# Multi-disciplinary Performance Assessment of A Building Unit Using A New Semi-quantitative Method of Building Lifecycle Assessment

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Today, increasing rates of energy and resource consumption in the world have led the building sector to challenge the development of a new Building Life Cycle Assessment (BLCA) method. Moreover, some building designers and decision makers are concerned about a group of related aspects of BLCA (e.g. energy and carbon efficiency) in their designs. This approach can sometimes cause further negative issues in terms of unregarded values (e.g. related to quality of the acoustic environment). The aim of this paper is to determine the relationship between energy/carbon efficiency and quality of the acoustic environment based on a numerical semi-quantitative method, using various material scenarios in a typical building unit. The results present findings of an objective study which would help building designers and decision makers to consider the unregarded values as well as to involve different aspects of building design (e.g. energy and carbon efficiency, and acoustic comfort) in a more sensitive and more precise numerical manner.

**Keywords:** Building Lifecycle Assessment, Embodied Energy, Embodied Carbon, Reverberation Time, Sound Reduction Index.

## 1. INTRODUCTION

A Life Cycle Assessment (LCA) of construction materials and complete structures measures lifetime environmental performance from extraction to manufacturing then transportation, installation, use, maintenance and finally disposal/recycling [1]. Therefore, LCA offers an effective way to decrease waste in different stages of design, build or manufacture. In recent years, this cyclical basis has been extended to an investigation of energy (embodied and operational) and carbon [2-5]. In terms of sustainability and environmental impact, the performance of materials and structures in a building should strive for minimising energy consumption and carbon footprint.

However, improving the performance of buildings from the perspective of one or two factors (e.g. energy and carbon) will not necessarily be good from the perspective of other parameters related to comfort in buildings e.g. representing the acoustic comfort. For example, certain types of thermal insulation can actually be bad for acoustic insulation, by increasing noise reverberation and flanking sound. Moreover, it is extremely difficult, if not impossible to retrofit proper acoustic performance and thus, it should be considered in advance, before the building construction or reconstruction. Hence, including acoustics in the BLCA will help to resolve specific problems the building industry is facing in terms of multidisciplinary assessment and optimisation of buildings performance.

Accordingly, the main purpose of this research is to determine the relationship between energy/carbon efficiency and parameters essential for acoustic comfort in buildings (e.g sound reduction index and reverberation time); moreover to highlight the role of each parameter in a multidisciplinary building design and decision making process. This is realized by a comparison of the results of a numerical simulation of the performance of three simulated scenarios in a typical building unit, using various materials. This action has been done to examine the results of the methodology in terms of showing the best choices of design from energy, carbon, and acoustics points of view.

The rest of the paper is organised as follows: section 2 presents the methodology of the research, section 3 describes the semi-quantitative methodology, in section 4 the CRR model/software is presented, section 5 presents the case-study site description, section 6 and 7 demonstrate, respectively, the results of a preliminary and final modelling and comparison between simulated scenarios, while in chapter 8 the conclusions are given.

## 2. METHODOLOGY

The methodology of this research is based on a new numerical semi-quantitative method recently developed in the University of Sheffield, using various material scenarios in a typical building unit. It considers embodied energy (EE) and embodied carbon (EC) of buildings through their lifecycle, within a proposed spreadsheet [6]. As previously stated, the semi-quantitative method [7] tries to answer some questions raised from the incomplete outputs of the existing BLCA tools in the category of *'design and decision support'* [7-9] as follows: *How sensitive and reliable are these tools?*, *What is the impact of geographical and climate changes on building's lifecycle inventory (LCI) data?, Are these building LCA tools having a global value or are they just useful for developed countries?*. Hence, it is designed to investigate and propose a complete and a more sensitive measurement approach to examine case studies, based on more credible input data taken from other research centres, and programmes e.g. Autodesk-Ecotect 2011 [10]. Therefore, the methodology is described as 'Semi-quantitative'. However, the following questions have not been answered yet, which are the main challenges of this paper: *How reliable are the results of BLCA tools in a multidisciplinary scope? Are the appropriate building scenarios from an energy/carbon view appropriate from a view of acoustic comfort as well?*

Accordingly, a spreadsheet has been prepared which measures the total embodied energy, and embodied carbon of the construction procedure in a simulated building. The acoustic parameters such as reverberation time and sound reduction index are added to the spreadsheet. Moreover, more precise input data are considered (using other handbooks, inventories and software) [11]. Furthermore, operational energy has been achieved through the outcome of Ecotect 2011, while reverberation time of simulated spaces have been calculated with CRR (Combined Raytracing and Radiosity, developed by the University of Sheffield) [12]. Sound reduction index data have been derived from the literature [19].

## 3. THE SEMI-QUANITATIVE METHODOLOGY

The semi-quantitative methodology is established on calculation-engine (an Excel based spreadsheet) which calculates the following values (see figure 1):

- Section;
- Detail;
- Material;
- Area ($m^2$);
- Height (m);
- Volume ($m^3$);

| ✓ | Section | Detail | Material | Area (M2) | hight (M) | Volume (M3) | Density (kg/m$^3$) | total Weight (Kg) | Tone | EE(MJ/Kg) | EC(Kg Co2/Kg) | EE-Total (MJ) | EC-Total (Kg Co2) | OE (From Ecotect 2011) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FL-BT | Flooring | Concrete Slab | Concrete (gen | 1739.0511 | 0.2 | 347.8102 | 2000 | 695620.44 | 695.6204 | 1.17 | 0.169 | 813875.9148 | 117559.854 | |
| | | | Virgin Steel-Ba | 193.2279 | 0.2 | 38.64558 | 7800 | 301435.524 | 301.4355 | 24.06 | 1.71 | 7252538.707 | 515454.746 | |
| | | Tiling | Plastic (Gener | 1932.279 | 0.01 | 19.32279 | 1050 | 20288.9295 | 20.28893 | 105.3 | 2.53 | 2136424.276 | 51330.9916 | |
| | | | glue (Plastic-re | 1932.279 | 0.001 | 1.932279 | 250 | 483.06975 | 0.48307 | 200 | 2.7 | 96613.95 | 1304.28833 | |
| | Internal Walls | Building Cent | Concrete (gen | 22.573512 | 5 | 112.8676 | 2000 | 225735.12 | 225.7351 | 1.17 | 0.169 | 264110.0904 | 38149.2353 | |
| | | | Virgin Steel-Ba | 2.508168 | 5 | 12.54084 | 7800 | 97818.552 | 97.81855 | 24.06 | 1.71 | 2353514.361 | 167269.724 | |
| | | | Plaster (gener | 17.52856469 | 0.002 | 0.035057 | 849 | 29.76350284 | 0.029764 | 3.5 | 0.12 | 104.17226 | 3.57162034 | |
| | | | Colour (paint- | 17.52856469 | 0.001 | 0.017529 | 633 | 11.09558145 | 0.011096 | 67.55 | 3.56 | 749.5065269 | 39.50027 | |
| | | Internal Walls | Wood (Timber | 8.46846 | 5 | 42.3423 | 600 | 25405.38 | 25.40538 | 7.79 | 0.46 | 197907.9102 | 11686.4748 | |
| | | | Recycled Pape | 5.64564 | 5 | 28.2282 | 250 | 7057.05 | 7.05705 | 16.82 | 1.5 | 118699.581 | 10585.575 | |
| | | | Resine (Plastic | 5.64564 | 0.001 | 0.005646 | 250 | 1.41141 | 0.001411 | 200 | 2.7 | 282.282 | 3.810807 | |
| | External walls | External walls | Concrete (gen | 65.58624 | 5 | 327.9312 | 2000 | 655862.4 | 655.8624 | 1.17 | 0.169 | 767359.008 | 110840.746 | |
| | | | Virgin Steel-Ba | 7.28736 | 5 | 36.4368 | 7800 | 284207.04 | 284.207 | 24.06 | 1.71 | 6838021.382 | 485994.038 | |
| | | | Plaster (gener | 910.92 | 0.002 | 1.82184 | 849 | 1546.74216 | 1.546742 | 3.5 | 0.12 | 5413.59756 | 185.609059 | |
| | | | Colour (paint- | 910.92 | 0.001 | 0.91092 | 633 | 576.61236 | 0.576612 | 67.55 | 3.56 | 38950.16492 | 2052.74 | |
| | Ceiling | Suspended Ce | mineral fibres | 1932.279 | 0.01 | 19.32279 | 60 | 1159.3674 | 1.159367 | 43.23 | 1.2 | 50119.4527 | 1391.24088 | |
| | | | metal wire (Iro | 0.007729116 | 0.2 | 0.001546 | 7830 | 12.10379566 | 0.012104 | 24.61 | 1.92 | 297.8744111 | 23.2392877 | |
| | | | Plastic (Gener | 1.5458232 | 0.03 | 0.046375 | 640 | 29.67980544 | 0.02968 | 105.3 | 2.53 | 3125.283513 | 75.0899078 | |
| | Collumns | Collumns | Concrete (gen | 12.927384 | 5 | 64.63692 | 2000 | 129273.84 | 129.2738 | 1.17 | 0.169 | 151250.3928 | 21847.279 | |
| | | | Virgin Steel-Ba | 1.436376 | 5 | 7.18188 | 7800 | 56018.664 | 56.01866 | 24.06 | 1.71 | 1347809.056 | 95791.9154 | |
| | | | Plaster (gener | 71.8188 | 0.002 | 0.143638 | 849 | 121.9483224 | 0.121948 | 3.5 | 0.12 | 426.8191284 | 14.6337987 | |
| | | | Colour (paint- | 71.8188 | 0.001 | 0.071819 | 633 | 45.4613004 | 0.045461 | 67.55 | 3.56 | 3070.910842 | 161.842229 | |
| | Windows | Glass | | | | | | | | | | | | |
| | | Frame | | | | | | | | | | | | |
| | Electrical | Wire | Copper | 0.54103812 | 2 | 1.082076 | 8940 | 9673.761586 | 9.673762 | 69.2 | 3.83 | 669424.3017 | 37050.5069 | |
| | | | Plastic (Gener | 23.187348 | 0.02 | 0.463747 | 150 | 69.562044 | 0.069562 | 105.3 | 2.53 | 7324.883233 | 175.991971 | |
| | | Lamps | Glass (general | 0.048306975 | 0.05 | 0.002415 | 2800 | 6.7629765 | 0.006763 | 18.5 | 0.85 | 125.1150653 | 5.74853003 | |
| | | Lamp holders | Plastic (Gener | 0.030916464 | 0.05 | 0.001546 | 640 | 0.989326848 | 0.000989 | 105.3 | 2.53 | 104.1761171 | 2.50299693 | |
| | | Sockets | Plastic (Gener | 57.96837 | 0.001 | 0.057968 | 640 | 37.0997568 | 0.0371 | 105.3 | 2.53 | 3906.604391 | 93.8623847 | |
| | | Suitches | Plastic (Gener | 19.32279 | 0.001 | 0.019323 | 640 | 12.3665856 | 0.012367 | 105.3 | 2.53 | 1302.201464 | 31.2874616 | |
| | | | Copper(Gener | 0.144920925 | 0.005 | 0.000725 | 8940 | 6.477965348 | 0.006478 | 69.02 | 3.83 | 447.1091683 | 24.8106073 | |
| | | Chanels | Plastic (PVC) | 1.44920925 | 0.8 | 1.159367 | 1430 | 1657.895382 | 1.657895 | 70.61 | 2.41 | 117063.9929 | 3995.52787 | |
| | Mechanical | Pipes | Plastic (PVC) | 1.23665856 | 2 | 2.473317 | 1430 | 3536.843482 | 3.536843 | 70.61 | 3.83 | 249736.5182 | 13546.1105 | |
| | | Fitting | Plastic (PVC) | 649.6321998 | 0.3 | 194.8897 | 1430 | 278692.2137 | 278.6922 | 70.61 | 2.41 | 19678457.21 | 671648.235 | |
| Total | | | | | | | | 2796434.168 | 2796.434 | | | 43168556.81 | 2358340.73 | 75,565.44 |

**Figure 1.** The new semi-quantitative methodology.

| ✓ | Section | Detail | Material |
|---|---|---|---|
| FL-BT | Flooring | Concrete Slab | Concrete (general) |
| | | | Virgin Steel-Bar & Rod (general-UK typical) |
| | | Tiling | Plastic (General) |
| | | | glue (Plastic-resin-general purpose polystyren) |
| | Internal Walls | Building Central Core | Concrete (general) |
| | | | Virgin Steel-Bar & Rod (general-UK typical) |
| | | | Plaster (general) |
| | | | Colour (paint-general) |
| | | Internal Walls | Wood (Timber-General) |
| | | | Recycled Paper (general-predominantly recycled) |
| | | | Resine (Plastic-resin-general purpose polystyren) |
| | External walls | External walls | Concrete (general) |
| | | | Virgin Steel-Bar & Rod (general-UK typical) |
| | | | Plaster (general) |
| | | | Colour (paint-general) |
| | Ceiling | Suspended Ceilling | mineral fibres (mineral wool) |
| | | | metal wire (Iron-1mmx20cm-4no/m2) |
| | | | Plastic (General) |
| | Collumns | Collumns | Concrete (general) |
| | | | Virgin Steel-Bar & Rod (general-UK typical) |
| | | | Plaster (general) |
| | | | Colour (paint-general) |
| | Windows | Glass | |
| | | Frame | |
| | Electrical | Wire | Copper |
| | | | Plastic (General) |
| | | Lamps | Glass (general) |
| | | Lamp holders | Plastic (General) |
| | | Sockets | Plastic (General) |
| | | Suitches | Plastic (General) |
| | | | Copper(General) |
| | | Chanels | Plastic (PVC) |
| | Mechanical | Pipes | Plastic (PVC) |
| | | Fitting | Plastic (PVC) |
| Total | | | |

**Figure 2.** High sensitivity of the new methodology in details of building materials and components.

- Density (Kg/m3);
- Total weight (in Kg and Tone);
- EE per $m^3$;
- EC per $m^3$;
- Total EE;
- Total EC;
- Total OE (resulted from Ecotect 2011 modelling).

One of the advantages of this methodology is the high sensitivity in building materials and components in a micro-detailed approach (see figure 2).

### 3.1. Providing the basic data (EE, EC, volume of building elements, weights and densities of materials)

The areas ($m^2$) have been measured based on the plans of the building (it can be measured either in AutoCAD based or manual approach). The volumes of the elements have been calculated based on the

| Section | Detail | Material | Area (M2) | hight (M) | Volume (M3) |
|---|---|---|---|---|---|
| Flooring | Concrete Slab | Concrete (general) | 1739.0511 | 0.2 | 347.8102 |
| | | Virgin Steel-Bar & Rod (general-UK typical) | 193.2279 | 0.2 | 38.64558 |

**Figure 3.** Calculation of the volume of concrete and virgin steel in floor of the basement in the case-study.

| Detail | Material | Area (M2) | hight (M) | Volume (M3) |
|---|---|---|---|---|
| Internal Walls | Wood (Timber-General) | 8.46846 | 5 | 42.3423 |
| | Recycled Paper (general-predominantly recycled) | 5.64564 | 5 | 28.2282 |
| | Resine (Plastic-resin-general purpose polystyren) | 5.64564 | 0.001 | 0.005646 |

**Figure 4**. Calculation of the volume of wood, recycled paper, and resin in internal walls of the basement in the case-study.

| | Density (kg/m³) | total Weight (Kg) | Tone | EE(MJ/Kg) | EC(Kg Co2/Kg) |
|---|---|---|---|---|---|
| Concrete (general) | 2000 | 695620.44 | 695.6204 | 1.17 | 0.169 |
| Virgin Steel-Bar & Rod (general-UK typical) | 7800 | 301435.524 | 301.4355 | 24.06 | 1.71 |

**Figure 5**. Calculation of the total weight of materials in the basement of the case-study.

| | EE-Total (MJ) | EC-Total (Kg Co2) |
|---|---|---|
| Concrete (general) | 813875.9148 | 117559.854 |
| Virgin Steel-Bar & Rod (general-UK typical) | 7252538.707 | 515454.746 |

**Figure 6.** Calculation of the total EE and total EC of the materials.

| | | | EE-Total (MJ) | EC-Total (Kg Co2) | OE (From Ecotect 2011) |
|---|---|---|---|---|---|
| Total | | | 43168556.81 | 2358340.73 | 75,565.44 |

**Figure 7.** Calculation of the total EE, EC, OE.

following approach:

*Volume of element ($m^3$) = (Area of element in $m^2$) × (height of element in meter)*

e.g. floor area × floor thickness, or wall area × height of walls. Hence, in breaking down the materials the volume of each material has been measured by considering the percentage/rate of that material in the considered element. For example, the volume of steel (as bars and rods) and concrete (general type) are being calculated by respectively timing the volume of armed concrete to 0.1 and 0.9 (the considered rate in this case-study) (see figure 3).

*Volume of armed concrete × 0.1 = Volume of steel*

*Volume of armed concrete × 0.9 = Volume of concrete*

In the case of volume of materials in the composite walls of this case-study, the calculation process is as follows (also see figure 4 and 5):

*Volume of walls × 0.4 = Volume of wood (timber-general)*

*Volume of walls × 0.4 = Volume of recycled paper (general-predominantly recycled)*

*Volume of walls × 0.004 = Volume of Resin (Plastic-resin-general purpose polystyrene)*

The total weights of the materials are calculated in the following approach (see figure 6):

*Density of 1$m^3$ of material × Total volume of material = Total Weight (Kg)*

The total EE and EC of each material is calculated by multiplying the total weight by EE and EC of one Kilo-Gram of that material as follows (see figure 6):

*Total weight of material × EE of 1Kg of material = Total EE of material in the floor*

*Total weight of material × EC of 1Kg of material = Total EC of material in the floor*

The total EE and EC of the floor is calculated by adding up all total EEs and ECs.

To continue, the results of the preliminary modelling of the case-study floors (OE from Ecotect 2011) are entered to the spreadsheet. This action is being conducted to reach the total number of energy consumption and environmental impact during construction process and service-life of the building (in this case the service life has been considered as 50 years). In that sense, the total OE resulted from Ecotect 2011 is multiplied by 50 (see figure 7).

*OE (Resulted from Ecotect 2011) × 50 = OE in 50 years of building service-life*

## **4.** Combined Raytracing and Radiosity **(CRR)**

CRR is a model/software that simulates sound propagation in indoor or outdoor space. It combines ray-tracing and radiosity models that takes into account specular and diffuse reflections from the space boundaries [12, 13]. The *ray-tracing* model is built on the concept of a sound ray, which is a small portion of a spherical wave with a vanishing aperture that originates from a source centre point. *Radiosity* is another geometrical method that can be used to elucidate the characteristics of a sound field with diffusely reflecting surfaces. The radiosity method has its basis in the field of thermal heat transfer [14], which describes radiation as the transfer of energy from a source when that source has been thermally excited.

The process of simulation with CRR starts with the data presentation of a simulated environment called scene modelling. It is a collection of audio and visual components which creates the simulated space. This is then stored in a text-based file. In CRR the scene modelling includes dividing the model geometry into a set of nodes (patches) (see below), defining the size and location of the source and receiver, and setting up the absorption and diffusion coefficients of the boundaries. The file also stores the camera position, camera angle, light illuminations and other information for OpenGL implementation [15] for visual purposes. The scene file is in either .obj or .nff format, which are the most widely used text-based data description languages. An example of the visual rendering using CRR is shown in figure 8.

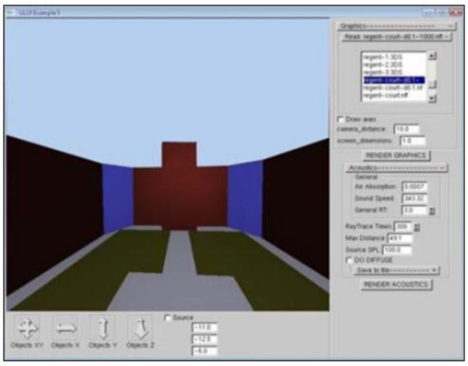

**Figure 8.** Simulation interface in CRR.

Acoustic simulations in CRR start from ray-tracing part. Hence, a number of rays are radiated from the sound source in random directions. The density of rays radiated in a particular direction may be constant for the whole space or may in some way reflect the spatial characteristics of the sound source. Rays then travel through the scene while their energy decreases due to the absorption in the air and in the boundaries during reflections. The energy of sound is obtained in predefined time intervals $\Delta ti$ by summing all that have crossed the receiver.

In radiosity calculation, the surfaces in the environment are assumed to be perfect (or Lambertian) diffusers, which reflect incident sound in all directions with equal intensity. Such formulation for the system of equation is facilitated by dividing the environment into a set of small area, called patches, and calculates the energy exchange between them. The patches are meshes of surface boundaries of a simulated space. The radiosity of a patch is the total rate of energy leaving a surface and it is equal to the sum of the reflected energies [16].

The combination between ray-tracing and radiosity is as follows: when a ray hits a surface patch, part of the incident energy is reflected specular and carried further along the reflected ray. If the ray hits a receiver, its energy is recorded into the receiver. Another part (diffuse energy) is stored into the patch; then patches carry out the energy exchange, to calculate the diffuse reflection. As a result of acoustic simulation with CRR, acoustic parameters such as early decay time (EDT), reverberation time (RT) and sound pressure level (SPL) are calculated at particular receiver positions.

CRR model has been proved to provide accurate results through comparison with other simulation models and with a number of measurement results [13, 17]. A number of parametric studies have also been carried out for the investigation of parameters, and for the investigation of the relationship between specular and diffuse reflections [17, 18].

**5. THE CASE-STUDY**

To validate the methodology of this research the *Arts Tower of Sheffield, UK* (see figure 9) has been selected as the case-study. This selection has been based on the significant situation of the tower regarding the recent refurbishment procedure (started in 2009). This, in turn, has provided a great opportunity to investigate the building through its 50 years of service-life.

From the typology point of view the tower is designed as a mixture of core and casing high-rise families. The structure of the Arts Tower building is based on armed concrete columns and slabs of floors in 23 stories (20 plus mezzanine and 2 basement floors). All the toilets, lifts, paternosters, stairways, and


**Figure 9**. Arts Tower, the University of Sheffield (left picture), general layout of structure and offices of a typical floor (floors 1-18) in the Arts Tower (right picture).

electrical-mechanical utility ducts are located in the central core, established on armed concrete load-bearing walls (see figure 9).

To continue, three material scenarios of the case-study's typical floor (floor 1-18) have been modelled in two phases of modelling (preliminary and final modelling) as follows:

**Scenario 1**

This scenario is established on the original structural system and materials, and also utilities of the Arts Tower. In this scenario, the structure and central core of the building have been considered as reinforced concrete made of 'general' concrete type [11], and virgin steel. Plastic tiling (general type) [11], suspended ceilings (made up of mineral fibres/mineral wool), windows (single glazing - general glass of 6mm width + aluminium profile - UK typical) have also been counted.

**Scenario 2**

In scenario 2 the size of the aluminium profiles of the windows is changed to 100×100mm and the single glazing is changed to 10mm×12mm with 6mm cavity between the glass. The type of ceiling is the acoustic suspended ceiling, same as in scenario 1.

**Scenario 3**

In this scenario the type of ceilings is changed. Therefore, instead of acoustic suspended ceilings (used in scenario1) the normal ceilings (based on plaster and painting) are proposed. The same profile of windows as in scenario 1 is considered.

## 6. PRELIMINARY AND FINAL MODELLING

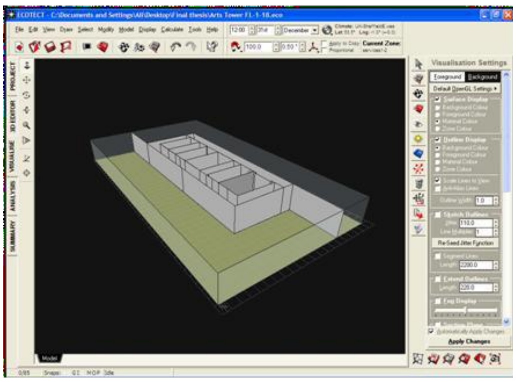

**Figure 10.** Modelling of the case-study based on all thermal zones.

**Table 1**. Operational energy (OE) of the typical floor in the existing situation in the Art Tower, calculated by Ecotect 2011 (scenario 1).

| Floor | OE (MJ) | |
|---|---|---|
| | Annual | Total in 50 years of Service-life |
| Floors 1-18/FL-1-18 | 25,865.96 | 1,293,298 |

| ✓ | Section | Detail | Material | Area (M2) | hight (M) | Volume (M | Density (k | total Weight (Kg) | Tone | EE(MJ/Kg) | EC(Kg Co2/Kg) | EE-Total (MJ) | EC-Total (Kg Co2) | OE | Sound Scape |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FL-1-18 | Flooring | Concrete | Concrete | 639.0432 | 0.2 | 127.8086 | 2000 | 255617.28 | 255.6173 | 1.17 | 0.169 | 299072.2176 | 43199.32032 | | |
| | | | Virgin Ste | 71.0048 | 0.2 | 14.20096 | 7800 | 110767.488 | 110.7675 | 24.06 | 1.71 | 2665065.761 | 189412.4045 | | |
| | | Tiling | Plastic (Ge | 710.048 | 0.01 | 7.10048 | 1050 | 7455.504 | 7.455504 | 105.3 | 2.53 | 785064.5712 | 18862.42512 | | |
| | | | glue (Plas | 710.048 | 0.001 | 0.710048 | 250 | 177.512 | 0.177512 | 200 | 2.7 | 35502.4 | 479.2824 | | |
| | Internal W | Building C | Concrete | 22.573512 | 3.5 | 79.00729 | 2000 | 158014.584 | 158.0146 | 1.17 | 0.169 | 184877.0633 | 26704.4647 | | |
| | | | Virgin Ste | 2.508168 | 3.5 | 8.778588 | 7800 | 68472.9864 | 68.47299 | 24.06 | 1.71 | 1647460.053 | 117088.8067 | | |
| | | | Plaster (g | 17.52856469 | 0.002 | 0.035057 | 849 | 29.76350284 | 0.029764 | 3.5 | 0.12 | 104.17226 | 3.571620341 | 1,293,298 | 937638 |
| | | | Colour (pa | 17.52856469 | 0.001 | 0.017529 | 633 | 11.09558145 | 0.011096 | 67.55 | [illegible] | [illegible] | 39.50026996 | | |

**Figure 11**. Modelling of Sheffield Arts Tower- floors 1-18 in the new semi-quantitative method.

**Table 2**: Embodied (EE), operational (OE), and total energy; embodied carbon (EC); reverberation time **(**RT) and sound reduction index (Rw+Ctra) in the simulated scenarios.

| Scenario | Energy, MJ | | | EC, Kg | RT, s | Rw+Ctra, dB |
|---|---|---|---|---|---|---|
| | EE | OE | Total | | | |
| Scenario 1 | 356,584,555 | 1,756,382 | 358,340,937 | 19,060,758 | 1.8 | 26 |
| Scenario 2 | 362,370,737 | 2,265,809 | 364,636,546 | 19,300,646 | 1.8 | 32 |
| Scenario 3 | 352,900,345 | 1,308,319 | 354,208,665 | 18,876,217 | 2.4 | 26 |

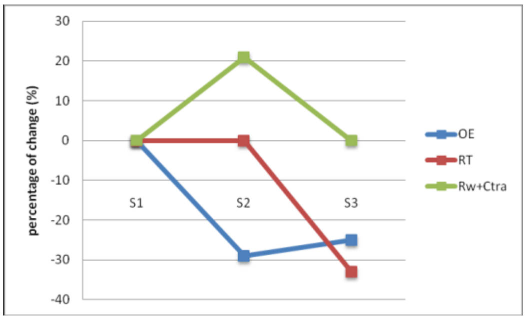


**Figure 12.** Percentage of changes of operational (EC), reverberation time (RT) and sound reduction index (Rw+Ctra) from scenario 1 (S1) to scenario 2 (S2) and from scenario 1 to scenario 3 (S3).

As formerly stated, during the preliminary modelling Ecotect-2011 has been employed to measure the operational energy in the tower based on the original structure and materials (scenario 1). Established on the nature of the programme, the modelling has been done based on thermal zones. Accordingly, the spaces in each floor which provide separate thermal zones have been considered based on the existing materials of construction (floors, walls, ceiling, and utilities) (see figure 10). The result of this modelling which is relevant to this research is the operational energy. Thus, the annual losses of energy/operational energy of the building have been calculated in Mega Joules (MJ). The OE has been multiplied by 50 to show the total operational energy of the tower during a 50 year service-life considered in the climate situation of Sheffield (see table 1).

The annual usage of energy due to

operational energy (OE) of the building has been calculated in Wh (Watt-hour). The number of OE multiplied by 50 to reach the total operational energy of the tower building during a 50 year of service-life, using the climate data of Sheffield (see table 1).

To continue, an acoustic simulation with CRR, a model of an inner space of the Arts Tower floor that includes a corridor, lift and paternoster (see figure 9) has been selected. It has been chosen just for the purpose of comparison in the simulation scenarios. Acoustic properties of the materials were based on a previously stated material profile of the building scenarios, as described in Section 3. Simulation of sound propagation has been performed in full octave bands. However, in this paper the results of RT are presented only for 1kHz octave (to be used for the comparison purpose). Moreover, the sound reduction index has been calculated, established on the previously mentioned case-study material scenarios. In this case, spectral adaptation for traffic noise (as Rw+Ctr) of windows represents an ability of glass to reduce the road traffic noise [19], applied in a simulation of the case-study scenarios.

In the final modelling phase, the whole of the modelling is performed on one spreadsheet based on the imported results coming from previous modelling faces, performed by other mentioned programmes (Ecotect 2011, and CRR) (see figure 11).

The results of previous programmes (Ecotect 2011 and CRR), also the input data (EE and EC) from the inventory of Bath University [11], have been imported to the final spreadsheet. This action has been conducted to finalise the energy and the acoustic comfort evaluation, and to reach the total EE, EC, OE, and acoustic parameters of each building scenario, as discussed above. (Consideration: The ICE 2010 is determining EE and EC based on 'cradle to gate' [11]; hence the scope of determination of EE and EC in the present modelling is 'cradle to gate').

## 7. COMPARISON BETWEEN SIMULATED SCENARIOS

Table 2 shows EE, OE, total energy, EC, and acoustic parameters regarding altering structural systems and material profiles in the three simulated scenarios of the case study.

Analysing results presented in table 2, it has been calculated that change from scenario 1 to scenario 2 results in an increase of OE by 29% (negative impact), the increase of EE and total energy are only by 2%, and increase of EC by 1%. However, scenario 2 significantly increases sound insulation of external walls by 21% (positive impact) compared to scenario 1. On the other hand, in the comparison between scenario 3 and scenario 1, a significant drop in OE by 25% can be observed; however EE and total energy increase only by 1%, while EC decreases by 1% and RT is increased by 33% (negative impact).

Comparing obtained results, it can be noticed that changes in EE, total energy and EC are insignificant. Thus, the decisions upon selection of the optimal scenario should be based on changes in OE, RT, and Rw+Ctra. In order to support the decision-making, a graph that reflects percentages of positive and negative changes in these parameters has been proposed (see figure 12). In scenario 2 (in comparison with scenario 1), it can be seen that the only negative impact is in OE. However, in scenario 3 although the negative impact of OE is less than in scenario 2, a significant negative impact of RT is highlighted. Thus, it is possible to conclude that scenario 3 is suggested to be rejected in favour of scenario 2 established on a logic basis.

The obtained results outline a logic basis for building design and decision support established on a multidisciplinary assessment methodology, in terms of EE, OE, carbonic, and parameters that represent the quality of acoustic environment in a building unit. This, in turn, confirms the advantages of the introduced semi-quantitative method.

## 8. CONCLUSIONS

The paper has compared the results of changing material scenarios in energy (EE, OE and total) and carbon (EC), as well as some parameters related to acoustic comfort (RT and Rw+Ctr) in a case-study based on a new semi-quantitative method. Accordingly, the process of preliminary modelling (in Ecotect 2011 and CRR) and the final modelling of the typical floor in the new methodology have been elaborated. Therefore, three scenarios of building material profile have been modelled in the new methodology/spreadsheet. This action has been conducted to examine the results of the methodology in terms of showing the best choices of design from energy, carbon, and acoustics points of view.

This study has revealed the significance of multidisciplinary measurements in building design and decision making. Accordingly, it has been shown that assessing the environmental performance of buildings through their lifecycle should be completed based on various factors. These factors are supposed be the directly related factors (e.g. energy, carbon, etc.) as well as the other values (e.g. related to acoustic comfort, etc.). This attitude will improve the preciseness and logic basis of BLCA to support designers and decision makers in the construction sector. The paper also opened new doors to further research and projects to provide more sensitive methodologies and tools with more credible results in terms of BLCA multi-disciplinary measurements.

## 9. REFERENCES


[1] Athena. (2009, March). The Athena Institute - Impact Estimator for buildings. Available: www.athenasmi.ca/tools/impactEstimator/

[2] Masters, N. (2001). Sustainable Use of New and Recycled Materials in Coastal and Fluvial construction: A gaidance manual. London, United Kingdom: Thomas Telford.

[3] Hauschild, M. Z. (2005). Assessing environmental impacts in a life-cycle perspective. Environmental Science & Technology, vol. 39(4), pp. 81a-8a.

[4] ISO14040, "Environmental management - life cycle assessment - principles and framework," International Standardization Organization 2006.

[5] LexicueEncycloBio (2009). Definition of energy management or energy efficiency. Available: www.citesciences.fr/lexique/definition1.php ?id_expo=11&id_habillage=22&iddef=312 &idmot=141&lang=an.

[6] Kashkooli, A. M. S. and Altan, H. (2010). Critical Building Life-cycle Assessment Methodology: Developing a simple tool. In the 9th International Detail Design in Architecture Conference, Preston, UK.

[7] Ortiz, O., Castells, F. and Sonnemann, G. (2007). Sustainability in the Construction Industry: A review of recent developments based on LCA. Construction and Building Materials, vol. 23, pp. 28-39 2007.

[8] Haapio, A. and Viitaniemi, P. (2008). A critical review of building environmental assessment tools. Environmental Impact Assessment Review, vol. 28, pp. 469-482.

[9] Forsberg, A. and Malmborg, F. V.

(2004). Tools for environmental assessment of the built environment. Built Environment, vol. 39, pp. 223-228.
[10] Autodesk. (2011, June). ECOTECT Building Analysis for Designers. Available: www.ecotect.com
[11] Hammond, G. and Jones C. (2010). Inventory of Carbon and Energy (ICE) Available: http://www.bath.ac.uk/mech-eng/sert/embodied/ Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, University of Bath, Bath, United Kingdom.
[12] Meng, Y. and Kang, J. (2007). Combined ray tracing and radiosity simulation for urban open spaces. In the 19th International Conference on Acoustics (ICA), Madrid, Spain.
[13] Meng, Y. (2008). Acoustic simulation and auralisation in urban open spaces. PhD Thesis, School of Architecture, University of Sheffield, Sheffield, UK.
[14] Siegel, R. and Howell, J.R. (1992). Thermal Radiation Heat Transfer. Washington, DC: Hemisphere.
[15] Foley, J. D., Van Dam, A., Feiner, S.K. and Hughes, J.F. (1990). Computer Graphics: Principles and Practice, Addison-Wesley, UK.
[16] Kang, J. (2002). Numerical modelling of the sound fields in urban streets with diffusely reflecting boundaries. J. Sound Vib. 258, 793–813.
[17] Y. Meng, J. Kang, and Y. Smyrnova, “Numerical modelling of sound fields with mixed specular and diffuse boundaries using combined ray tracing and radiosity method”, Proceedings of the Institute of Acoustics 30(2), UK, 2008.
[18] Meng, Y. and Kang, J. Combined ray-tracing and radiosity model for sound field simulation. Journal of the Acoustical Society of America, submitted.
[19] ERD, Planning guidance note for Developers: Noise Control, ed. Warrington, UK: Environment & Regeneration Department, 2004.