Incorporating embodied energy in the BIM process

Graham Capper
Jane Matthews
Professor Steve Lockley
School of the Built and Natural Environment,
Northumbria University,
Newcastle-upon-Tyne, NE1 8ST
graham.capper@northumbria.ac.uk

Abstract
This paper examines the incorporation of carbon data into the Building Information Model (BIM) process and considers option appraisals that will enable design team members to evaluate both operational and embodied CO_2 emissions over the life cycle of a project. The paper is based upon work, funded by the Technology Strategy Board, to develop a toolkit that utilises interoperable standards around a BIM. This allows for architects, energy advisors and others to develop and share design information on CO_2 emissions whilst each design team member is free to use their own preferred software solution. At the core of the process is a three-dimensional BIM with links to elemental, system and material databases. The work on the model is described along with its application to a case study on a recently completed new school, built to sustainable standards in the North East of England.

Keywords BIM, Carbon, Embodied Energy, Interoperability, Sustainability

1.0 Introduction
This paper describes some of the works undertaken as part of the Interoperable Carbon Information Model (iCIM) project funded by the Technology Strategy Board (TSB) under its 'Design and Decision Tools for Low Impact Buildings' programme. The broad aim of that funding programme was to develop 'integrated tools that facilitate the progress of a design from briefing through concept, feasibility and detailed design, to construction, post-occupancy evaluation and building management'. This paper focuses on some of the issues involved in the classification and incorporation of embodied energy data into an interoperable BIM model.

The full details of the consortia members are listed in the acknowledgments below. From an energy and carbon perspective, these include the University of Bath (the originator of the Inventory of Carbon and Energy (ICE) database [1] and BSRIA who have recently published the latest version of the ICE data [2].

2.0 BIM and Interoperability
The Department for Business Innovation and Skills describe BIM as "a managed approach to the collection and exploitation of information across a project." [3], and recently the term has become somewhat of a buzzword. It is widely viewed as having the potential to offer significant improvements to the construction industry, particularly in the areas of collaboration and design integration. The UK Governments

construction strategy [4] requires fully collaborative BIM (with all project and asset information, documentation and data being electronic) as a minimum on government projects by 2016. The strategy aims to empower the supply chain to drive the construction industry to higher levels of maturity in its use of BIM technology.

Currently the industry is generally recognised to be operating in its discipline silos with working practices optimised for isolated drawing-centric working rather than integrated, collaborative working. Collaborative working necessitates better integration across the different construction project disciplines, the different libraries and tools they use, and outputs they produce. This project has utilised the eXtensible Building Information Modelling (Xbim) platform. This is a software development toolkit that enables researchers and innovators to develop new BIM applications and to support new BIM processes without aligning with proprietary software products.

It was envisaged that the ability to feed appropriate carbon 'costing' information into the BIM during the initial stages of a project would enable better informed early design. The carbon data libraries developed for this project have been built on the Industry Foundation Classes (IFC) open standard to enable interoperability between processes in the supply chain as well as between proprietary BIM technology solutions. Energy appraisal packages and dynamic simulation models that can utilise IFC standards have been developed in Europe and particularly in Scandinavia but little work has been done so far in the UK.

3.0 Carbon 'costing'

The embodied energy in any product is the total primary energy consumed during the life of that product. In the case of a building the total embodied energy is the sum of all the individual products considered over the expected life of the building.

To calculate the carbon footprint of a complex system such as a school, it is necessary to identify system boundaries over the lifetime and total the impacts at each of the following stages:

i. Raw materials – sourcing, extraction, manufacturing, packaging, storage;
ii. Transportation from manufacturers' gate to construction site boundary;
iii. Construction site activities including contractor travel, disposal of construction waste;
iv. Operation – electricity and fuel for building services, occupant waste and travel;
v. Maintenance including materials to maintain a building through replacement of components;
vi. Disposal – deconstruction/demolition, transportation of waste materials.

Changes to the building regulations have progressively required buildings with lower operational energy and therefore the balance between operational energy use (stage iv. above) and the embodied energy content implicit in all of the other stages has changed.

Conveniently embodied energy can be measured in the same units as operational energy and the sum of the two gives a holistic view of the energy implications of design, construction and operation. Commentators such as

Sturgis and Roberts [5] have pointed towards a scenario where a new form of Energy Performance Certificate (EPC) could give details of both.

The Olympic Delivery Authority have calculated the embodied energy content of some of the major venues for the London 2012 Olympics and have published details of some of the lessons learned [6]. However, the benchmarking of embodied energy values for typical buildings across the UK is still in its infancy. The UK government has expectations in this area however and the Strategy for Sustainable Construction looks to establish “stretching but achievable targets for embodied carbon for different building types, considering each part of the project life cycle, in order to encourage innovation by design teams and input from the supply chain” [7].

Whilst this paper focuses on embodied energy calculations relating to raw materials, the iCIM project is designed as an extensible toolkit to facilitate consideration of all aspects of life cycle assessment.

4.0 Level of detail

Operational energy calculations are currently well supported by BIM technologies and data libraries throughout the design process, from briefing through preparation, design, and pre-construction. However, this is not the case with embodied energy data, with little data available at the appropriate level in particular to support early design stage decisions. As a design progresses so does the required level of detail. Table 1 shows the relationship between the construction design process and the appropriate level at which energy (and/or carbon) data should be stored in order to enabled informed decision making.

<table>
<tr><td></td><td colspan="5">Progression through design process</td></tr>
<tr><td rowspan="9">Increasing Level of Detail</td><td></td><td>Conceptual Design</td><td>Schematic Design</td><td>Detailed Design</td><td>Construction</td></tr>
<tr><td>Building</td><td rowspan="2">✓</td><td></td><td></td><td></td></tr>
<tr><td>e.g. school</td><td></td><td></td><td></td></tr>
<tr><td>System</td><td></td><td rowspan="2">✓</td><td></td><td></td></tr>
<tr><td>e.g. external walling</td><td></td><td></td><td></td></tr>
<tr><td>Element</td><td></td><td></td><td rowspan="2">✓</td><td></td></tr>
<tr><td>e.g. cavity wall</td><td></td><td></td><td></td></tr>
<tr><td>Material</td><td></td><td></td><td></td><td rowspan="2">✓</td></tr>
<tr><td>e.g. brick</td><td></td><td></td><td></td></tr>
</table>

Table 1 – Level of Detail by Stage of Design

At the early stages of a project broad ‘optioneering’ should be possible, supported by benchmarking data and/or validated rules-of-thumb. The decisions may be made at the level of an assembly or system as indicated in Table 1. An example at this stage, involving a decision with a significant carbon impact, would be the choice of a steel frame rather than a concrete frame.

As the design is progressed towards a firm outline proposal it is necessary to ensure that the proposed project is both technically and financially feasible. It is at this stage that the client may be provided with an appraisal together with recommendations in order that they may determine the form in which the project can proceed. The strategic brief is developed towards the full project brief and outline proposals and cost estimates are prepared. The cost estimates can be in both capital and energy terms. The former is likely to be presented at a system level – a cost consultant will typically utilise the Standard Form of Cost Analysis, which sets out how to analyse the cost of a project in an elemental manner.

At the scheme design stage compliance issues, such as operational carbon, are addressed. An embodied energy assessment could also be carried out at this stage.

The detailed design and production stages require specification information, and the quantification of materials and components. The iCIM project is currently working with materials and specifications and is generating embodied carbon information at this detailed level. The BIM process enables the aggregation (semi-automatically) of these values to elements. This gives, for example, a generic wall window (system/assembly or product) that can then be used at an earlier design stage. The process can be repeated for systems, buildings and portfolios.

5.0 Embodied energy

For a global perspective, the ecoinvent Centre [8] is probably the leading exponent of life cycle inventory data. In the UK there a number of potential sources for embodied energy data, but the main, authoritative, and open-source of data is the ICE database at the University of Bath [1], [2]. This contains over 400 values of embodied energy/embodied carbon with 30 main material classifications broken down into approximately 170 different building materials. The data are values calculated on a 'Cradle to Gate' basis (they therefore omit any allowances for transport, waste etc.) and there are both energy and carbon coefficients. The use of energy data enables changes to be made to the coefficients as de-carbonisation of the electricity supply grid changes. However, it would appear that CO_2 has become the common currency. The ICE database prior to 2010 was CO_2 only, but now, in Version 2, incorporates the effect of other greenhouse gases and is 'CO_2 equivalent' (CO_2e). Similar coefficients are contained in the Green Guide published by the Building Research Establishment (BRE) [9]. The embodied energy values there are presented as one part of the assessment of elements that are given overall environmental ratings such as A+, A, B etc. The BRE data is stated as 'Cradle to Grave' over the life of the element. It is understood that the source data was provided in confidence and it therefore lacks the transparency of the ICE database. Franklin and Andrews' 'Blackbook' [10] also contains embodied energy data, derived from the ICE database and is presented in an elemental format suitable for costing purposes.

Analysis of the values for various building elements and using each of the three UK sources of data, with adjustments made for life cycles etc. demonstrates considerable variation and reinforces the need for an agreed metric. The issues that would need agreement in any metric include the explicit boundary definitions, the basis for and rules of measurement of elements, the assumptions and allowances for transport, waste etc., life-spans, replacement intervals, recycling rates and changes in recycling rates over the lifespan of an element. Much of this may be achieved if PAS 2050 [11] were widely adopted (this is a publicly available standard for assessing the life cycle greenhouse gas emissions of goods and services and is supported by an implementation guide and a code of good practice). Moves towards the adoption of CEN/TC 350 – Sustainability of Construction Works [12] and EN 15804 on the rules for Environmental Product Declarations (EPDs) will also drive the issues.

5.1 Carbon Data development
The 'heart' of the data for this project is deliberately the ICE database [1], in part because it is open-source and therefore transparent. The database has been 'developed' into a product/system/elements dataset and a user interface has been added so that enhanced building elements or composite components can be imported into a BIM model to provide carbon 'costs' alongside capital costs.

One driver for the necessary development is the fact that the ICE database is a material science database, not a building materials database. There are very few examples of 'pure' materials in common use in construction, for example, bricks are part of brickwork, which may form part of an external wall; cement is a constituent of concrete which may be part of ground floor construction along with other layers from the aggregate sub-base through to the carpet finish. The framework for data aggregation detailed in Table 1 above has been used to derive useable embodied carbon data for each project stage. This includes the development of aggregation methodologies for moving 'pure' materials through to and elements and systems.

The work required, for each layer in a composite system, includes individual material identification and associated data such as density (this is because the energy and carbon coefficients are per kg of material and therefore volumes and densities are required in order to derive mass). It was also necessary to derive data for non-continuous layers in elements – such as framing, joists, battens and the like – based on the spacing/centres and dimensions. Although what might at first glance appear a perhaps rather trivial matter materials need careful consideration in terms of identification. Both in design and construction there has been an adoption and use of terms in a generic rather than in a detailed, definitive manner. 'Damp proof course', 'vapour control layer', 'single ply roofing', 'building-paper' are all examples of terms in common parlance. In establishing a useable database it must be confirmed that these equate with high-density polyethylene; a multi-layered low-density polyethylene membrane with an aluminium core; pvc-p and spun high-density polyethylene.

In the development of any database there are a number of issues that need to be addressed in respect of the availability/completeness of the source data. The issues are not unique here and some have still to be resolved. They will need resolution, as part of any agreed protocol if embodied energy data is to be acceptable and useful. The development of any similar database, such as the New Zealand embodied energy database [13], faces similar issues and has to address:

- Completeness of data;
- Completeness of records from which data is drawn;
- Reliability of records from which data is drawn;
- Age of data;
- Relevance of time period of the data.

The completeness of data is determined to a large extent by the extent of the original ICE database. The Carbon Trust and the Engineering and Physical Sciences Research Council largely funded ICE but it is no longer financially supported and has not been expanded. It has only been recently updated from CO_2 to CO_2 equivalent. The ICE database is open source and gives statistics on all data sources used to compile the information. Without further development, the age and therefore the relevance of data in the original database may become questionable and require 'flagging' in some way for potential users. The development of new materials and composites may also limit the value of the original database.

6.0 Case study – Primary School

To illustrative the type of work that has been undertaken it is useful to consider two different materials in a typical school building and to describe the development of the embodied energy values associated with each. It is then possible to appraise the materials within the framework of a life cycle assessment of the elements and systems that make up the school. The following develops the examples referred to above - the brick in an external wall and carpeting as one of the floor finishes in the school.

6.1 Material - Brick

The brick industry is an energy intensive industry and consequently individual bricks have high levels of embodied energy and CO_2 (the industry as a whole has had to respond to rising fuel prices and some manufacturers have ceased production and many have invested in technologies to reduce energy costs [14]. Both of these affect embodied energy values in that, as indicated above, the source data sets are limited in number and historical data is no longer as valid).

The ICE database for "General (Common Brick)" gives an embodied energy value of 3.0 MJ/kg and an embodied carbon value of 0.24 $kgCO_2e/kg$. The latter is equivalent to a value of 0.55 $kgCO_2e$ for an individual brick.

6.2 Element – Cavity Wall

A cavity wall, comprising a brickwork outer leaf and a block work inner leaf, insulated to current building regulation standards has an embodied carbon value of between 70 and 80 $kgCO_2e/m^2$. The bricks themselves contribute approximately 50% of that total. These values are derived from the identification and consideration of all the individual materials in a wall, their sizes, volumes and densities linked to their ICE embodied energy and carbon coefficients. The resulting carbon value is from cradle, through manufacturing, to site and includes allowances for transport and waste.

Over the sixty-year life of the school the walls may require some minor maintenance but they are unlikely to be replaced and therefore the 'Cradle-to-Site' value also approximates to 'Cradle-to-Grave' (no allowance has been made for reuse or recycling of the wall after demolition).

Table 2 demonstrates some of the detail of necessary calculation (the format is deliberate and replicates that presented in the "Worked examples and case studies" section of the BSRIA publication of the ICE database). It illustrates the scale of the problem if such a manual extrapolation was required for each and every variant of material through to elements, systems and whole buildings.

Material	Quantity	Unit	$kgCO_2e$/unit	Waste	Total $kgCO_2e$
Bricks	60.00	No.	0.55	+5%	34.65
Mortar	23.20	kg	0.174	+10%	4.40
Insulation	1.60	kg	3.40	+5%	5.71
Blocks	9.86	No.	1.23	+5%	12.73
Mortar	13.70	kg	0.174	+10%	2.62
DPC	0.18	kg	1.60		0.37
Wall Ties	0.10	kg	6.15		0.60
Plasterboard	15.00	kg	0.38	+5%	5.99
Paint	1.00	m^2	1.60	+5%	1.60
Transport	42.80	tkm	0.10		4.28
				Total	**72.95**

Table 2 – The embodied carbon content of a cavity wall

In order to 'optioneer' on the embodied carbon values at this elemental level a designer would have to appreciate how 'good' or 'bad' the value of 73 $kgCO_2e/m^2$ is; what alternatives might be available for the external walls and indeed whether any variation in the embodied energy content of the wall contributes significantly to the overall embodied energy footprint of the building.

6.3 Material - Carpets
The ICE database gives an embodied energy value of 74 MJ/kg and an embodied carbon value of 3.9 $kgCO_2/kg$ for "General Carpet". The latter equates to 9.8 $kgCO_2/m^2$.

For new-build projects, at present, the selection of a particular carpet is unlikely to involve a consideration of embodied energy. An examination of typical specifications for floor finishes show that manufacturers are responding to client/design team demands with an emphasis on recycled content and recyclability (in terms of the quantity of used carpet treated as waste). The use of environmental assessment tools, such as BREEAM and LEED, may also have focussed attention on the presence or otherwise of Volatile Organic Compounds (VOCs) in both the carpets and associated items such as adhesives and/or floor levelling screeds.

In the selection of floor finishes for a new school it might be convenient to consider a carpet with a fifteen year anticipated life and therefore three replacements over the sixty-year period (i.e. at 15, 30 and 45 years). The choice of carpet might be contrasted with an option for linoleum with different capital and maintenance costs, different anticipated lifespan and consequently different replacement requirements.

This approach, with a detailed consideration of embodied carbon, has been demonstrated in the report prepared for the Royal Institution of Chartered Surveyors by Sturgis [5] and referred to in the BSRIA publication [2]. The work reported there is, however, a refurbishment project and therefore one where it is perhaps fairly easy to focus on a single issue such as embodied carbon. Overall there does not appear to be a demand for, and consequently a supply of, embodied energy information for carpets by manufacturers.

6.4 Systems
The external wall example above illustrates the development of values from materials through to elements. Table 3 below gives values for systems derived

from elements and shows the total embodied carbon values for the fabric of a recently constructed school in the Newcastle area. It is a two-storey, steel framed, primary school with an overall area of approximately 2500m^2.

	System	**kgCO$_2$e**	**%age**
Substructure	Foundations	159000	11
	Ground Floor	155000	10
Superstructure	Frame	493000	33
	Upper Floors	120000	8
	Roof	173000	12
	External Walls	170000	11
	Windows and External Doors	91000	6
	Internal Walls and Partitions	120000	8
	Internal Doors	1300	0
Internal Finishes	Wall Finishes	inc	-
	Floor Finishes	17000	1
	Ceiling Finishes	5000	0
		1505000	100

Table 3 – Embodied carbon content of systems

There are a number of points to note with the above table, but the first is that the table relates only to the major building fabric elements and it does not include any services systems or external works.

It is clear that the steel frame accounts for the majority of the embodied carbon in the school. This value will also be closely correlated with the volume of concrete supporting that steelwork and therefore the carbon in the foundations. Together they account for over 40% of the total carbon. In terms of the materials and elements that are discussed above the external walls account for 11% of the total footprint and the floor finishes account for only 1% of the total. The 1505 tonnes of carbon equates to a figure of approximately 600 kgCO$_2$e/m^2.

It is at the building and systems levels that it becomes apparent that embodied energy is an important consideration. The benchmarks figures can be compared with operational energy use values and for this type of school it would be expected that energy consumption would be of the order of 40 kgCO$_2$e/m^2 i.e. the embodied carbon equates to 15 years ‘worth’ of operational energy.

With data on embodied energy at a system level ‘optioneering’ can be better informed but the relationships between the systems is also important. A ‘straightforward’ decision on frame material is likely to interrelate capital cost, construction implications such as time on site, fire engineering implications, span requirements, column spacings and consequential foundation details.

The school in this example was built to the 2006 Part L Building Regulations Standards and was not intended as an exemplar school in terms of sustainability. It is interesting therefore to compare the embodied carbon values with some of the few comparables that are available. The Target Zero school guidance [15] presents three schools – a base case, a concrete framed school and a steel framed school. The total embodied carbon in each is indicated in Table 4 below:

Option	Total Embodied Carbon (tCO_2e)	Embodied Carbon per m^2 ($kgCO_2e$)
Base case	2981	309
Concrete Frame	3315	344
Steel Frame	2897	301

Table 4 Embodied Carbon in a Target Zero School

Relative to the base case, the in-situ reinforced concrete structure building has a higher (11%) embodied carbon impact whereas a steel composite structure has a marginally lower (3%) impact. The operational carbon values for the three options have little variation, with a Buildings Emission Rate of approximately 27 $kgCO_2/m^2yr$. The operational: embodied energy ratio is approximately 1:13 in the case of the concrete frame.

Apart from highlighting the magnitude of the embodied carbon content in the Newcastle school and the Target Zero examples, the comparison are not straightforward and the boundaries and assumptions made in each assessment differ. The Target Zero report advises that sensitivity analyses are carried out on key assumptions and methodological decisions used in the embodied carbon assessments. One example is perhaps illustrative. The Target Zero makes an end-of-life assumption for steel sections of 99% 'closed loop' recycling (1% going to landfill). Annex B of the BSRIA publication [2] discusses the recyclability of steel in detail and the values for the Newcastle school are based on the 'compromise' 50:50 recycled content approach and substitution method. The adoption of different techniques and assumptions for significant elements gives different results and could consequently lead to different decisions being made. An agreed metric would resolve some of these issues.

7.0 Conclusions

Detailed embodied energy figures are being prepared for specifications and these can be automatically aggregated upwards to elements and systems. Benchmark figures for embodied energy will be available at element, system and building levels. The embodied energy content of buildings is significant and this will be even more marked as operational energy use reduces. Although the work reported here has deliberately targeted embodied energy, the research team fully appreciate the potential difficulties with the use of embodied energy and embodied carbon figures in design decisions. The use of the IFC format means that other material; element or system attributes can be incorporated in a similar manner.

Whether embodied energy values should be combined with operational energy values is a wider issue. On the operational 'side', the EPC is the result of the UK's implementation of the EU's Building Performance Directive and as such has a long, validated history with clearly defined procedural mechanisms and, almost, an industry that supports the production of SAP and SBEM calculations. The implications of combining the two sets of data would, to some, be daunting, and at present the contrast between the two is marked. The embodied energy 'side' will develop quickly and an agreed metric and the wider take-up of Environmental Product Declarations will make a difference.

The different time horizons also present a challenge – the EPC is typically produced at design stage for certification purposes and, thereafter, annual Display Energy Certificates are produced for some buildings. In contrast embodied energy values require a whole-life approach. It may be the case that the use of BIM can facilitate the production of more holistic models at all stages of a project and perhaps better identify the issues that lead to DECs that do not accord with EPCs. However, a root-and-branch re-assessment of the value of EPCs is probably necessary to address such an issue.

One issue that has been highlighted in this work, and is pervasive in BIM implementations, is the potential for changing the traditional roles of individual design team members and the way in which design teams collaborate. There are questions as to educational requirements if some design team members carry out tasks that have traditionally been the preserve of others. There is also the potential for new specialists, in the mould for example of SAP and SBEM assessors. There are clearly implications on liability amongst the design team members.

It is interesting to speculate for example on the identity of the design team member who might provide energy data at feasibility stage after having developed a conceptual BIM model. Similarly, who might be the ‘expert’ who provides embodied energy information at concept stage? Is the production of embodied carbon information a form of energy simulation or is it simply an adjunct to specification information?

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References

[1] Hammond, G. and Jones, C., *Inventory of Carbon and Energy.* Bath: University of Bath, 2010.

[2] Building Services Research and Information Association (BSRIA). *Embodied Carbon - The Inventory of Carbon and Energy.* BSRIA, 2011.

[3] Great Britain. Department for Business Innovation and Skills. *BIM Management for Value, cost & carbon improvement*, Department for Business Innovation and Skills, London, 2011.

[4] Great Britain. Cabinet Office. *Government Construction Strategy.* Cabinet Office, London, 2011.

[5] Sturgis, S. and Roberts, G., *Redefining zero: Carbon profiling as a solution to whole life carbon emission measurement in buildings.* London: RICS, London, 2010.

[6] Henson, K., *Learning Legacy – Lessons learned from the London 2012 Games construction project – The procurement and use of sustainable concrete on the Olympic Park*. Olympic Delivery Authority, London, 2011.

[7] Department for Business Innovation and Skills. *Innovation and Growth Team Strategy for Sustainable construction.* Department for Business Innovation and Skills, London, 2010.

[8] ecoinvent. *Swiss Centre for Life Cycle Inventories.* http://www.ecoinvent.com/, 2011.

[9] Anderson, J., Shiers, D. and Steele, K., *The Green Guide to Specification, 4th Edition.* iHS, BRE Press, Wiley-Blackwell., 2009.

[10] Hutchins. *The UK Building Blackbook - The Cost and Carbon Guide.* Franklin & Andrews, 2011.

[11] British Standards Institute. *PAS 2050:2008 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services.* British Standards Institute, 2008.

[12] European Directive CEN TC 350. *Sustainability of Construction Works.* http://www.cen.eu/cen/Sectors/Sectors/Construction/SustainableConstruction/Pages/CEN_TC350.aspx, 2005.

[13] Alcorn, J A. and Wood, P., *New Zealand Building Materials Embodied Energy Coefficients Database - Volume II - Coefficients.* Wellington: Centre for Building Performance Research, 1998.

[14] Brick Development Association. *Sustainability Strategy for the Brick Industry.* http://brick.org.uk/wp-content/uploads/2011/05/Sustainability-Strategy-Update-2010.pdf

[15] Target Zero. *Target Zero: Guidance on the design and construction of sustainable, low carbon school buildings.* Leeds: Target Zero, Leeds, 2010.