li, 2006, Stephan et al., 2011, Pullen, 2007), therefore people involved in the development of buildings have a great responsibility towards achieving sustainability standards.

The built environment has been under development for thousands of years (Fazio et al., 2008) and it is only at a very late stage of history that ‘Green’ Design appeared into the picture (Vallero and Brasier, 2008, Edwards, Sassi, 2006). Hence it can be deduced that the challenges faced by the so called “Sustainable design/ Low carbon design/ Green design” are vast. Thus, this is likely to be due to the fact that a few decades of environmentally conscious design are being implemented in a built environment that already has thousands of years of history. In the past, the main influencing factors considered in building design were based on aesthetics and human comfort, in the history of architecture the well known “Roman architect and engineer Vitruvius [...]

considered the essentials of Architecture to be [...] *firmness, commodity and delight*” (Fazio et al., 2008), however the consideration of sustainable design principles only arose in modern times.

This analysis through history merely aims to provide an idea on the scale of the problem that urbanisation development is facing:

*Cities have been under development for several thousands of years without considering environmental design, which now makes it difficult to overlay environmental design on them.*

Therefore, existing and new developments must be analysed in conjunction. There is an imperative need for large-scale solutions, hence the importance of this research project.

When building designers realised the impact on GHG emissions originated from the building industry, many efforts were focused towards improving the design and materials of buildings in order to reduce their Operational Energy (OE) (Stephan et al., 2011, Yeo and Gabbai, 2011), however, this often resulted in higher Embodied Energy (EE) (TargetZero, 2012). In recent years, focus has been directed towards controlling the impact of the existing and potential EE in the built environment. This acknowledges the fact that in order to be able to control, improve and account for the use (and misuse) of EE, greater information on the matter should be made available, as a result large EE databases are being developed (Hammond and Jones, 2008, Hammond and Jones, 2011). Information of this nature has been helping the research community, as well as the industry, to attribute embodied energy values to most of the available construction materials and processes (Treloar et al., 1999, Hammond and Jones, 2011). Furthermore, there have been various attempts to develop case studies, methods and protocols that could be used as guidance to calculate embodied energy values within a variety of contexts (Hammond and Jones, 2011, Dixit et al., 2012, TargetZero, 2012, Treloar, 1998). However, these databases and processes are still under development and scrutiny. Due to its complexity many different sources disagree on specific values (Dixit et al., 2012). Research development on Life Cycle Analysis (LCA) greatly considers the impact of embodied

energy an operational energy in the built environment (Pullen, 2007), however the research project presented in this paper deals with different thresholds than the LCA. Instead of using values from a Life Cycle Inventory (LCI) (Lee et al., 1995) where figures are cradle-to-grave, the values used in this analysis are taken from Embodied Energy (EE) databases, widely available in the research community, primarily figures from the Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2011) since the case studies are located in the UK.

The emphasis of this project is not to agree on specific Embodied or Operational Energy figures, but to describe a methodology through which initial estimates can be modelled for the overall Embodied and Operational Energy use of a whole site, possibly at a regional scale, and viable at an early stage of a design process. However, embodied energy of roads and services infrastructure (i.e. pipelines and electrics) are not considered in this investigation.

The software tools used here provide the flexibility of altering specific energy values assigned to the simulation, since such values can vary significantly across the different contexts. i.e. the EE values for concrete will differ according to the geolocation, since it can be highly dependent on the predominant type of fuel of a country, or on the various sources of the raw materials and the distances to transport them, amongst many other affecting variables.

Essentially, Embodied Energy in the built environment is an issue of great importance and it requires urgent advance, it cannot be allowed to remain 'wedged' between arguments regarding the best accuracy of specific values of single materials. It requires a new approach, perhaps from another vantage point, viewing it from a place that could take the matter to a further level. This research method aims to move in such direction.

Additionally, the expansion of urbanised areas is a reality (Vos et al., 2011, Soubbotina, 2004) and a large number of influencing actors are already developing designs, plans, investigations and strategies towards finding ways to tackle this issue (Scott and Ben-Joseph, 2012, Rogers, 1999, Brueckner, 2007, Barton et al., 2003). However, as previously mentioned, the existing urban form and layout was developed without considering its impact on energy consumption, as a result one of the main research challenges is to tackle these issues at a significantly large scale: *How is it then possible that the majority of building energy simulations that are being developed are mainly focused on individual scale?* There is enough evidence that the building design industry is in urgent need of tools and methods that can help towards finding energy efficient focused solutions, at a larger scale.

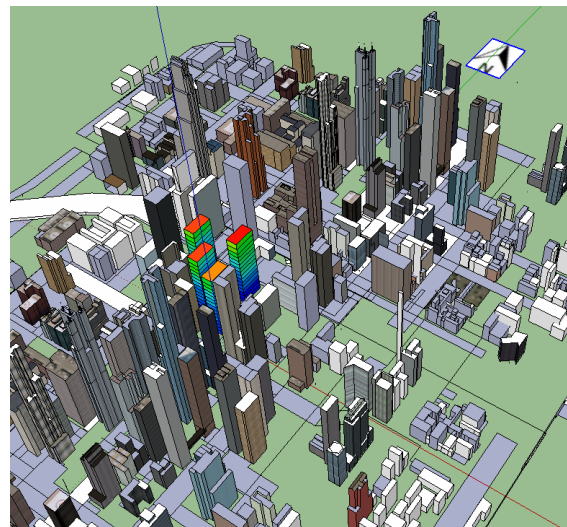
This paper aims to illustrate by means of three case studies, a new approach to building modelling, considering a larger scale scenario (regional scale).

The studies will present a comparative analysis of typical urban layouts: High-rise, Mid-rise and Low-rise.

## THE CASE STUDIES

The case studies were selected from a variety of urban contexts. Similar floor areas have been simulated under three different conditions: High-rise, Mid-rise and Low-rise. All of the scenarios share the same glazing ratios (50%), geolocation and weather; and different building uses established the simulation characteristics such as occupancy schedules, etc.

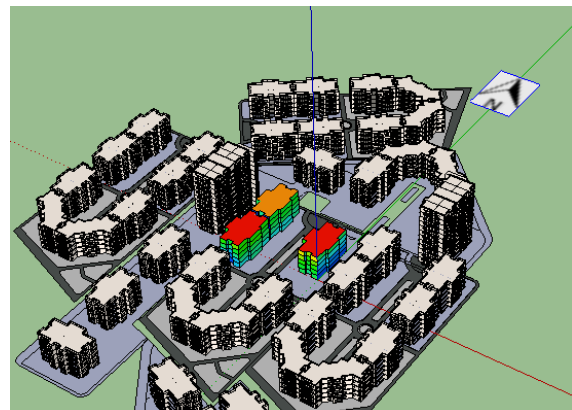
### **Case 1: High-rise buildings**



*Figure 1 High-rise case study*

Four standard high-rise buildings were chosen from a typical densely urbanised city. They are 15- and 16-storey buildings with heights ranging between 45 and 50 meters (Figure 1). Simulations have been performed on the buildings marked with bright colours (as it can be seen in Figures 1-3). The total floor area for the High-rise case study is 6,076 m<sup>2</sup>.

### **Case 2: Mid-rise buildings**



*Figure 2 Mid-rise case study*

The second case study developed has been the Mid-rise urban distribution, with 6,030 m<sup>2</sup> floor area (Figure 2). The analysis in this scenario comprises 5-storey buildings of approximately 17 meters high.

### Case 3: Low-rise buildings

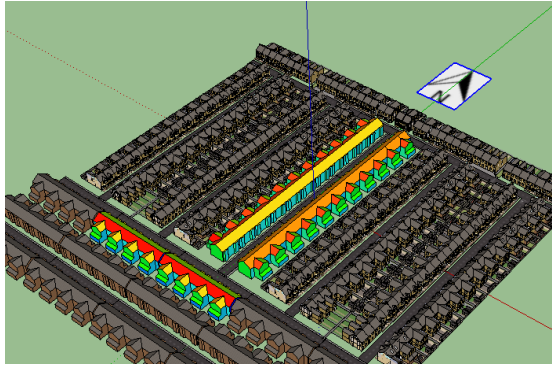


Figure 3 Low-rise case study

Finally, a similar procedure has been followed to develop the Low-rise urban distribution study with a total floor area of 6,082m<sup>2</sup>. This scenario analyses typical British terrace houses (Figure 3).

### METHODOLOGY

As previously mentioned, the main focus of this investigation is to compare the energy impact of the different types of urban layouts, based primarily on their Embodied and Operational Energy (EE and OE). In order to attempt this, building thermal simulations of the three case studies have been implemented.

Since there is not current publicly available software that would allow the development of the described investigation, novel software tools are being used in this project. Such software is under development within the Low Carbon Research Institute (LCRI) at the Welsh School of Architecture and it is currently under testing. This project aims to contribute to this development. The main software tools used in this project are the VIRVIL plugins (Bassett et al., 2012) which link SketchUp 3D models with HTB2 (Heat Transfer in Building) (Lewis and Alexander, 1990) which is a thermal simulation software (Bassett et al., 2012) that has been used in a number of thermal simulation projects around the world.

The VIRVIL software allows regional scale building modelling. This approach has been chosen due to the importance of the surrounding landscape in an urban context, especially when developing energy calculations. Bassett et al. (Bassett et al., 2012) provide demonstrations on the capabilities of the VIRVIL tools while considering the impact of the urban surroundings on energy calculations, also proving its importance when considering the solar gains potential of buildings.

Below are the basic steps followed in this analysis:

1. The first step has been to collect relevant data to provide realistic figures for the calculation of both operational and embodied energy.
2. Three case studies have been proposed, in order to develop grounds on which the measurements

can be analysed and compared. High-Rise, Mid-Rise and Low-Rise cases have been designed, considering their total exposed area (the fabric of building) and approximating their total floor area and orientation, so that the final figures can be compared.

3. Each case study is then modelled using Sketchup, thereafter the VIRVIL plugins are used to develop the database focused on the characteristics of the 3D model and finally thermally simulated with HTB2. Initial figures can then be gathered to compare the Operational Energy (OE) of the three cases.
4. Thereafter, embodied energy calculations are generated and compared. The VIRVIL database of EE values for materials is populated with average, cradle-to-gate values taken from the ICE database (Hammond and Jones, 2011); however, the software is flexible to allow for users to input other validated or referenced EE values. The EE values are converted from the standard unit of MJ/kg to MJ/m<sup>2</sup> of construction using the density of the materials. The areas in m<sup>2</sup> of the structural geometries modelled in SketchUp are then exported to a database using the VIRVIL plugin and combined with the EE values to calculate the EE for each layout. These results are then presented and compared. Values obtained from simulations coupled with relevant values from literature, allow calculating the energy impact (OE and EE) of the different types of urban distribution/layouts.

A vital concept behind the new software tools used in this project is to provide an alternative to the current approach to energy building simulation. Most available simulation tools are complicated and directed to specialised users. This new simulation process aims to simplify the process of this type of analysis, but not to the point of making results unreliable. To make this possible, a database is created and regularly updated to expand on the possible characteristics of different scenarios. This database can then be recalled and used to run simulations. The database covers typical data on *building uses* and *materials*. To define occupancy patterns and types of materials three main possibilities exist within the software: Residential, Commercial and Industrial, but the number of *building uses* provided by the software is expected to increase with the expansion of the database. In this paper, the simulations are modelled for buildings under Residential and Commercial use only.

By providing scenario typical values for simulations, all parties interested in understanding the thermal performance of the built environment could be involved in the analysis. However, the software is flexible enough to allow specialised modellers to add further accuracy to the thermal calculations

(recommended). This level of simplicity, with a good dose of accuracy, provides the potential of merging the thermal analysis process into the typical design stream followed by building construction practises.

The three case studies presented here reflect how a process that may be rather complex by nature can be thermally analysed more simply by using a widely available and user-friendly software: Sketchup Trimble. The suggested process provides a 'bridge' between Sketchup 3D models and HTB2 which is a building physics simulation software (Jones et al., 2009, Lewis and Alexander, 1990). HTB2 has been validated and is a powerful tool capable of developing complex energy building simulations (Jones et al., 2009).

The three case studies have similar characteristics: floor area, location, weather and occupancy schedules (according to their use) but differing urban distribution. Using these tools the user can then thermally simulate a group of buildings using some initial assumptions provided by the VIRVIL database, and this process can generate initial estimates, which can thereafter be refined and compared.

Typical construction types and materials were chosen according to the contexts of the case studies: standard brickwork construction for the Low-rise case study and steel-frame for Mid- & High-rise; moreover different types of materials were chosen according to their use: Residential or Commercial, despite having the same layout. Thus, the impact of changing the type of construction can be demonstrated. Data is extracted from the 3D models based on the buildings' volumes and orientation, glazing ratio is assigned by clicking on the 3D model, in these cases all facades were given 50% glazing ratio. Thereafter, the 'bridge' between SketchUp and HTB2 can be built. Subsequently simulations can run using various parts embedded in the VIRVIL software to add weather characteristics, occupancy schedules, etc.

If specific values are not available in the database (even the desired EE value for certain materials) they can be added and simulations can then be run more accurately.

## RESULTS

Figure 4 illustrates an example of how some of the information embedded within the model can be viewed after simulation. The VIRVIL plugins have great potential for solar analysis; Figure 4 is showing how the software has calculated the amount of solar radiation falling on all the surfaces of the analysed buildings (the brightly coloured surfaces).

The inset window (viewed within the SketchUp environment) displays relevant information about the section of a façade or roof that has been selected. This information window contains a diagram of the shading mask of this specific surface, as well as the amount of solar radiation falling on it (in

kWh/m<sup>2</sup>/year), also its orientation, area, etc. The colour scale shown on this window represents the levels of solar radiation (red being the highest) and this range of colours are used to colour-code the surfaces of the actual 3D model (as seen in Figure 4). Every single face of the model has a shading mask and all this information is stored within the model. However, the focus of this research is not 'solar analysis', nevertheless this feature of the software is highly important, particularly when developing thermal simulations of the urban sites.

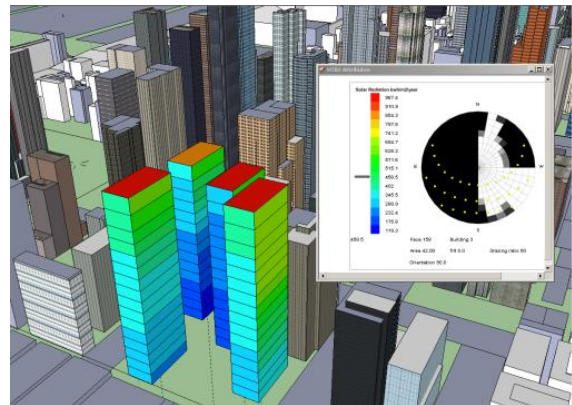


Figure 4 High-rise. Sample of a shading mask and visualization of some of the results.

After running the thermal simulations, the VIRVIL plugins automatically create an Excel spreadsheet to store the large amount of data, as well as having information stored within the 3D models, thereby generating a dynamic database. In this investigation, a number of simulations have been developed in order to create a variety of possible urban settings that are relevant to the analysis, i.e. high, mid and low-rise. Table 1 shows the total floor area and exposed area for each of the case studies.

Table 1  
Total floor area and exposed area  
for each case study

|           | Total Floor Area (m <sup>2</sup> ) | Total Exposed Area (m <sup>2</sup> ) |
|-----------|------------------------------------|--------------------------------------|
| High-rise | 6,076                              | 8,456                                |
| Mid-rise  | 6,030                              | 6,027                                |
| Low-rise  | 6,063                              | 12,338                               |

It should be noted that some building forms and layouts are more appropriate for specific uses (i.e. terrace houses are usually linked to residential use; or commercial use may be commonly linked to mid-rise), but in the interest of comparing the impact of the building form and materials, both building uses were evaluated for all layouts.

### Results on Operational Energy (OE)

The following graphs display the main results that provide an adequate comparison amongst the different scenarios, for Residential and Commercial uses.

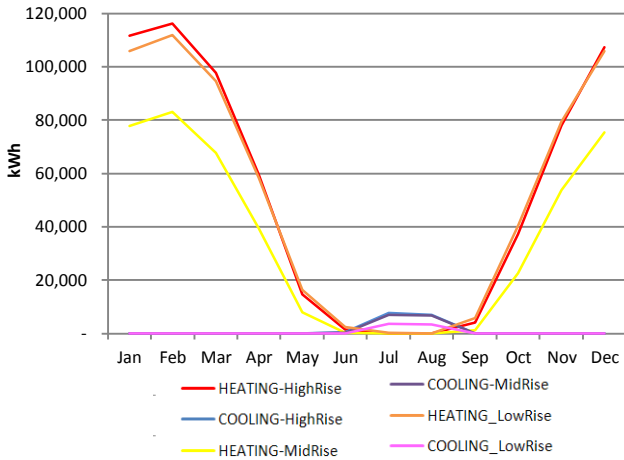


Figure 5 - Comparison of the Total Operational Energy (OE) of the 3 case studies – Heating and Cooling [Residential Use]

Figure 5 shows the overall behaviour of the case studies throughout the year. While heating appears to be almost the same for High-rise and Low-rise residential buildings, Mid-rise incurs significantly less operational energy. However when focused on cooling, the Low-rise layout seems to have the advantage. Nonetheless, cooling has significantly less impact than heating in the grand scheme of these cases. Normalised data can be observed in Figures 6 and 7.

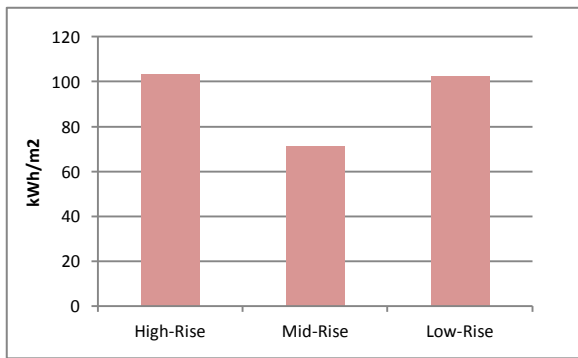


Figure 6 - Normalised data of the annual energy use for Heating - per square metre [Residential Use]

Figure 6 clearly shows how the Mid-rise layout uses about a third less energy (OE) in heating than the other two scenarios. By comparing Figure 6 and 7, Heating can be immediately identified as the relevant influencing design feature (under the analysed climate and materials).

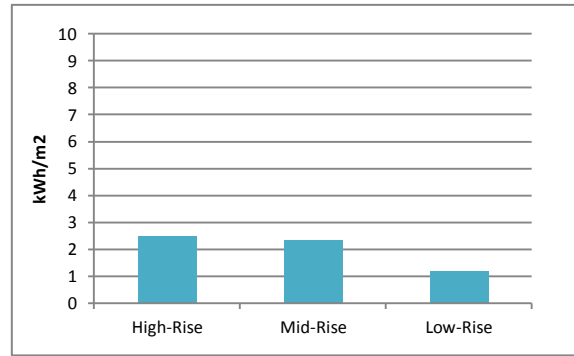


Figure 7 - Normalised data of the annual energy use for Cooling - per square metre [Residential Use]

Figure 8 displays the same features as Figure 5, but with a different use of buildings: Commercial use.

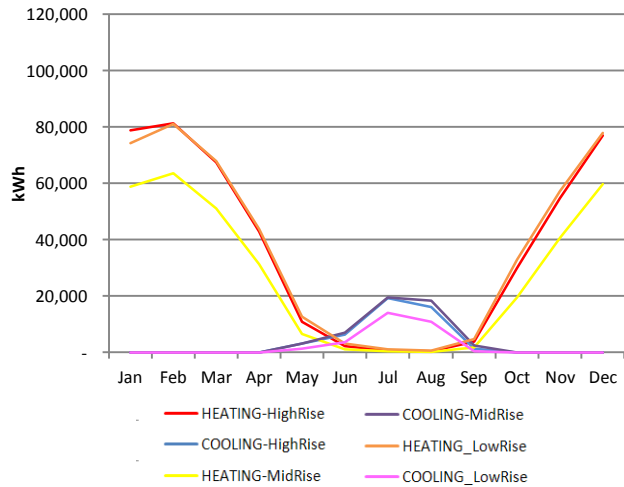


Figure 8 - Comparison of the Total Operational Energy (OE) of the 3 case studies – Heating and Cooling [Commercial Use]

Figures 9 and 10 show the results of the commercial case studies. The materials, occupancy schedules and other features have been altered to fit the new use of buildings for the three different layouts.

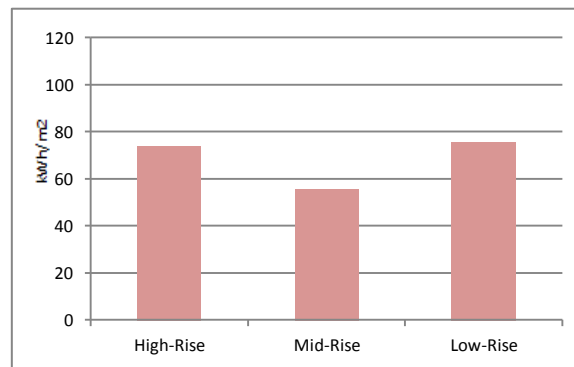


Figure 9 - Normalised data of the annual energy use for Heating - per square metre [Commercial Use]

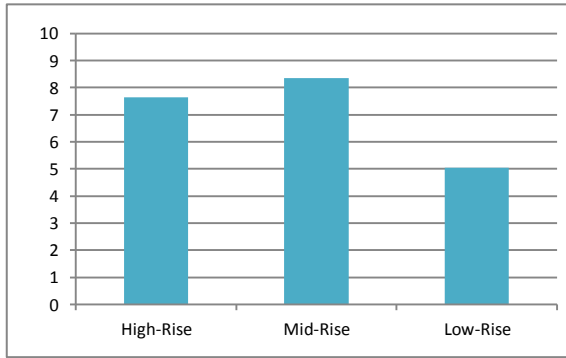


Figure 10 - Normalised data of the annual energy use for Cooling - per square metre [Commercial Use]

Figures 9 and 10 show that for commercial use the different layouts do not pose a large impact on the OE require for Heating. Cooling, on the other hand, is starting to have a more significant role, hence the need to consider this issue before designing these commercial types of buildings. However, Heating continues to be the most significant influence, and again the Mid-rise scenario shows a slight advantage over the other layouts.

It can be observed that for both residential and commercial use, the Mid-rise layout seems to be the more efficient type of layout when looking at the overall picture. However, in terms of operational energy for cooling the evidence shows that it depends on the use of the building. Furthermore, the fact that the Low-rise case study has a significantly larger exposed area (see Table 1) than the other two cases should also be considered, since it increases the potential for heat losses through fabric.

### Comparing OE results to EE

Figure 11 displays the contrast between the initial figures for OE and EE across the various urban layouts and building uses.

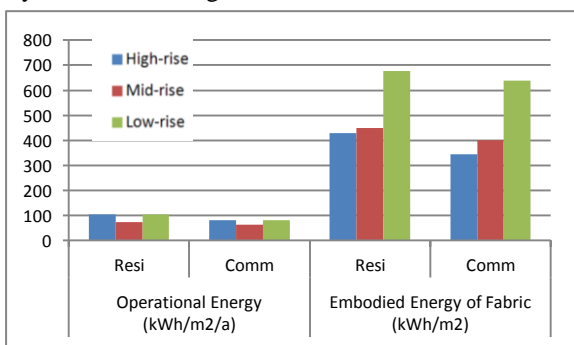


Figure 11 - Comparison of both building uses in terms of OE and EE of building fabric

The building simulation presented here has been an initial attempt to make the comparison between OE and EE something viable, in order to provide a rough estimate of the overall context. The results of this analysis have shown an advantage of Mid-rise

buildings over High-rise and low-rise (mainly terrace houses) in terms of OE. However, in terms of embodied energy (EE) the evidence is less clear with respect to the type of layout that may be more beneficial to the different building uses. As previously mentioned, Residential and Commercial cases have been designed based on different settings in terms of occupancy patterns and construction materials. One definite factor that Figure 11 suggests is that the EE of the fabric of Low-rise building is significantly higher than the other two scenarios, this is probably due to the fact that the exposed area of the Low-rise case study is also larger. In terms of EE of commercial buildings, Mid-rise and High-rise scenarios exhibit little difference in their effect on Embodied Energy.

Despite the availability of current EE databases, the variability of final numbers on the issues that affect EE calculations poses a significant obstacle to truly reflect reliable figures. Data is still being collected to create more standard figures for this comparison. This document presents the first attempt to achieve such comparison and aims to establish a sound methodology, which will generate high quality results when more accurate values on EE are established.

There are a number of issues that should be considered when comparing OE and EE in buildings, the process followed here is just a first step towards achieving other level of calculations at an urban scale. Usually, when the cumulative Operational Energy of buildings is considered the tendency is to tackle its reduction, before truly considering the consequent impact on the Embodied Energy. As a result, this trend is creating a distortion in the 'balance equation' previously mentioned, where by blindly improving OE, the other side either remains the same or most commonly increases on EE, potentially creating new problems to the built environment.

The spreadsheets with the modelled data for each case study have been used to compare the impact on the EE when adding insulation. Two materials have been used for this comparison Polystyrene board (EPS) and Wool. Both materials have almost the same conductivity, hence no much difference in thickness of the material was needed to obtain the same thermal performance. However, the Embodied energy of EPS is significantly larger than Wool. The calculated results for the different scenarios showed a larger increase of embodied energy for EPS in comparison to Wool (see Table 2), whilst achieving the same thermal performance. The aim of this exercise was to compare the energy savings in OE after adding the insulation (hence increasing EE), finally being able to calculate the payback period of the invested EE against the OE of buildings, i.e. recovered EE in terms of equivalent OE consumption.

Table 2  
Comparison of EE for different insulation materials

| INSULATION | comparing EE (kWh) |           |           |
|------------|--------------------|-----------|-----------|
|            | HIGH               | MID       | LOW       |
| none       | 2,606,148          | 2,703,777 | 4,254,556 |
| Wool       | 2,611,592          | 2,707,032 | 4,258,638 |
| EPS        | 2,740,111          | 2,783,876 | 4,344,951 |

The results shown in Table 2 were compared to the OE of the various case studies; such values suggested that the longest payback period of the insulation material with the highest Embodied Energy (EPS) would be six months, which seemed significantly small, and the payback period of Wools were merely weeks. This comparative method has great potential, however it must be revised with updated EE values.

Research papers can be found with significant details on EE values of windows, internal and external walls, roofs, ceilings, floors, etc. (Treloar et al., 2001, Treloar et al., 1999), which can be used to make the different cases more accurate according to their context. Due to the size of the database produced by the types of simulation outlined in this paper, there is a potential to compare the embodied energy of *fabric*, *structures* and possibly *foundations*. This part of the simulation is still under development, initially the comparison has been made between the EE results obtained from simulations against results suggested by similar case studies obtained in research literature (Treloar et al., 2001). Figure 12 shows the comparison between the EE of fabric (obtain from the simulations) versus the EE of structures (obtained from literature (Treloar et al., 2001)). Future research on these case studies will aim to include the energy impact of the different types of foundations.

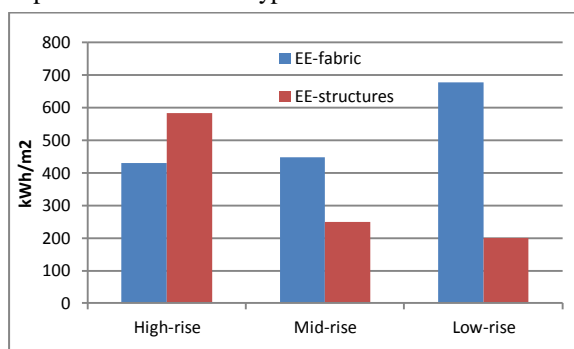


Figure 12- Comparison of the EE of the fabric, and structures, across different urban layouts

## CONCLUSION

Significant amount of time and effort is being directed towards reducing the OE of buildings in our society's current *green efforts* to minimise the waste of energy. However, as this investigation has indicated, OE is only 'the tip of the iceberg'. EE is a significantly important issue and its complexity

makes it an even more urgent matter, in need of further investigation and improvement.

Little work has been done on developing large/medium scale energy solutions, particularly on Embodied Energy, this could arguably be due to the fact that the main focus has been directed towards improving the databases, which are significant, but not the sole issue. This research aims to lay the foundations for a methodology that may provide sound results while still being simple enough to use in the current design process.

Initial research based on this methodology, suggested that Mid-rise has a lower OE; however, the most efficient scenario for EE is less clear and seems to depend more on the application (use) of the building.

Being able to predict EE at an early stage as well as OE could provide clues towards the appropriate strategies to reduce the overall energy consumption. Furthermore, jointly EE and OE can be used to 'counteract' the negative effect of each other, as it was demonstrated during the testing of the 'payback' periods of the EE of different materials.

An area that requires a deeper understanding is the analysis of the role played by several other influencing elements of the built environment, such as structures, foundations and services infrastructure. While their presence is more subtle than the actual buildings, they also account for a large part of the energy used. A future goal in the development of this methodology is to build up towards exploring those issues.

## ACKNOWLEDGEMENT

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