Embodied Energy at an Urban Scale:

A paradigm shift in calculations

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Embodied energy has long been a focus of research, and improved operational energy demands in modern structures cause the proper analyses of embodied energies to be critical for full building life cycle analysis. Many different calculation techniques exist to arrive at an embodied energy value, and literature is full of the application of these values to predominantly single or small numbers of buildings. Embodied energy at an urban scale is studied in this paper, and a new software tool for estimating embodied energy impacts at the design stage is introduced. Two case studies are discussed using the software, and embodied energies are calculated and presented in context with their operational energy savings. The importance of choosing an embodied energy value calculated according to the process-based hybrid analysis method when looking at the urban scale is discussed.

Keywords: embodied energy, urban scale, VirVil for HTB2

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A paradigm shift in calculations

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ABSTRACT: Embodied energy has long been a focus of research, and improved operational energy demands in modern structures cause the proper analyses of embodied energies to be critical for full building life cycle analysis. Many different calculation techniques exist to arrive at an embodied energy value, and literature is full of the application of these values to predominantly single or small numbers of buildings. Embodied energy at an urban scale is studied in this paper, and a new software tool for estimating embodied energy impacts at the design stage is introduced. Two case studies are discussed using the software, and embodied energies are calculated and presented in context with their operational energy savings. The importance of choosing an embodied energy value calculated according to the process-based hybrid analysis method when looking at the urban scale is discussed.
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INTRODUCTION

Published literature on embodied energy is full of figures of single products and materials [1-4]. These are a combination of calculated and referenced figures. Far less journal papers have been published about the embodied energy of complete buildings [5-7], and still less about embodied energy at large scales (urban and regional) [8, 9]. Complicating matters further are the differing calculation methods for embodied energies: process-based, input/output-based, process-based hybrid, and input/output hybrid methods are all on offer and all seemingly valid [10].

The focus of this paper is to discuss embodied energy at an urban scale. Comprehensive embodied energy analysis can only be performed post-construction, when all material volumes and their points of origin and manufacturing processes are known. Arguably, however, this is too late as calculating any type of energy load of a proposed development at the end of the construction process leaves little room or time for reduction or change. Whilst embodied energy calculations at the outset of a project will not be comprehensive, a general idea of the embodied energy burden can be introduced and considered. Twinned with advanced thermal energy analysis, these embodied energy values can be placed in perspective with the operational energy demands of a proposed development, leading to informed decisions as to how best to deliver a genuinely low-carbon development at an urban scale.

Looking closer at publications, the popular embodied energy calculation technique for individual materials is the process-based calculation method[11]. It is an efficient, fairly simple method of calculating the energy burden embodied in a product before its installation. The idea is the EE figure for the product (MJ/kg) – taken from the first 3 to 4 orders of direct energy inputs - is then multiplied by the total mass of material in a product; this total is then summed with the identical calculations for the other products in a project to achieve the total EE impact of the overall product or project. However, it suffers truncation errors due to these boundary conditions to the order of as much as 50% [12] – fine for small numbers of materials, but unsuitable at an urban scale. For urban areas, as far more material is involved in construction at this scale, it is critical further, indirect orders of energy inputs are accounted for in the embodied energy calculations, as these will lend significantly more weight when large orders of materials are used than just one or two.

Treloar and Lenzen [13] have argued input/output tables can be disaggregated logically to have these broad figures be applied to individual houses, Alcorn [4] has argued the hybridisation by Treloar, et. al., of input/output tables complicates an otherwise simple procedure, and Peters [14] has argued each calculation method is appropriate for a given scale of construction, insinuating the application of one method to an inappropriate scale is futile. His paper concludes the process-based hybrid method is most appropriate for urban scale and regional calculations. In terms of structures, it is a sensible conclusion as a process-based analysis covers the primary, direct embodied energies of each construction material, and the hybrid analysis extends the calculations further to account for the indirect, overhead embodied energy contributions factories and equipment add to the products [15].
I/O analysis takes an expansive view on all processes across a single economy involved in leading to the manufacture of a product, but for many reasons it is

discouraged as a calculation method for all but the largest of studies [10]. In fact, embodied energy calculation methods extend beyond country boundaries; multi-regional I/O analysis allows embodied energies within regions larger than just countries to be calculated properly, a method particularly appropriate for larger economic zones such as Europe and south-east Asia [14].

Returning to hybrid methods of calculation, discovering values based upon these methods – or any declared method of calculation – is difficult in literature. Some tables will expressly define which method was used in tabulating its values, but most are undefined. Other factors such as feedstock and recycled content are also often lacking. As aforementioned, Alcorn's database is generated by PB-H analysis [2], as is Goggins, et. al. [16], and Pullen [9]. Treloar has demonstrated the applicability of an I/O extraction tool for application for residential buildings [13]; this method is useful for very large urban areas, as it includes infrastructure as well as building materials. Infrastructure, water, sewerage, etc., are not considered with the VirVil for HTB2 tool, which makes it unsuitable as a fervent urban planning tool. The ICE database [3], arguably the most widely referenced source in the UK, does not define which method is used for its values; as its figures are an average of literature-based values, it effectively covers all bases. However, with average values fluctuating between +/- 30%, outputs at large scales can be misleading. Indeed, Pullen highlights how his and others' aggregated hybrid values differ considerably from ICE data [9].

It is this paper's argument, in line with publications mentioned above, that embodied energy reference values ought to be selected according to the scale of the project. For the purposes of urban scale energy analysis, hybrid analyses figures must be used above others for accuracy. This will be demonstrated through case studies using the recently developed SketchUp plugin *VirVil for HTB2*, combining the popular drafting program with HTB2, a dynamic thermal calculation engine.

VIRVIL FOR HTB2

The recent development of a new plugin for the popular drafting program SketchUp has combined both embodied and operational energy analysis for large scales within the built environment. The VirVil for HTB2 plugin links SketchUp with HTB2, a validated dynamic thermal energy analysis program. Its other capabilities have been presented elsewhere [17, 18]; however, here its embodied energy vs operational energy analyses are outlined. Embedded in the plugin are published embodied energy values for many popular construction materials. New or modified figures may be appended to the plugin by the user, depending on the project or project's location.

In basic terms, the plugin grabs the geometric data from a SketchUp model, combines it with the construction and material types HTB2 requires for its thermal analysis, and multiplies these figures by the embedded embodied energy figures in a method not unlike a quantity survey. The construction types used in HTB2 are limited to:

- the ground floor (slab)
- intermediate floors
- exterior walls
- interior walls
- roof
- windows

These cover the significant contributors to a project's embodied energy; accessories such as doors, cabinets, white goods, and other interior specifications, which do not contribute to thermal analysis, are not analysed with the VirVil for HTB2 plugin.

Several widely established embodied energy programs are available – BEES [19], GaBi [20], CRTI [21], Athena Institute Eco Calculator [22], etc. VirVil for HTB2 focusses solely on material embodied energy (instead of LCA, like the above) and uses the materials required for thermal calculations, i.e. the materials of greatest mass, and combines this data with geometries imported directly from a SketchUp model. SketchUp is currently used by over 50% of architects, predominantly at the early design stage [25]. Embodied energy calculations and parallel thermal calculations are thus performed natively within SketchUp at a stage in design where their impact may provide the greatest influence on design, without the requirement of learning an additional program. Outputs are, similar to existing LCA/ EE programs, in Microsoft Excel format.

As the construction industry targets the universal use of BIM (Building Information Modelling)[23], integrated energy modelling tools such as VirVil for HTB2 will play an increasingly significant role in the process.

CASE STUDY 1

Tourism forms a strong proportion of the Welsh economy (13% annual GDP) [24]. Occupancy numbers in holiday parks in Wales fall to 20% in winter compared with peak summer numbers. Shoulder seasons remain at 40% levels. One potential solution (offered by questionnaires) to increase visitor numbers in cooler weather is to increase the comfort levels experienced in holiday homes. One such holiday park in west Wales is modelled using the VirVil for HTB2 SketchUp plugin to contextualise the retrofit embodied energy of a large group of homes in parallel with potential operational energy reductions and warmer homes.

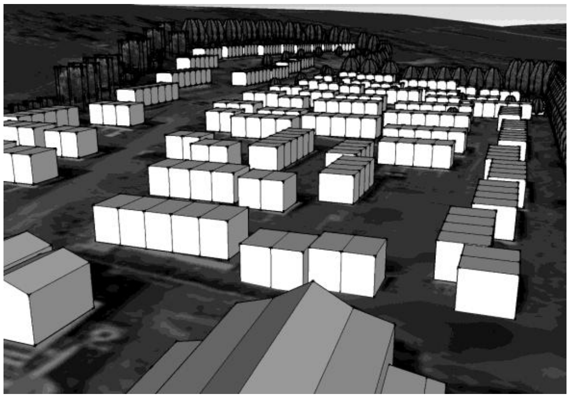

Figure 1: SketchUp model of the holiday park in west Wales, looking west. Note terrain and trees to boundary.

The holiday park consists of 271 identical houses constructed in the 1970s and sits in a tree-ringed depression adjacent to the coast, with the land sloping upward toward the south (Figure 1). The properties are split with 146 (54%) facing east/west and 126 (46%) north/south. The current construction of the properties is a timber frame, uPVC cladding to the exterior, uPVC windows and doors, a flat, timber-framed roof, a concrete ground floor, and timber-framed interior walls and floors. Glazing ratios are 30% to the front and 40% to the rear. These properties are all modelled as existing in SketchUp to calculate volumes of spaces and materials, the retrofitting option proposed by the park owner is introduced as a comparative construction in HTB2 (cementitious cladding in place of the uPVC and a pitched steel roof over the existing flat roof which remains), and the plugin is run with typical mean year (TMY) climate data to ascertain the thermal benefits of the retrofit option. In this way, the embodied energy of the retrofit option can be expressed in context with occupant comfort.

An occupancy schedule based upon social norm movements of occupants was introduced to the model, and internal gains inside the homes were set according to a provided equipment list to a maximum of 13.3 W/m^2. No heating or cooling was introduced into the thermal calculations to ascertain the change in occupant comfort solely due to solar and internal gains and fabric and ventilation losses. Two scenarios were tested: existing fabric with 50mm insulation and a proposed fabric with insulation doubled to 100mm to the walls and roof. The embodied energy impact to the tourist park was calculated and considered.

CASE STUDY 2

Modern housing estates built by housing developers are a popular construction method in the UK. The proposed Parc Derwen in Bridgend, Wales, about 20 miles west of Cardiff, positioned on a slightly southerly sloping open plain, is no exception. 976 2-storey homes are proposed, with a ratio of 80:20 semi-detached to detached. The township provided a masterplan, from which a SketchUp model was created (Figure 2). The houses are haphazardly orientated in clusters of varying porosity, with 409 (42%) generally facing east-west and 567 (58%) facing generally north-south. As they are to be constructed in the near future, a regulatory-compliant construction is anticipated: brick, insulated cavity wall construction with large levels of insulation in the roof and floor. Glazing ratios to front and rear facades are 30%.

The VirVil for HTB2 plugin is invoked for the model, with both baseline and thermally improved, lower embodied energy constructions modelled for embodied vs. operational energy comparative analysis. The 'improved' construction consisted of a change of insulation from polystyrene in the walls and roof to sheepwool, internal wall construction change from brick to timber frame, and an increase in insulation beneath the floor slab. The outputs from this study are of a significantly larger scale than Case Study 1, due to the greater number of residences and construction materials. A typical residential occupancy schedule was used across the site. Two studies were performed – occupancy comfort in terms of degree days above 18°C with no additional heating and heating reductions using a set point of 18°C compared with the embodied energy investments of improvements in the building fabric.

Figure 2: SketchUp model of Parc Derwen near Bridgend, Wales, looking east

RESULTS

The first interrogation was to visualise the impact a change in fabric would have on the occupant comfort in holiday homes in west Wales using only internal gains without the addition of supplemental heat. Figure 3 shows the average number of annual degree days at the holiday park over 18°C in regards to each construction scenario – as existing, refurbished with a new facade and cold roof, and refurbished with a new skin and cold roof and including doubling the insulation thickness to 100mm. These values are presented along with average and maximum monthly temperatures. There are less degree days in the well insulated houses in the shoulder seasons and more in the summer season. The winter season experiences no changes. In total, the insulated option provides 61 degree days over 18°C, with the existing and new options providing 57. This will be due to the insulation retaining warmth for longer in the hottest periods of the year, and not getting warm enough in the shoulder seasons due to a tighter fabric.

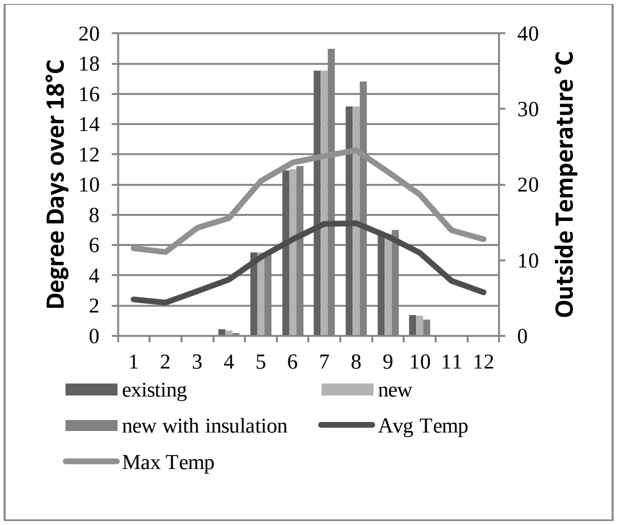

Figure 3: Annual degree days over 18°C for homes at the holiday park in regards to construction type.

Figure 4 illustrates the changes in embodied energy per construction element for all 271 homes. The park owner is only proposing to change the walls and roof. Both the walls and roof have an increase in embodied energy do to the increased insulation, but the walls see a greater increase in embodied energy than the roof due to a greater volume of materials. The rest of the elements remain unchanged (Table 1). The totals for the embodied energies for all materials to retrofit all properties at the holiday park are 8.46 GWh for the new construction and 10.29 GWh for the improved construction, a difference of 1.83 GWh (6.59 TJ).

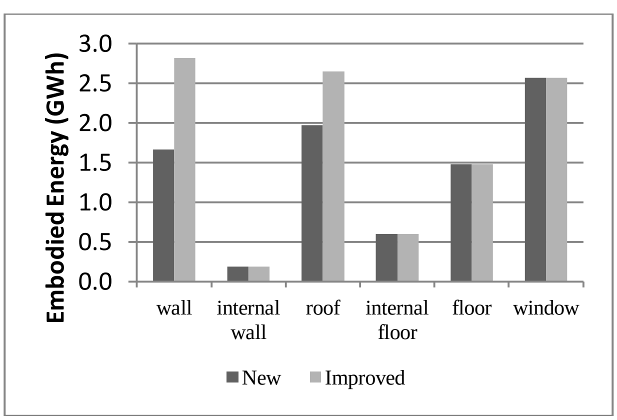

Figure 4: Embodied energy changes per construction element for the holiday park.

Table 1: Material amounts for the 271 homes at holiday park.

Construction	Area (m^2)	Volume (m^3) (new)	Volume (m^3) (improved)
External wall	10958	896	1444
Internal wall	3203	115	115
Roof	6406	616	936
Internal floor	4272	184	184
Floor	6406	1364	1364
Window	3675	45	45

Identical studies were carried out for the Parc Derwen residential estate outside of Cardiff, UK. Figure 5 shows the average change in annual degree days above 18°C with regards to the different construction scenarios – existing and improved. Increased degree days over the proposed construction are seen throughout the shoulder and summer seasons with the improved construction, unlike the scenario seen at the holiday park. The proposed (existing) construction yields 54 degree days over 18°C and the improved construction yields 60 degree days over 18°C.

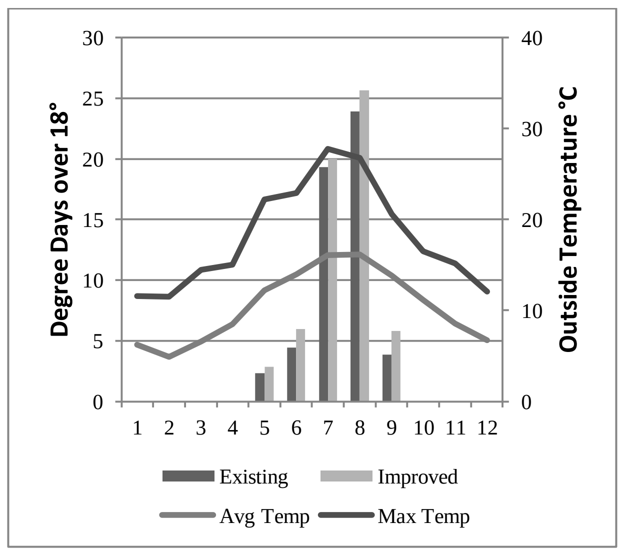

Figure 5: Annual degree days over 18°C for homes on the Parc Derwen estate in regards to construction type.

In regards to embodied energies, Figure 6 shows the differences in embodied energy expressed in GWh (in order to directly compare it with operational energy) between the two construction options for the housing development. The floor slab is the only element to undergo an increase; this is due to the materials unchanging in the slab, but an increase in thickness of the slab insulation (expanded polystyrene) from 200mm to 300mm. Reductions can be seen from swapping polystyrene insulation to natural wool, in the external walls and roof, and changing from brick to timber framing for the internal walls. Windows and the internal floor remain unchanged (Table 2). The total embodied energy amounts for all materials at Parc Derwen are 104.40 GWh for the existing construction and 97.04 GWh for the proposed construction, a difference of 7.34 GWh (26.44 TJ) for the site.

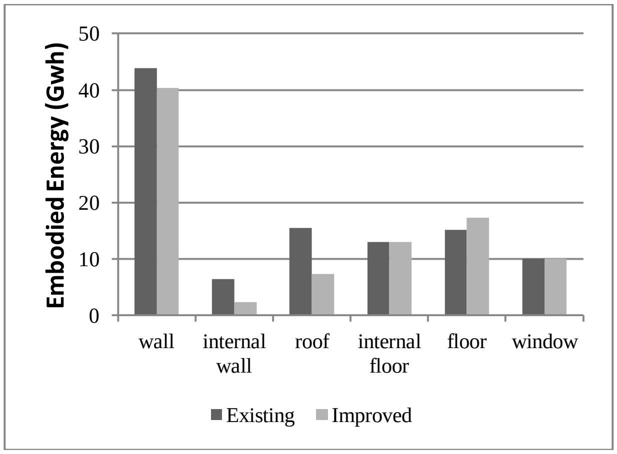

Figure 6: Embodied energy differences between the two construction options for Parc Derwen.

Table 2: Material amounts for the 976 homes at Parc Derwen.

Construction	Area (m^2)	Volume (m^3) (new)	Volume (m^3) (improved)
External wall	107630	32952	51787
Internal wall	31382	4048	1130
Roof	61779	21756	27934
Internal floor	79035	3399	3399
Floor	46491	31289	35938
Window	14529	177	177

Figure 7 shows the annual reductions in heating energy for the entire site at Parc Derwen achieved by utilising different options for the construction elements. A total annual reduction of 1.1 GWh is realised, or 55 GWh over the lifetime of the houses (50 year lifespan). These results demonstrate that the proper selection of materials prior to construction can return a combined embodied and heating energy savings of 62 GWh over the lifetime of the estate. Amortised, this is a reduction of approximately 10 kWh/m² of liveable floor space on the estate.

For the purposes of proper embodied energy analysis for the scales of these two case studies, values were used which were calculated according to the process-based hybrid analysis. As aforementioned, this calculation method has the most appropriate boundary conditions for embedded material energies for large scale projects. Figure 8 shows material values calculated according to the process-based analysis and the hybrid analysis, demonstrating the capacity of hybrid analysis to envelope the higher orders of energy impacts on products.

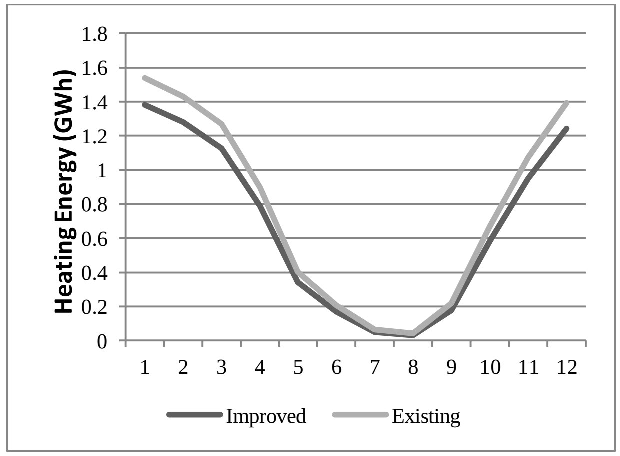

Figure 7: Heating energy reductions for Parc Dewen due to fabric changes.

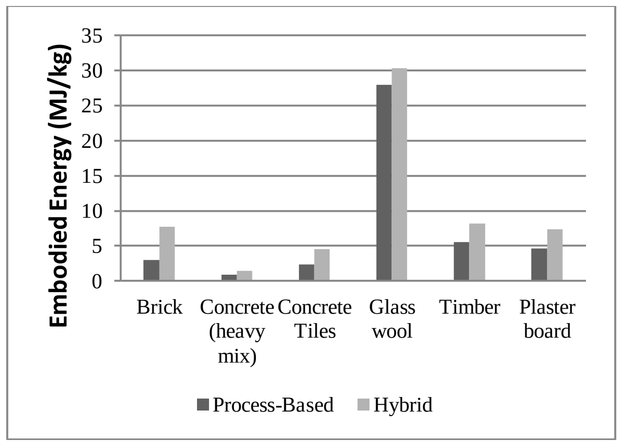

Figure 8: Embodied energy material values are dependent upon which calculation method is used.

In terms of embodied energies, for construction projects of this scale all contributory energy inputs per material need proper accounting. For a single house, process-based embodied energy analysis is sufficient; the most important energy input stages are calculated for the small amount of materials required. However, once the scale increases to a neighbourhood, estate, or urban area, higher energy input stages need to be accounted for, as their inputs become more substantial per unit of material. Table 3 expresses this difference more clearly in terms of these two case studies.

Table 3: Total material embodied energies for holiday park (HP) and Parc Derwen (PD) as calculated using hybrid analysis (HA) and process-based (PBA)

	HA	PBA	Difference
HP New	8.46	5.05	40%
HP Improved	10.29	6.75	34%
PD Existing	104.4	83.91	20%
PD Improved	97.04	76	22%

CONCLUSION

This paper used two case studies to present both a new urban scale energy analysis tool and a new way of thinking in terms of embodied energy calculations. The creation of a new plugin for SketchUp – VirVil for HTB2 – introduces an alternative method of early stage urban scale operational and embodied energy analysis which can be invoked without leaving the familiar SketchUp environment. This paper has shown how estates as large as almost 600 homes can be modelled and interrogated with the tool. Outputs include material volumes, construction element volumes, operational energy and embodied energy totals. Other outputs of the tool are discussed in parallel publications (above).

In terms of embodied energy, the selection of which figures to use has been discussed at length. Two practical case studies have underlined the importance of choosing figures respective to the scale of the project. Using process-based figures for large scale projects has been shown to create a misleading image of embodied energy values; large scale values have been shown here to be as much as 40% lower than if appropriate, hybrid-based values are used.

As embodied energy expands in importance and more materials' figures are calculated, validated and tabulated in publications, this paper has demonstrated discrepancies anticipated if figures are not logically selected. Future work will involve industrial, commercial, and mixed-use buildings for a clearer image of the embodied energy savings which can be made prior to a large retrofit or construction scheme.

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