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# Development of a Construction Sub-Sector Embodied Energy Hybrid Analysis

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## Abstract

**Background, Aims and Scope:**
Embodied energy analysis is used to evaluate the total energy consumed by any product during all the stages leading up to its manufacture and delivery and can also be used to determine the energy-related environmental impacts such as $CO_2$ emissions of buildings and other built infrastructure. In the wake of increase global awareness on climate change and the strong link between global warming and $CO_2$ emissions, the role of new and improved analytical models to evaluate the energy embodied in products and its associated environmental impacts therefore takes an important role in environmental research studies. The development of a new hybrid embodied energy analysis model which methodologically improves the accuracy of the energy intensity of the construction sector is presented in this paper. This hybrid methodology is applied to four built infrastructure and their respective energy intensities determined. The four construction projects are; a bridge and three different building types. The building types are- a 3-bedroom terrace house, a 3-bedroom semi-detached house and a 4 bedroom detached house all in Dublin, Ireland. The bridge is for a railway line spanning Cork-to-Midleton in County Cork, Ireland. A variability and uncertainty analysis termed applicability error is carried out to determine the inaccuracy in using the sectoral or average construction sector energy intensity rather than the sub-sectoral energy intensities.

**Material and Methods:**
In this paper, a new hybrid embodied energy analysis which combines process analysis inventory and input-output analysis is proposed – the latter being undertaken at a disaggregated construction sub-sector level rather than at an aggregated sectoral level. The construction sector is divided into five different sub-sectors with each having different input-output energy intensities and accounting for different construction activities. When embodied energy analysis is carried out at the construction sub-sector level, there is a methodological improvement in the calculated values for the direct input-output as well as the total energy intensities over other traditional hybrid methods because of the use of disaggregated sub-sector construction data. Moreover, this hybrid methodology ensures that the input-output energy intensity applied to any built infrastructure is unique and specific to it rather than applying a construction sector input-output energy intensity which is the same for all construction products as other methodologies do. The paper proposes further improvements to hybrid methodologies which improve the accuracy of embodied energy results through the introduction and use of disaggregation constants in the input-output model. Disaggregation constants disaggregate an aggregated energy supply sector in the national input-output tables into different sub-sectors consisting of energy supply sector(s) and other commodity sectors. Finally, an error or uncertainty analysis termed applicability uncertainty is carried out to establish the error that will occur if the average energy intensity of construction is used rather than the energy intensity specific to the railway bridge or the different building types.

**Results:**
The input-output total energy intensity of Irish construction evaluated at the sectoral level was found to be 0.003647 GJ/€ while that of the four case studies; the bridge, the 3-bedroom terrace house, the 3-bedroom semi-detached house and the 4-bedroom detached house calculated at the construction sub-sector level were found to be 0.002686GJ/€, 0.002398GJ/€, 0.002408GJ/€ and 0.002397GJ/€ respectively. The applicability errors of the bridge, the 3-bedroom terrace house, the 3-bedroom semi-detached house and the 4-bedroom detached house was also subsequently found to be 29%, 44.5%, 43.9% and 44.6% respectively. It was also established that input-output analysis carried without the use of disaggregated constants can be over 3.5 times greater.

**Discussion:**
Each of the five sub-sectors of construction analysed using the hybrid methodology have different input-output energy intensities. This ensures that each activity or process undertaken during the construction of any structure is correctly

allocated to a construction sub-sector and the accuracy of the calculated energy intensities enhanced. This is therefore a methodological improvement compared to other hybrid models in the determination of the input-output energy intensity of construction.

**Conclusion:**
Uncertainties and errors in aggregated input-output construction data can be significant when compared to disaggregated sub-sectoral construction data and can greatly affect the results of embodied energy results. The use of disaggregated sub-sectoral data results in a decrease of between 29-44.6% in embodied energies in the case studies analysed. The inclusion of disaggregation constants to disaggregate the energy supply sectors significantly changes the input-output energy intensities. Although different building and infrastructure types belong to the same input-output sectors, this hybrid model ensures that each has unique total energy intensity.

**Recommendation and Perspectives:**
In order to improve the accuracy of hybrid embodied energy models, two levels of disaggregation, that is, the disaggregation of energy supply sectors and the disaggregation of the construction sector must be carried out during the analysis of input-output data

**Key Words:**
Applicability Uncertainty; Bridge; Building; Construction Sub-Sector; Energy Intensity; Hybrid Embodied Energy; Input-Output Analysis; Ireland; Process Analysis

## Introduction

Scheckel (2005) defines embodied energy as the measure of all the energy inputs that goes into producing an end product. Embodied $CO_2$ however can be thought of as the $CO_2$ emissions that are released into the atmosphere through the consumption of energy during the production of a product. According to Yohanis et al (2002), the energy initially embodied in a building could be as much as 67% of the operational energy over a 25 year period. Pullen (2000) also states that the embodied energy of a building is a very significant portion of the total life cycle energy consumption. Traditionally, process analysis has been the method widely used to determine the energy embodied in products and it is usually undertaken at an industrial level through the measurements of energy and material flow during production processes. Input-output analysis developed by Leontief (1966) to model national economic production flow has been adopted in energy analysis (inter alia Bullard et al 1978, Treloar et al 2000, Ozkan et al 2004, Blok 2007). Hybrid embodied energy models which combines the more accurate process inventory data and the more complete system boundary of the I-O analysis have been used in the calculation of the energy embodied in different products (Crawford 2005 and Suh et al 2005).

The aims of this paper are to:

- introduce and develop a new hybrid model which improves the accuracy of the energy intensity of construction;
- use this model to determine the energy intensity of Irish construction and consequently how the energy and $CO_2$ embodied in the four case studies-a bridge, a 3-bedroom terrace house, a 3-bedroom semi-detached house and a 4-bedroom detached house can be evaluated; and
- estimate the error in applying the sectoral or average construction sector energy intensity rather than the sub-sectoral energy intensity to the case studies

## 1 Background

### 1.1 Input-Output (I-O) analysis

Embodied energy I-O analysis is undertaken using national economic data where by energy intensities are determined per unit monetary value of output. The main Irish data source for the I-O analysis is the National Supply and Use and Input-Output Tables derived from the national accounts and other sources. In the case of Ireland, it is published by the Central Statistics Office (2004). The national I-O tables consist of supply and use tables together with symmetric input-output tables.

The Irish I-O table consists of three aggregated energy supply sectors namely:

- Mining and Quarrying Products;
- ''Other Manufacturing Products'' and
- Electricity and Gas

The energy supply sector peat is aggregated together with other quarrying products. The second energy supply sector, oil is aggregated together with ‘other manufacturing products’ while the third energy supply sector ‘‘electricity and gas’’ consists of electricity, natural gas and renewable energy. These energy supply sectors provide all the other economic sectors with energy inputs. The direct and total I-O energy and $CO_2$ intensities of the construction sector (an economic sector in the I-O tables) can therefore be calculated from an energy based model of the national I-O tables.

### 1.1.1 Input-output (I-O) energy and $CO_2$ intensities

The I-O direct energy intensity of a product or process such as construction is the energy used directly during the main construction process itself while the I-O direct $CO_2$ intensity is the associated $CO_2$ emitted into the atmosphere as a result of the energy generated for the direct construction process. The 1998 national I-O data for Ireland was used in this study because it is the most recent data set for Ireland which contains the matrix of direct requirement coefficients.

According to Treloar (1998), the Direct Energy Intensity in GJ/€ of the construction sector can be evaluated using Equation 1 below.
Equation 1:

$$\text{Direct Energy Intensity} \quad = \sum_{\varepsilon=1}^{E} D_{RC} \times T_e \times PEF$$

$D_{RC}$ = Direct requirement coefficients [€/€]
E = the total number of energy supply sectors, e in the I-O table
$T_e$ = Average energy Tariff [GJ/€]
PEF = Primary Energy Factor [dimensionless]

The total I-O energy intensity of a product represents both the direct and indirect product energy into the product while the I-O total $CO_2$ intensity is the associated $CO_2$ emitted. The total I-O energy intensity of the construction sector is calculated using the Leontief Inverse Matrix. The Leontief inverse matrix or total requirement coefficients can be deduced by the power series approximation (Suh et al 2007, Peters 2007). Given that $A$ is the matrix of direct requirements coefficients, the Leontief inverse matrix is derived from $(I - A)^{-1} = I + A + A^2 + A^3 + A^4 + \cdots$ (Leontief, 1966). The total I-O energy intensity of construction sector can be calculated as shown in Equation 2 below (Treloar, 1998).
Equation 2:

$$\text{Total Energy Intensity} \quad = \sum_{e=1}^{E} T_{RC} \times T_e \times PEF$$

Where;
$T_{RC}$ = Total requirement coefficients [€/€]

A significant limitation with this approach however has to do with the aggregation of different products into one sector in the national I-O tables. To tackle this problem, it is being proposed that a constant factor, $C_d$, termed ‘‘disaggregation constant’’ henceforth, is introduced into the input-output analysis in order disaggregate the energy supply sectors. A detailed analysis of the disaggregation of the energy supply sectors in Ireland was first undertaken by Wissema (2006) in a study undertaken to construct a Social Accounting Matrix for Ireland. The use of the disaggregation constants enables each aggregated energy supply sector to be split into disaggregated sectors consisting of strictly an energy supply and other non-energy or commodity sectors. The use of the disaggregation constant therefore ensures that only the energy supply inputs into a particular sector are used in the analysis rather than the inputs from an energy supply sector together with other commodity sectors. A summary showing the disaggregation of the energy supply sectors is outlined in Table 2.

The I-O Direct and Total Energy Intensity [GJ/€] of construction are therefore recalculated using Equations 3 and 4 below.
Equation 3:

$$\text{Direct Energy Intensity} \quad = \sum_{e=1}^{E} D_{RC} \times C_d \times T_e \times PEF$$

Equation 4:

$$\text{Total Energy Intensity} \quad = \sum_{e=1}^{E} T_{RC} \times C_d \times T_e \times PEF$$

Where;
$C_d$ = Disaggregation Constant [dimensionless]

The total I-O embodied energy can therefore be evaluated as the product of the total energy intensity and the cost of the product (Treloar 1998). That is;

Equation 5:
I-O embodied energy = Total I-O energy intensity × Cost of product

Because the three energy supply sectors of the national I-O tables are known and the associated $CO_2$ emitted for each GJ of energy generated for each of the energy supply sectors is also known, Equations 3 and 4 can be extended to calculate the I-O direct and total $CO_2$ intensities. The units will be in tonnes of $CO_2$/€; that is $tCO_2$/€.

Equation 6:

$$\text{Direct Energy Intensity} = \sum_{e=1}^{E} D_{RC} \times C_d \times T_e \times PEF \times I_e$$

Equation 7:

$$\text{Total Energy Intensity} = \sum_{e=1}^{E} T_{RC} \times C_d \times T_e \times PEF \times I_e$$

Where;
$I_e$ = $CO_2$ intensity for each energy supply sector, e [$tCO_2$/GJ]

### 1.2 Process Analysis

Process analysis is undertaken at an industrial level by measuring the inputs and outputs of energy and materials flow during the manufacturing processes of a product. The sum of all the energy used directly and indirectly during the manufacture of the product per unit output of the product is the process energy intensity for that particular product. According to Born (1996), process analysis suffers from truncation due to the setting of system boundaries but can be combined with I-O analysis into a hybrid model which has the advantages of the more accurate process analysis data and an I-O framework more complete in system boundary (Suh et al 2002, Mongelli et al 2005).

## 2 Hybrid model

### 2.1 A new construction sub-sector hybrid model

A new hybrid model which combines input-output sub-sectoral analysis and process analysis inventory is introduced. The I-O direct energy intensity of construction is determined at a sub-sector level rather than at the aggregated sectoral level to improve accuracy. This is a methodological improvement which will ultimately improve the accuracy of the I-O total energy intensity. According to Bullard et al (1978) and Tiwari (2000) the I-O direct and total energy intensity of different but similar products such as a building or a bridge belonging to the same I-O economic sector will be the same even though the production or construction processes undertaken in each is different. This new hybrid analysis tackles this problem in traditional I-O analysis by calculating an I-O direct energy intensity which is always unique and consequently a unique total energy intensity for every construction product even if they are similar and belong to the same I-O economic sector. The analyses undertaken in the new hybrid model are described below;

Step 1:
The Irish construction sector is divided into five sub-sectors (NACE 45.1 to NACE 45.5) as defined by the NACE classification system in the European System of Accounts. A description of the sub-sector processes are outlined below;

Where NACE= Sub-Sector

| | |
|---|---|
| NACE 45.1: | Site preparation, demolition of buildings, earth moving, ground work, drilling and boring, etc |
| NACE 45.2: | Building of complete constructions or part thereof; civil and structural construction works, etc |
| NACE 45.3: | Building installation, installation of electrical wiring and fittings, insulation, plumbing and other installations, etc |
| NACE 45.4: | Building completion, joinery installation, plastering, floor and wall, covering, painting, glazing and general fit-out, etc |
| NACE 45.5: | Renting of construction equipments, etc |

Step 2:
The energy intensity in GJ/€ of each of the five sub-sectors of construction is evaluated for the years 2003, 2004 and 2005 using the census data of the building and construction industry conducted in Ireland (Central Statistics Office,

2006, 2007a). The mean energy intensities of each of the five sub-sectors is then determined as a weighted average of the total output of each sub-sector over the three years under consideration. Between 682 and 738 construction firms representative of the entire Irish construction industry were sampled each year in the census and the amount of energy in primary energy terms used (evaluated in GJ per Euro output of construction) determined. To achieve conformity with the 1998 national input-output data used, the output in Euros was discounted to 1998 price levels using yearly price indices published by the Central Statistics Office (CSO, 2007b). 2003, 2004 and 2005 price indices to that of 1998 are 1.085, 1.130 and 1.450 respectively. Refer to Table 3 for the energy intensities of the construction sub-sectors.

Step 3:
The direct and total I-O energy intensities of construction as described in Section 1.1.1 are calculated. The indirect energy intensity of construction is then calculated as a difference of the total I-O energy intensity and the I-O direct energy intensity.

Step 4:
From the bill of quantities of the built infrastructure in this case the bridge and buildings, all construction processes are grouped under one of the five construction sub-sectors outlined in Step 1. The total expenditure of construction activities/processes undertaken onsite for the bridge and buildings are grouped under each of the sub-sectors

Step 5
A single and unique value for the direct energy intensity specific to the bridge and each of the buildings are calculated as a weighted average of the total expenditure of each sub-sector which has been determined in Step 4 and the energy intensities of the five sub-sectors determined in Step 2. Because all built infrastructure employ unique construction processes and are grouped under one of the five sub-sectors, determining the direct energy intensity by weighting would produce a unique energy intensity value for each project. The energy intensity at the construction sub-sector level is methodologically more accurate than the sectoral I-O direct energy intensity obtained from the national I-O table because of aggregation. The sub-sector direct energy intensity is therefore used in place of the sectoral direct energy intensity in the calculation of the unique total energy intensity for each project.

Step 6:
The new and methodologically improved total energy intensity is then calculated by adding the construction sub-sector direct energy intensity specific to the bridge and each of the buildings calculated in Step 5 and the I-O indirect energy intensity evaluated in Step 3.

Step 7
Process analysis inventory is collected for the main building materials used for the project and the process analysis component of the embodied energy evaluated

Step 8:
The input-output component of the embodied energy which will consists of the cost of the miscellaneous construction activities outlined in the bill of quantities for the bridge and each of the buildings is then calculated using Equation 5. The I-O embodied energy and the process analysis embodied energy are added to determine the total embodied energy.

### 2.3 Applicability variability/uncertainty analysis

Applicability uncertainty or variability provides a measure of the level of error that would exist if the I-O total energy intensity of construction is applied to the bridge and the different building types instead of the total energy intensity specific to each of projects and evaluated at the construction sub-sector level. Refer also to Figure 1 for a flow chart description of the methodology. The energy intensity of the construction sector evaluated at the sub-sector level may not be representative of a particular project depending on the construction work being undertaken. For example, the I-O total energy intensity of construction which is an average value for the whole construction sector might be lower than a very high energy intensity construction process such as welding or higher than another low energy intensity construction process such as compaction. The applicability uncertainty is calculated using Equation 8 below.

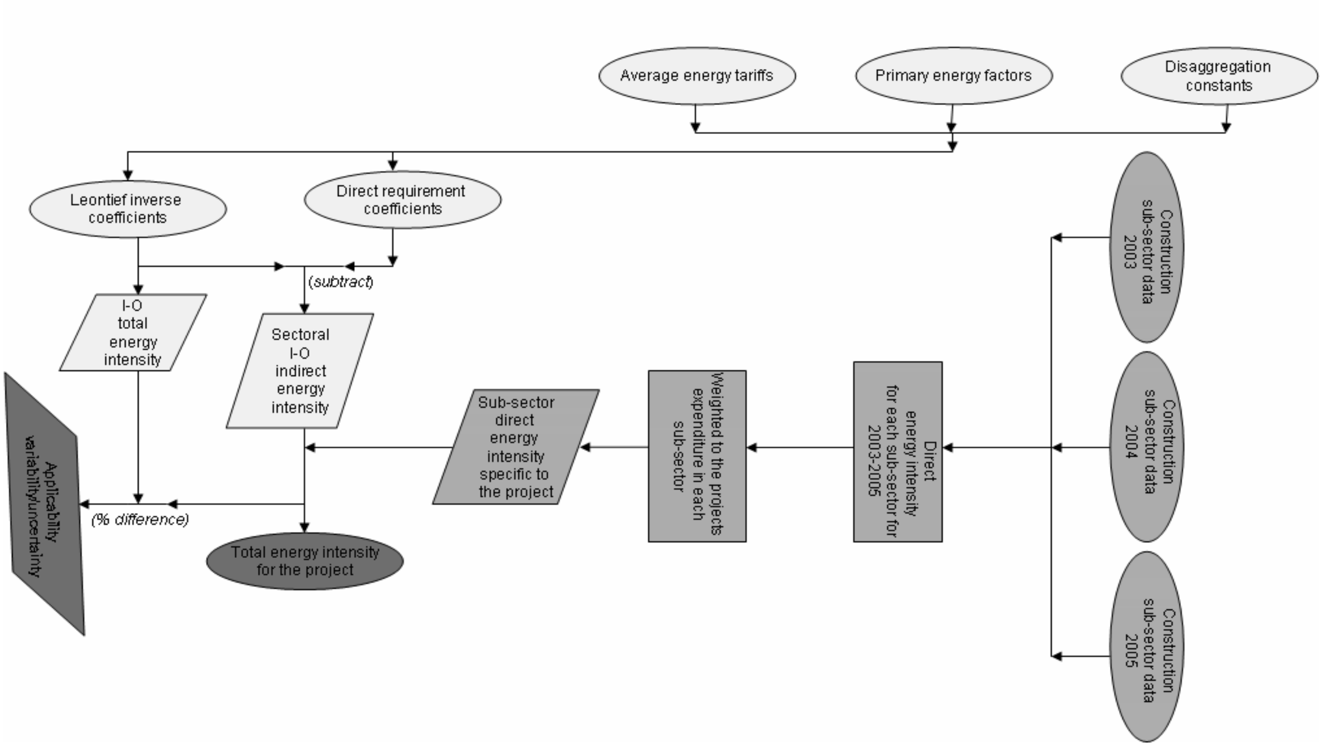
$$\text{Applicability Variability/Uncertainty} = \left(\frac{\mathrm{TEI}_{\text{sub-sector\_project}} - \mathrm{TEI}_{\text{I-O}}}{\mathrm{TEI}_{\text{sub-sector\_project}}}\right) \times 100\%$$

Where

$\mathrm{TEI}_{\text{sub-sector\_project}}$ = The Total Energy Intensity specific to particular project or case study and evaluated at the construction sub-sector level

$TEI_{I-O}$ = The I-O Total Energy Intensity of construction

Figure 1: Determination of the new I-O total energy intensity of the bridge and applicability variability/uncertainty



## 3.0 Description of case studies

The bridge spans the Cork-to-Midleton railway line in County Cork, Ireland and it is a 28.1m long. It has a minimum of 14.8m wide and 5.1m high clearance for passing trains. It has roadside safety barriers connected to 1.5m high pre-cast concrete parapets. The three building types-the 3-bedroom terrace house, the 3-bedroom semi-detached house and the 4-bedroom detached house all constructed in Ireland using precast concrete and in-situ concrete works with steel formwork. The construction cost of the bridge is €564,648.56 whiles that of the buildings are €77,702.07, €82,680.76 and €109,241.33 respectively.

## 3.1 Data sources

The primary energy factors for Ireland were calculated using the weighted total energy consumption of each energy supply sector and the energy losses as a result of conversion and transmission. The data used in the calculation was sourced from Irish energy statistics (Sustainable Energy Ireland, 2006a). The use of the primary energy factor ensures that the actual energy embodied in the natural energy resource is used in the analysis. Refer to column 2, Table 1 below.

The average energy tariffs for the energy supply sectors was calculated in GJ/€ using published energy prices data from Sustainable Energy Ireland (Sustainable Energy Ireland, 2006b). These are presented in column 3, Table 1 below.

The 1998 $CO_2$ emission factors for the energy supply sectors (Sustainable Energy Ireland, 2008) was adopted in the calculations to conform to the 1998 baseline year and the use of the 1998 input-output data. This is because $CO_2$ emission factor for electricity for example changes each year depending on the fuel mix used in power generation. It assumed that the emission factor for renewable energy is zero. Refer to column 4, Table 1 below.

**Table 1:** Primary Energy Factors, Average energy Tariffs and Emission Factors for Ireland

| Energy Supply Sector | Primary Energy Factor | Average Energy Tariff [GJ/€] | $CO_2$ Intensity [$tCO_2/GJ$] |
|---|---|---|---|
| Peat | 1.01 | 0.28570 | 0.1167 |
| Oil | 1.01 | 0.07094 | 0.0733 |
| Electricity | 2.90 | 0.02577 | 0.2286 |
| Natural Gas | 1.03 | 0.06673 | 0.0568 |
| Renewable Energy | 1.00 | 0.02577 | 0 |

The aggregated energy supply sectors for Ireland was disaggregated into ''energy only sectors'' using disaggregated constants as shown in Table 2 below.

**Table 2:** Disaggregation constants for Ireland

| Aggregated Energy Supply Sectors | Disaggregated Energy Supply Sectors | Disaggregated Constants $C_d$ |
|---|---|---|
| Mining and Quarrying | Peat | 0.290 |
| 'Other Manufacturing' | Oil | 0.700 |
| Electricity and Gas | Electricity<br>Natural Gas<br>Renewable Energy | 0.755<br>0.205<br>0.040 |

## 4 Calculations, Results and Discussions

As described in Section 1.1.1, the I-O direct energy intensity and the I-O direct $CO_2$ intensity of the Irish construction sector are 0.001812 GJ/€ and 0.0002103 $tCO_2$/€ respectively. While the I-O total energy intensity and the I-O total $CO_2$ intensity of the Irish construction sector are calculated to be respectively 0.003467 GJ/€ and 0.0004343 $tCO_2$/€.

**Table 3:** Summary of construction sub-sectors energy intensities for 2003, 2004 and 2005

| Construction Sub Sectors/ Year | **NACE 45.1** Ground Work & Demolition, etc | **NACE 45.2** Civil Works, etc | **NACE 45.3** Wiring & Plumbing, etc | **NACE 45.4** Joinery & Fit Out, etc | **NACE 45.5** Construction Machinery, etc |
|---|---|---|---|---|---|
| **2003** | 0.002068 | 0.000644 | 0.000269 | 0.000629 | 0.003742 |
| **2004** | 0.001989 | 0.000971 | 0.000370 | 0.000648 | 0.003843 |
| **2005** | 0.002312 | 0.001057 | 0.000500 | 0.000634 | 0.005976 |
| **Weighted Average[GJ/€]** | 0.002148 | 0.000889 | 0.000376 | 0.000637 | 0.004487 |

The direct energy intensity at the construction sub-sector level which is specifically unique to the bridge, the 3-bedroom terrace house, the 3-bedroom semi-detached house and the 4-bedroom detached house and calculated as a weighted mean of their respective expenditure distributed under each of the five sub-sectors are 0.001031GJ/€, 0.000743GJ/€ , 0.000753GJ/€ and 0.000742GJ/€ respectively. The average of the whole construction sub-sector was however found to be 0.000873 GJ/€. The I-O indirect energy intensity which equals 0.001655GJ/€ is evaluated as a difference between the I-O total energy intensity and the I-O direct energy intensity of the construction sector. By adding the I-O indirect energy intensity and the direct energy intensity specific to the different case studies as described in Step 7 of Section 3.1, the total energy intensity unique to the case studies- the bridge, the 3-bedroom terrace house, the 3-bedroom semi-detached house and the 4-bedroom detached house were found to be 0.002686GJ/€, 0.002398GJ/€, 0.002408GJ/€ and 0.002397GJ/€ respectively. An average total energy intensity calculated for the whole construction sector at the construction sub-sector level was found to be 0.002528 GJ/€. The applicability uncertainty or variability of the bridge, the 3-bedroom terrace house, the 3-bedroom semi-detached house and the 4-bedroom detached house was also subsequently found to be 29%, 44.5%, 43.9% and 44.6% respectively.

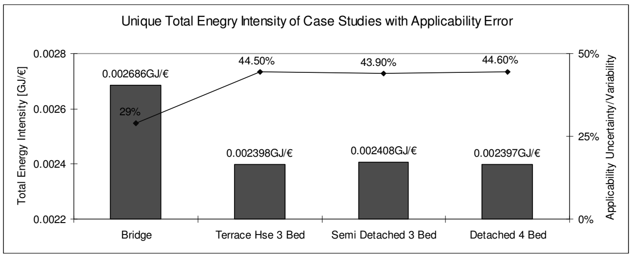


**Figure 2:** Total energy intensity of case studies and applicability uncertainty/variability

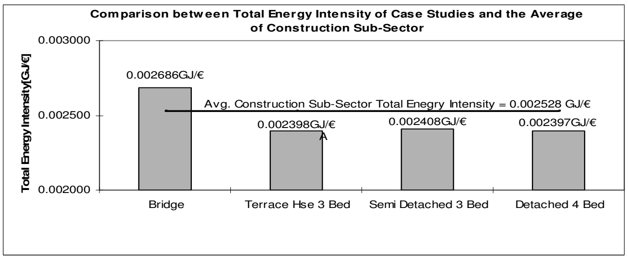


**Figure 3**: Total energy intensity of case studies relative to the average of the construction sub-sector

As can be seen from the Figure 3 above, the total energy intensity can be smaller than the average of the construction sector (as in the case of the three buildings) or greater than that of the construction sector as in the case of the bridge. The reason behind this is that every construction project has its unique construction activities as such while some of these activities might be high in energy intensity, others might be low in energy intensity. Most of the activities involved in the construction of the houses belong to sub-sectors Nace 45.2 and Nace 45.4 which have lower energy intensities. This therefore reduces the overall total energy intensity of the buildings. The bridge on the other hand has higher total energy intensity because there is a significant increase in the amount of groundwork (Nace 45.1 is a much higher energy intensity sub-sector) carried out during the construction of the bridge.

The values of the direct and total energy intensities of construction calculated without the use of the disaggregation constants were 0.0071 GJ/€ and 0.0122 GJ/€ respectively. These are 3.9 and 3.5 times more than the values obtained when the disaggregation factors are introduced.

## 5 Conclusions and Recommendations

The hybrid approach to embodied energy analysis has the advantage of undertaking the analysis at a disaggregated construction sub-sector level and by determining unique energy intensity for the bridge and the different building types rather than using an average value which will also apply to many other building types and other construction projects such as towers and roads which has specifically different energy intensities.

A major grey area of embodied energy and life cycle energy analysis research has to do with the evaluation of uncertainty and validation of different assessment techniques (Ciroth et al 2004, Ciroth et al 2006). Such uncertainties can either exist in the available data or inherent in the model being used. The fusion of disaggregated sub-sectoral data with the I-O data however reduces the level of uncertainty in the input-output model. The uncertainty/variability that exists in applying the average total energy intensity of the construction sector to the bridge was determined to be 29% while that of the three building types ranged closely from 43.9-44.6%. By adopting this hybrid methodology in the calculation of the energy intensities, a measure of the uncertainty/variability that will occur when the I-O total energy intensity of the whole construction sector is used can be evaluated.

It was found out that the values of the direct and total I-O energy intensities of construction calculated without the use of the disaggregation constants were 0.0071 GJ/€ and 0.0122 GJ/€ respectively. These are 3.9 and 3.5 times more than the values obtained when the disaggregation factors are introduced. It is therefore important that in order to reduce errors significantly in input-output energy intensities, input-output energy supply sectors must be disaggregated as demonstrated in this case by the use of disaggregation constants.

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