# Technical Report: Energy Cost Metric. Energy Design Guide for the Civil Engineering Building in West Cambridge

## Part 1: Early stage design decisions

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UNIVERSITY OF CAMBRIDGE
DEPARTMENT OF ENGINEERING

# Energy Cost Metric: Energy Design Guide for the Civil Engineering Building in West Cambridge

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April 2020

*Technical Report*
*for the Submission to the*
*Department of Engineering Library*

# *From idea to reality*

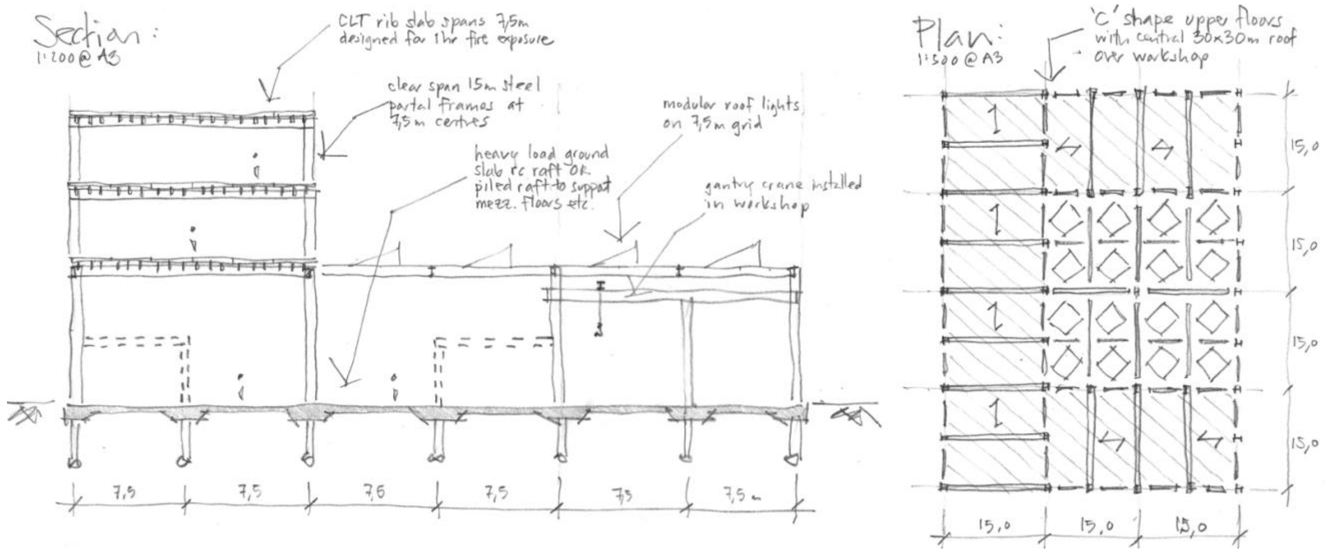


***Figure 1: Concept design (source: Smith and Wallwork, SK005)***

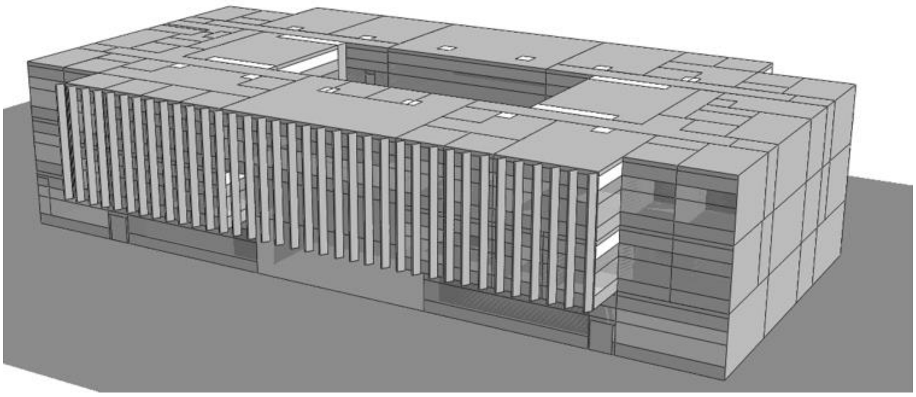

***Figure 2: Model of UKCRIC Building with fins (Appendix A5)***

***Figure 3: Artist's view of the new Civil Engineering Building (Image courtesy of Grimshaw Architects) [1]***

## ABSTRACT

The construction and operation of buildings is responsible for 36% of global energy use and 39% of energy-related carbon dioxide emissions. More than 80% of energy used in buildings result from building operation, including heating, cooling, providing the light [2]. If international carbon emission targets set by the 21st Conference of the Parties [3], the European Commission "A Clean Planet for all" [4] and the UK's "Climate Change Act 2008 (2050 Target Amendment)" [5] are to be met, then the demand for energy in buildings must be reduced, cost effectively, due to their large contribution to global emissions [6][7][8].

The environmental impact of the buildings depends on the materials and energy required to: construct the building (i.e. embodied carbon/energy to practical completion [9][10]); operate the building (the energy needed for all activates undertaken in the building over the service life including lighting, heating and cooling [11]); maintain the building (i.e. the embodied carbon/energy needed over the building life, for maintenance, repair, replacement, refurbishment); take down the building (i.e. demolition and material disposal at the building end-of-life). Nevertheless, embodied carbon/energy over time is not included in the calculations.

Environmental impacts from operating building have been the focus of evaluation for many years, however in recent times awareness of the impact of embodied carbon has increased [12]. Numerous sustainable building certification schemes now exist, including Active House, BREEAM, DGNB, Green Star, HQE, LEED, Living Building Challenge, Miljöbyggnad, Nordic Ecolabel, WELL) [13], and some have begun addressing the impact of embodied energy and emissions, for example BREEAM and LEED). The introduction of energy assessment into the building regulations in the UK has helped to reduce operational impacts (e.g. [14][15][16]) by implementing innovative solutions (e.g. [17][18]), however there remains a lack of comparable methodologies, data, and regulation to address impacts from material production, construction and demolition practices [19][20][21][12].

Despite these advances in practice for new buildings, low-energy buildings will remain the exception rather than the rule, unless cost considerations are addressed. Further, evidence from practice shows that many award-winning building projects are not performing better in terms of overall life cycle energy consumption [22][23], where reductions in operational energy can be offset by increases in embodied energy.

To address these challenges, a buildings energy committee at the University of Cambridge conceived the **Energy Cost Metric** (ECM) that seeks to bridge the performance gap between cost and energy considerations in a transparent and effective manner. The ECM relates the total lifecycle energy required to construct, operate, maintain and take-down the building, to the construction costs:

$$\mathrm{F} = \mathrm{E} + \mathrm{C}/\alpha$$

where $F$ is the objective function to optimise for, $E$ captures whole-life energy, $C$ building capital cost, and $\alpha$ is a weighted factor relating to the current or anticipated cost of energy such as 25 p/kWh. It is agnostic to the scale and detail of considered design options and was put into application at West Cambridge Development Site to guide design decisions from initial stage to construction.

In this report, the Energy Cost Metric is firstly explained and then tested in practice with outside partners on the Civil Engineering Building (CEB) development project. This report includes the following design stages: the Brief to Design, the Concept Design and early Developed Design (Stages 1-3 according to RIBA Plan of Work 2013 [24]) and consists of 5 main chapters: *Meeting Sustainability Requirements*; *Energy Brief for Civil Engineering Building*; *Energy Cost Metric*; *Application of Metric*; and *Discussion and* Conclusion.

This report includes information, notes, technical reports produced between 2015 – 2017 according to the best available knowledge, experience and using available data sources at this time.

The Civil Engineering building was completed in July 2019 and operates for almost 10 months. There are attempts to assess effectiveness of ECM and revise this methodology for further applications in 2020. The post-construction ECM effectiveness is planned to be included in the second part of this report. Nevertheless, recent experience shows that the Energy Cost Metric is beneficial in guiding the decision making for improved outcomes.

The ECM is anticipated to provide a novel and meaningful approach to designers to achieve very-low energy designs at early stages of the design project, without undue cost. It also serves as a common method and language between beneficiaries, project managers, architects, engineers, contractors and quantity surveys, where matters relating to capital cost, sustainability and energy use can be debated in an inclusive and holistic manner.

*"By focusing on energy, rather than Carbon, the ECM avoids the confusion, complexity and potential for doctoring to favour a particular design choice that carbon conversions often bring to the design process. David MacKay had the foresight to predict the decarbonisation of grid electricity in the UK and recognise that building designers cannot claim these emissions reductions as their own, and if we are to reduce emissions to the levels required to avoid catastrophic damage from climate change, they must make real change too. The ECM gives designers a way for their efforts to be recognised and held to account."*

*Katie Symons, Smith and Wallwork*

*“We started using the ECM in 2015. Its application then and now created and still creates much needed debate, on data sources, reclaimable energy, design efficiency and carbon. There is no doubt that the ECM impacted the choice of structural frame for the Civil Engineering building and led to an overall reduction in the whole life energy of the structure. By embracing the ECM, structural engineers will learn useful lessons on the impact of our designs – lessons that need to be learnt with urgency.”*

*Simon Smith, Smith and Wallwork*

*“Working with the ECM so early in my career has opened my eyes to the simple considerations once can take during early stages of the design process to reduce the lifetime impact of the building, both through embodied/committed and operational carbon”*

*Aurelia Hibbert*

ACKNOWLEDGEMENTS

We express a special gratitude to the late Sir David MacKay, the University of Cambridge's Regius Professor of Engineering, who served as Chief Scientific Advisor to the Department of Energy and Climate Change between 2009 and 2014, and made significant contributions to the fields of Information Theory, Physics, and Policy Making. David was an exceptional mind, mentor and friend to us. He continuously expanded our understanding not just in energy and sustainability but across the disciplines, by providing the clear insight and tools to guide our decision making across all aspects of life. The ECM and Civil Engineering Sustainability Brief is one of the many gifts he has left with us.

We would like to acknowledge the collaborative community around David both within and outside the department, that has further led to the ECM. A special thanks to Kirsten Henson, Shaun Fitzgerald, Tim Jervis, and Danielle Densley-Tingley for their generous expert advice; to the Move West Energy Committee – David Cebon, Andrew Gee, David Green, Peter Guthrie, and Jonathan Cullen; to Joanna Chamberlain as the University's Sustainability Officer; to Emily Dunning at University's Administration Office; to Brian Williams at Estates Management; to our colleagues at Civil Engineering; and to our industry partners at Max Fordham, Grimshaw Architects, Smith & Wallwork, AECOM, and SDC, who provided formidable reports on the ECM's application in the early design stages of the project.

UNIVERSITY OF CAMBRIDGE

GRIMSHAW

MAX FORDHAM

smithandwallwork engineers

AECOM

sdc

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# DEFINITIONS

**Initial embodied carbon** (carbon to practical completion, cradle-to-handover) - carbon emissions associated with a building's product and construction [25] (Modules A1-A5, BS EN 15804 [26]);

**Embodied carbon in use and end-of-life** - carbon emissions associated with materials and processes related to maintenance, repair, refurbishment and water use during the building operation (Modules B1-B5 & B7 according to BS EN 15804 [26]) and demolition, waste and disposal (Module C according to BS EN 15804 [26]);

**Operational carbon** - carbon emissions associated with the building's operational energy during the service life (e.g. for lighting heating, cooling) (Module B6 according to BS EN 15804 [26]);

**Whole-life carbon** - sum of initial embodied carbon, embodied carbon in use and end-of- life, and operational carbon for assumed time period [9];

**Net zero (initial / to practical completion / cradle-to-handover) carbon** - situation when the amount of carbon emissions associated with a building's product and construction stages up to practical completion is zero or negative, through the use of offsets or the net export of on-site renewable energy [25];

**Net zero operational carbon** - situation when the amount of carbon emissions associated with the building's operational energy on an annual basis is zero or negative. A net zero carbon building is highly energy efficient and powered from on-site and/or off-site renewable energy sources, with any remaining carbon balance offset [25];

**Net zero whole-life carbon** - situation when the amount of carbon emissions associated with a building's embodied and operational impacts over the life of the building, including its disposal, are zero or negative [25];

**Future environmental credit** - emission reduction, beyond the building lifecycle, taking carbon savings from material re-use or recycling (Module D according to BS EN 15804 [26]);

**$CO_2$e unit** - Global Warming Potential (GWP) - a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide. The metric for assessing the climate change impacts, expressed in units of CO2 equivalent (CO2e) over 100 years [27];

**Required service life** - service life required by the client or through regulations [28, 29];

**Design life** - service life intended by the designer [28, 29];

**Service life (working life)** - period of time after installation during which a building or an assembled system (part of works) meets or exceeds the technical and functional requirements [28]; for building structures and other common structures minimum service life is 50 years accordind to Eurocode [30] or 60 years according to BS 7543 [31];

**Building's life extension** - extension of the building's service life beyond the design life (service life);

**Reuse** - use of materials, systems, structures, all buildings, after their design life;

**Renovation** - conversions of existing places, changes in structure, the replacement of a defective object or area in the building and the addition of extensions, improving a structure that is broken, outdated or damaged;

**Adaptation** - change of use, example of Renovation;

**Refurbishment** - process of cleaning, equipping, or retrofitting as well as improving the building performance from operational point of view (e.g. adding thermal insulation);

# CHAPTER 1:
# MEETING SUSTAINABILITY REQUIREMENTS

*Based on the "CUED, Technical Report: Embodied Energy/Lean Design" [32] prepared by Katie Symons, Smith and Wallwork Engineers*

*Updated in 2020 by Michal P. Drewniok, Department of Engineering, University of Cambridge.*

## Drive for Sustainability

Operational energy has been the focus of efforts within the construction industry to reduce demand to date, and having achieved many easy wins here, such as energy efficient lighting, heating and ventilation; attention has turned to reduce the energy associated with the building fabric itself, known as embodied energy.

World leading research is being undertaken at the Department of Engineering, University of Cambridge, on issues surrounding the sustainability of the built environment. In line with the Department of Engineering's research in this area, the design of the new development on the West Cambridge site considered the embodied energy of the buildings and sought to reduce it wherever possible.

Lean design is the term being used within the construction industry to describe a way of designing buildings that meet the performance and quality requirements of the client using the least amount of construction materials. Whilst the evaluation of embodied energy may have many difficulties and complexities (primarily in obtaining representative embodied energy data for materials), reducing the quantity of material used in the construction of buildings is an obvious and very simple way of reducing the energy expended by producing and assembling the building fabric. For many years, the construction industry has been associated with a culture of wastage and overdesign, in order to save time or cut corners [8][33][34][35]. The concept of lean design shifts the focus back to using only as much material as is needed, being smart with how primary materials such as steel, concrete and timber are used to their natural advantages, and reducing waste, for example by making use of off-site construction processes. In these ways, the embodied energy of the building is automatically reduced.

It is noted that as interest in the environmental impact of a building's fabric has grown over time, the preferred metric has shifted from "embodied energy" to "embodied carbon". These are respectively defined as:

- the energy consumed during the extraction, manufacture, transportation, assembly, replacement and deconstruction of construction materials or products,
- the carbon emissions ($CO_2$) resulting from that energy consumption in addition to any associated chemical processes.

At the very early design stage the University wished to focus on embodied energy rather than embodied carbon for the new Civil Engineering Building project as this is the best way to achieve very low carbon building. This approach minimise unintended consequences and uncertainty compared to accounting for carbon emissions. Much of the most recent research and guidance in this area deals with embodied carbon in the first instance, and although many of the findings are equally applicable to embodied energy, care needs to be taken when converting between the two metrics.

## Embodied Carbon Standards

In 2010 the UK Government's Innovation and Growth Team (IGT) published their final report on Low Carbon Construction [36]**.** The IGT report recognised that embodied and operational energy, and resulting Carbon emissions, made up a building's 'life cycle' impacts. Those impacts can be identified and quantified to produce a life cycle footprint for a building, which can then be used to plan an effective reduction strategy.

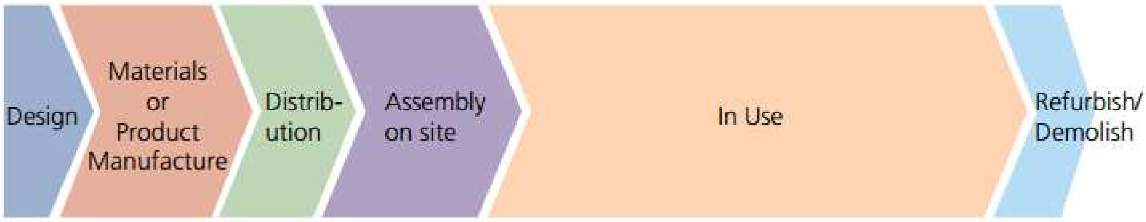


***Figure 4: An estimate of the amount of Carbon emissions for different stages of a building's life cycle from the IGT report [36].***

One of the report's conclusions was that embodied impacts were important enough to warrant the need to be brought into systems used for appraisal of projects, and hence into the design decisions made in developing projects.

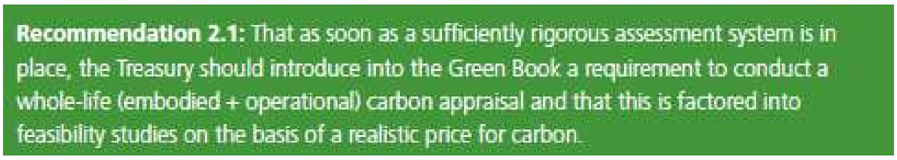
**Recommendation 2.1:** That as soon as a sufficiently rigorous assessment system is in place, the Treasury should introduce into the Green Book a requirement to conduct a whole-life (embodied + operational) carbon appraisal and that this is factored into feasibility studies on the basis of a realistic price for carbon.

***Figure 5: Recommendation 2.1 from the 2010 IGT report [36].***

In response to the IGT report, the UK Government published the Low Carbon Construction Plan in 2011 [37], calling for the construction industry to support the development of embodied carbon measurement tools. The report highlighted the apparent confusion within the industry on the measurement of embodied carbon, recognising that the construction industry sees this as a vital area and is motivated to address it, but that the enthusiasm has resulted in multiple standards and methodologies.

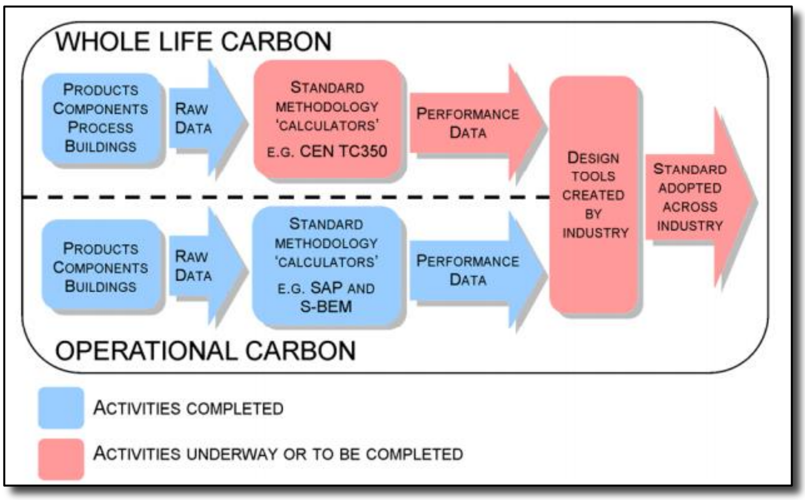


***Figure 6: Extract from the 2011 UK Government's Low Carbon Construction Plan [37]***

The Plan goes on to state that the methodology being developed by the European Committee for Standardisation on sustainability of construction works (CEN/TC 350 [38]), would be supported by the Government through collaboration with industry and the British Standards Institution. The report made clear that legislation to drive the reduction of embodied impacts in buildings would not be introduced until there was a single methodology that could be adopted by the construction industry for the measurement and calculation of embodied carbon.

The CEN/TC 350 committee published final versions of their standards between 2011-2012, providing voluntary methods for assessing the sustainability aspects of new and existing construction works. The aim is for the standards to be generally applicable and relevant for the assessment of integrated performance of buildings over its whole life cycle. Figure 7 shows the framework adopted in the standard BS EN 15978:2011 "Sustainability of construction works: Assessment of environmental performance of buildings" [26] and presents a modular approach, within the system boundary (Figure 8).

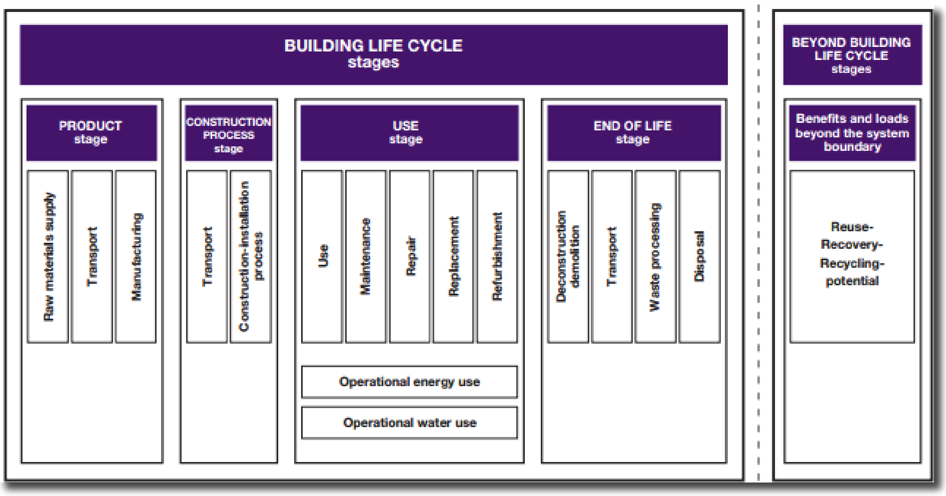


*Figure 7: Building life cycle stages as defined in the CEN/TC 350 suite of [26].*

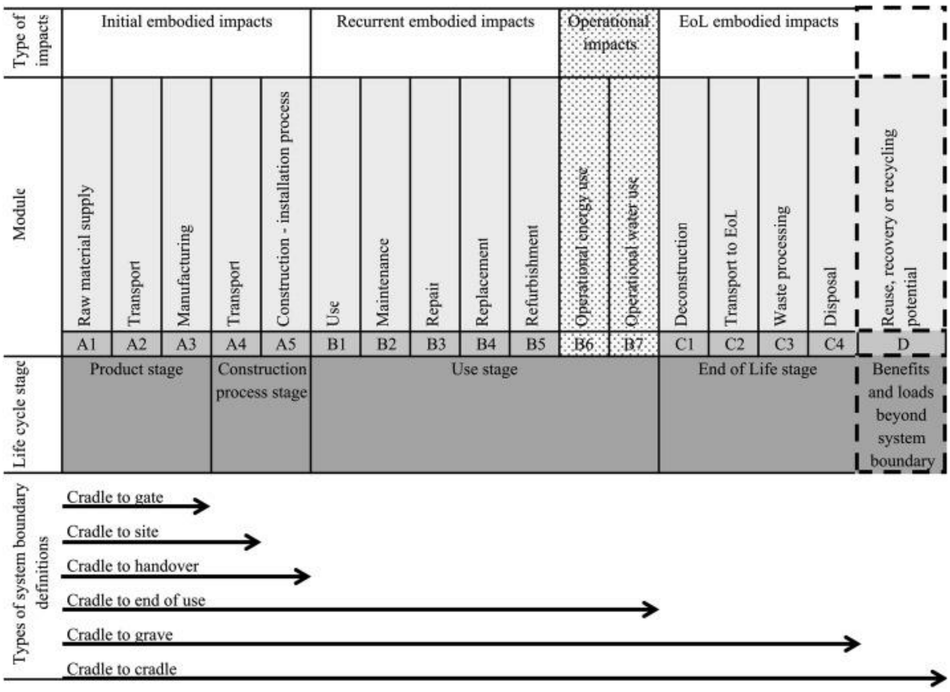


*Figure 8: System boundaries definitions in relation to the life cycle stages of a building [39]*

The same approach was adopted in BS EN 15804:2014 "Sustainability of construction works: Environmental Product Declarations - core rules for the product category of construction products". This standard presents in detail how a life cycle assessment should be conducted for products used in buildings [28]. Of fundamental importance to an Environmental Product Declaration (EPD), is that the life cycle assessment results, which includes the embodied energy and carbon, is verified by a qualified and independent third-party organisation (e.g. BRE [40] or IBU [41]). BS EN 15804:2014 standard was published with the aim of providing clear guidance on how the whole life cycle impacts of construction products, from primary materials such as ready-mix concrete or fabricated steel, through to engineered products such as windows or cladding panels, should be measured and calculated by product manufacturers and communicated in EPDs. Unfortunately, EPDs do not have to conform to the TC/350 standard: in fact, there are many different EPD databases and systems emerging around the world including the US and Australia. The most widely used databases are shown in Table 1.

***Table 1 Widely available EPD databases***

| **EPD database** | **Comment** |
|---|---|
| http://www.envirodec.com/ | Library of EPDs from around the world, for products from a range of industries, not just construction, developed according to the International EPD® system. European EPDs are in accordance with BS EN 15804. |
| https://epd-online.com/ | Over 500 construction product EPDs verified by IBU, a German organisation commonly used as a 3rd party verifier of EPDs. |
| http://www.theepdregistry.com/ | A register of EPDs for construction products primarily from the USA. |
| http://www.epd-australasia.com/ | Based on the Envirodec International EPD® and set up by the Life Cycle Associations of Australia and New Zealand. Note EPDs registered in these countries will comply with EN 15804, the European standard. |
| https://ibu-epd.com/en/published-epds/ | Scientifically-based, quantitative data from life cycle assessments, detailing all of a construction products. EPDs are in accordance with BS EN 15804 and ISO 14025 |
| http://www.greenbooklive.com/index.jsp | Scientifically-based, quantitative data from life cycle assessments, detailing of different products. EPDs are in accordance with BS EN 15804 and ISO 14025 |

Sourcing the data on all the construction materials and products used in a building is the main obstacle to carrying out a life cycle assessment of energy or carbon. There are a few databases and libraries of embodied energy and carbon data for construction materials available, the most widely used in the UK being the Inventory of Carbon and Energy (ICE) [10] first developed by researchers at Bath University. The latest version (V3.0 Beta) of this database was released in 2019 [42] and contains data for over 200 materials, broken down into over 30 main material categories. ICE is popular because it is free to use and covers a wide range of construction material. Version 3.0 compared to version 2.0 from 2011, in which the data was taken from general sources, and therefore could not be representative of the materials of a particular supplier in a particular project, is based on available EPDs.

Over the last few year, sustainable building certification schemes has increased (e.g. Active House, BREEAM, DGNB, Green Star, HQE, LEED, Living Building Challenge, Miljöbyggnad, Nordic Ecolabel, WELL) [13] and there have started to include the embodied impacts of buildings (e.g. BREEAM, LEED). However, due to the absence of legislation, ‘voluntary’ embodied or whole life carbon assessments are carried out for buildings at various stages of design and construction. In 2012 the Royal Institute of Chartered Surveyors (RICS) published an information paper entitled “A methodology to calculate the embodied carbon of materials – information paper” [43]. The methodology presented draws heavily on the CEN/TC 350 standard BS EN 15978. However, document only address the first stage, known as ‘cradle-to-gate’ (Figure 8) of the life cycle of construction materials and products. Research carried out by academics at Cambridge and elsewhere has shown that life cycle stages further down the line, including transportation of products to the building site, construction processes, maintenance, and very importantly what happens to materials when the building is demolished, have a significant energy and carbon impact, that needs to be considered when doing a full embodied impact assessment of the building over its life. A whole life approach identifies the overall best combined opportunities for reducing life-time emissions, and also helps to avoid any unintended consequences of considering only embodied or operational and not considering them together over time [9, 44].


***Figure 9: The RICS methodology information paper (2011) [43], The RICS Professional Guidance (2014) [45], the UKGBC report (2015) [46]***

In 2014, RICS released the Professional Guidance, Global Methodology to calculate embodied carbon (1st edition) [45] with recommendation for specific professional tasks that were intended to represent the ‘best practice’ in embodied carbon calculations, including some embodied impacts from the use stage (e.g. material replacement).

In February 2015, the UK Green Building Council (UKGBC) published the report “Tackling Embodied Carbon in Buildings” [46] with support from the Crown Estate. It provides a good introduction to the technical aspects of the subject to those who aren’t familiar with it, and provides pointers to many other useful resources.  The report concludes, once more, that a lack of embodied energy data, and a single clear methodology that covers the whole life cycle of a building, is delaying the introduction of effective legislation that will force the UK construction industry to reduce the energy consumption and Carbon emissions associated with the fabric of the buildings they produce. In 2018, RICS released mandatory for RICS members: “RICS professional standards and guidance: Whole life carbon assessment for the built environment” [9] that introduced whole life carbon assessment methodology based on BS EN 15978 [26].

In 2019 based on RICS work, UK GBC in a collaboration with the industry published “Net Zero Carbon Buildings: A Framework Definition” [25]. Apart from whole life carbon assessment guidance, this report defined “Net whole life operational carbon”, “Net zero (initial / to practical completion / cradle-to-handover) carbon” and “Net zero whole-life carbon” (see: section Definitions).


***Figure 10: The RICS Whole life carbon assessment for the built environment (2018) [9], the UKGBC Net Zero Carbon Buildings: A framework Definition report (2019) [25].***

Even if assessment methods are known, due to the lack of data, it is very difficult to evaluate WLC, especially embodied carbon in use [25] [39]  [47], even if some countries (e.g. in the UK) has already accepted targets to reduce "whole life greenhouse gas emissions in the built environment" [48]. Currently used carbon assessment approach does not cover all WLC impacts and therefore it is not clear where our efforts should be focused to get the biggest carbon savings. As a result, the real environmental impact of buildings is not fully recognized.

## Case studies

In 2007, the sustainability consultancy, dcarbon8 [49] (now part of Deloitte), carried out an embodied carbon benchmarking study on a steel framed, high rise speculative office building: 1 Kingdom Street, London. The resulting graphic, shown in Figure 4, was subsequently published in Building Magazine, raising the profile of embodied impacts and provided a striking illustration of the relative Carbon intensity of different components of a building.

The results show that the significant contributors to the embodied carbon of the building are the steel frame and concrete basement. What can be taken from this is when looking to reduce the embodied carbon of buildings, these are the components of the building where applying a ‘lean design’ attitude will have the greatest effect.

Davis Langdon, a cost consultancy now part of the AECOM group, have developed their own in-house carbon calculator. In 2011 they created an assessment tool to quickly but robustly calculate the embodied carbon in a given design. Recognising the difficulties in linking cost plan information (which groups multiple materials together into components) with materials-based embodied carbon data, they created an extensive schedule of ‘recipes’ that combine materials together in a way that the embodied carbon of composite specifications can be used with standard cost plan structures. The results of running this calculator through the designs of 29 new build offices is shown in Figure 5, in units of Kg $CO_2e/m^2$, providing useful benchmarking guides for similar projects.

Development of this tool and analysis of these results led the team to conclude what were the most effective factors that reduced embodied carbon, which included:

- The use of cement replacement in concrete mixes for all the concrete elements of the structure,
- An efficient structural engineering solution, that is suitable for the building requirements, but also has structural elements working to at least 90% of their capacity,
- Incorporation of lightweight structural solutions, such as void formers in concrete or post-tensioned concrete solutions, which reduces material required for the frame and foundations,
- The use of reused or recycled materials,
- The use of organic materials, such as timber, which, if sourced from sustainable forests, can be argued as having a negative carbon footprint.

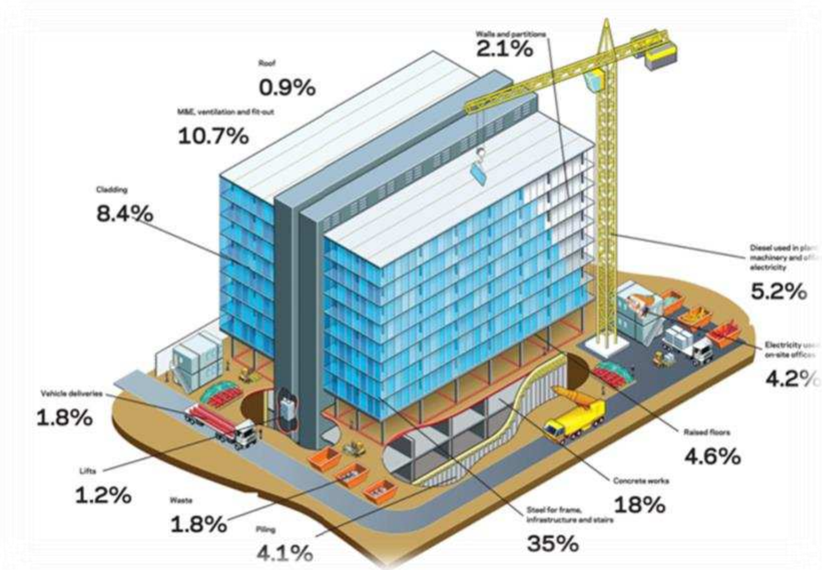


***Figure 11: One Kingdom Street breakdown of embodied carbon impacts***

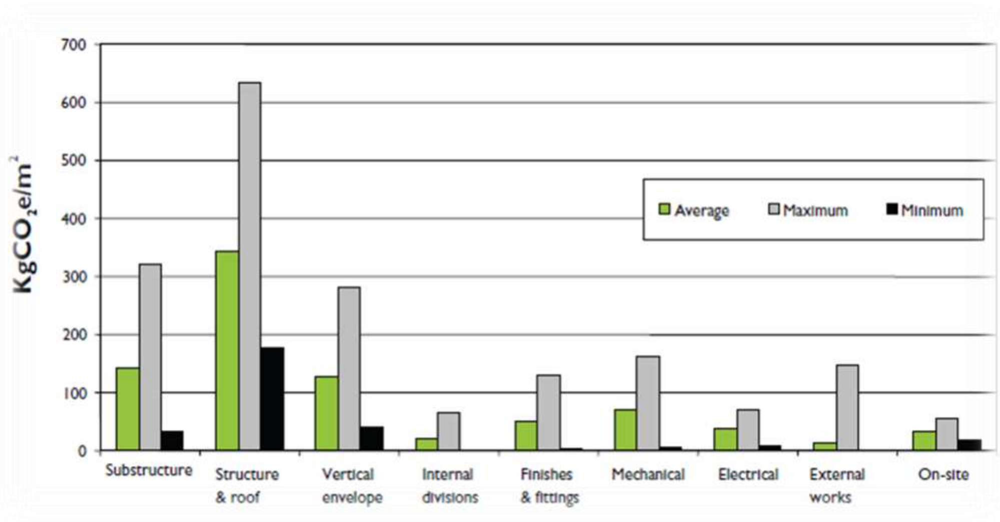


***Figure 12: Embodied Carbon for building components for 29 new build offices, according to the Davis Langdon carbon calculator [50]***

Sustain Ltd worked with the design team for a semi-detached PassivHaus design (90m$^2$) to reduce the embodied carbon of the project within the economic constraints. The results consider only the cradle-to-gate embodied carbon based on life cycle assessment (LCA) and a cradle-to-grave approach over 60 years (service life according to BS 7543:2015 [31]). The building used a concrete ground floor, precast first floor, render finished external walls, concrete roof tiles and triple glazed timber frame windows. The measures to reduce embodied carbon included wood-fibre based insulation boards for the external wall insulation (which are made from natural material that would have a positive end of life carbon benefit if recovered for incineration), concrete roof tiles in place of clay, and a high use of cement replacement (ground granulated blast-furnace slag) in all concrete mixtures. These measures ensured that the embodied carbon of the project was far lower than the average UK domestic dwelling.

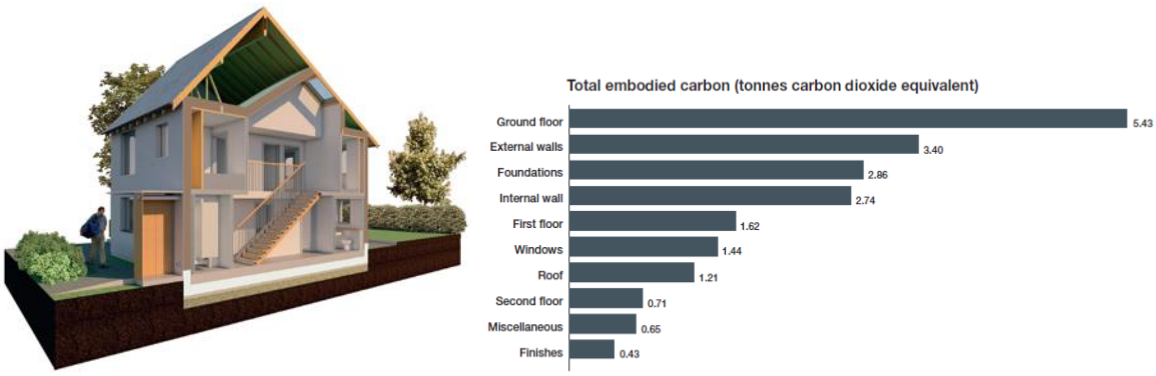


***Figure 13: Results of an embodied carbon analysis of a Paasivhaus domestic building, carried out by Sustain [43]***

Since 2010, many projects assessed whole life impacts (operational and embodied), however they usually assessed cradle-to-gate and operational impact due to lack of data [25] [39] [47].

It can be estimated that for an average office building located in London and assumed 60-year service life (according to BS 7543:2015 [31], 1/3 of whole life building emissions represent initial embodied carbon (2/3 of which comes from the building structure), 1/3 embodied carbon in-use and emissions connected to end-of building life, and 1/3 operational carbon Figure 14 [9] [25]. For a 50-year lifespan commercial building (design life-time according to the EC [51] the structural frames can represent 20–30% of whole life carbon (WLC) [52] [53] [54], 25% of which can come from the columns [55]. For different typologies embodied and operational share is different Figure 14.

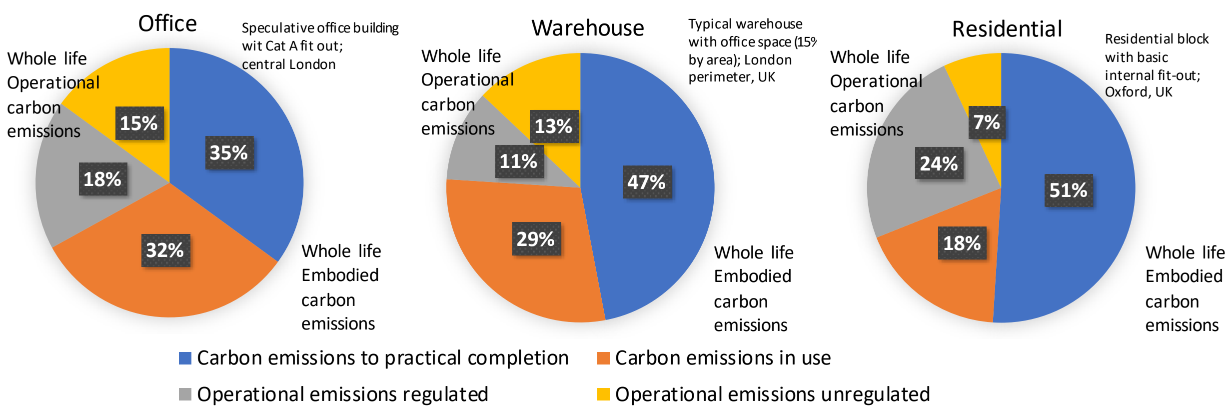


***Figure 14: Whole life carbon for different building typologies [9] [25].***

## Current Trends

Following a successful 'Embodied Carbon Week' organised by the UKGBC in April 2014, a task group was set up by developers and key practitioners across the construction industry. They produced a document in the form of a White Paper [56], and delivered it to the Department of Communities and Local Government (DCLG) and the Department of Environment and Climate Change (DECC) in June 2014. This White Paper set out how embodied carbon has matured as a metric, described a proposed standardised measurement model for embodied carbon and provided a route map for its inclusion as an Allowable Solution for inclusion in the 2016 Building Regulations (this still not been accepted). The recommended first stage is to include only carbon emission assessments for structure, sub structure and envelope and only up to Practical Completion. Subsequent stages will become more comprehensive over time, in a similar way to Part L. Work in this area is still ongoing.

There is still a need for reliable embodied energy and carbon data for commonly used construction materials, and this is frequently used as the main barrier to the wider take-up of embodied impact studies for buildings. Data needs to be freely available, easily searchable and simple to manipulate in in-house tools. The most widely used in the UK is the Inventory of Carbon and Energy (ICE) (V3.0 Beta) updated in 2019 [42], which includes over 200 materials, however this database still does not comprise the full range of other materials used in construction.

Environmental Product Declarations (EPDs) are the obvious solution to this problem, but at the time of implementing ECM (2014/2015), although the contents of EPD databases have been growing, the range of the products covered was not wide enough to enable a full life embodied energy or carbon analysis of a building of any type.

In more recent years, next to commercial whole life carbon benchmarking tools (e.g. OneClick LCA [57]) there were attempts to create open source tools which could guide and set targets of embodied carbon for different building typologies (WRAP ECD that became the RICS Building Carbon Database in 2018 [58], Embodied Carbon Benchmark Study, University of Washington [59] [60], "deQo" - database of embodied Quantity outputs [61] [60]). Nevertheless, the embodied calculations were limited to production of materials used in buildings. Also, even within the same database, calculations were made using different methodologies (except "deQo", where collected data are recalculated, and therefore the buildings can be compared). Due to simplicity, these databases present only a part of buildings' environmental impacts and what is more important, does not show the broader picture of impact from buildings. What is more, embodied carbon for different typologies are in the range 20 – 1150 kgCO2e/m2 (i.e. office building) and therefore benchmarking seems to be impossible (Figure 15). Uncertainty gives also the fact that some buildings are model buildings and databases are usually not updated. Between 2017 and 2020 no building was added to the RICS Building Carbon Database. From 248 buildings, 132 are theoretical; from 92 office buildings, 34 are theoretical. From 34 theoretical, 24 represent the same building, but different options, 8 represents buildings with GIFA = 1m$^2$. Carbon assessment is made for different stages, mostly cradle-to-gate, and is done based on different carbon assumptions.

Quantity Surveyors are becoming more knowledgeable in this area, seeing managing carbon as an extension of managing cost in construction projects.

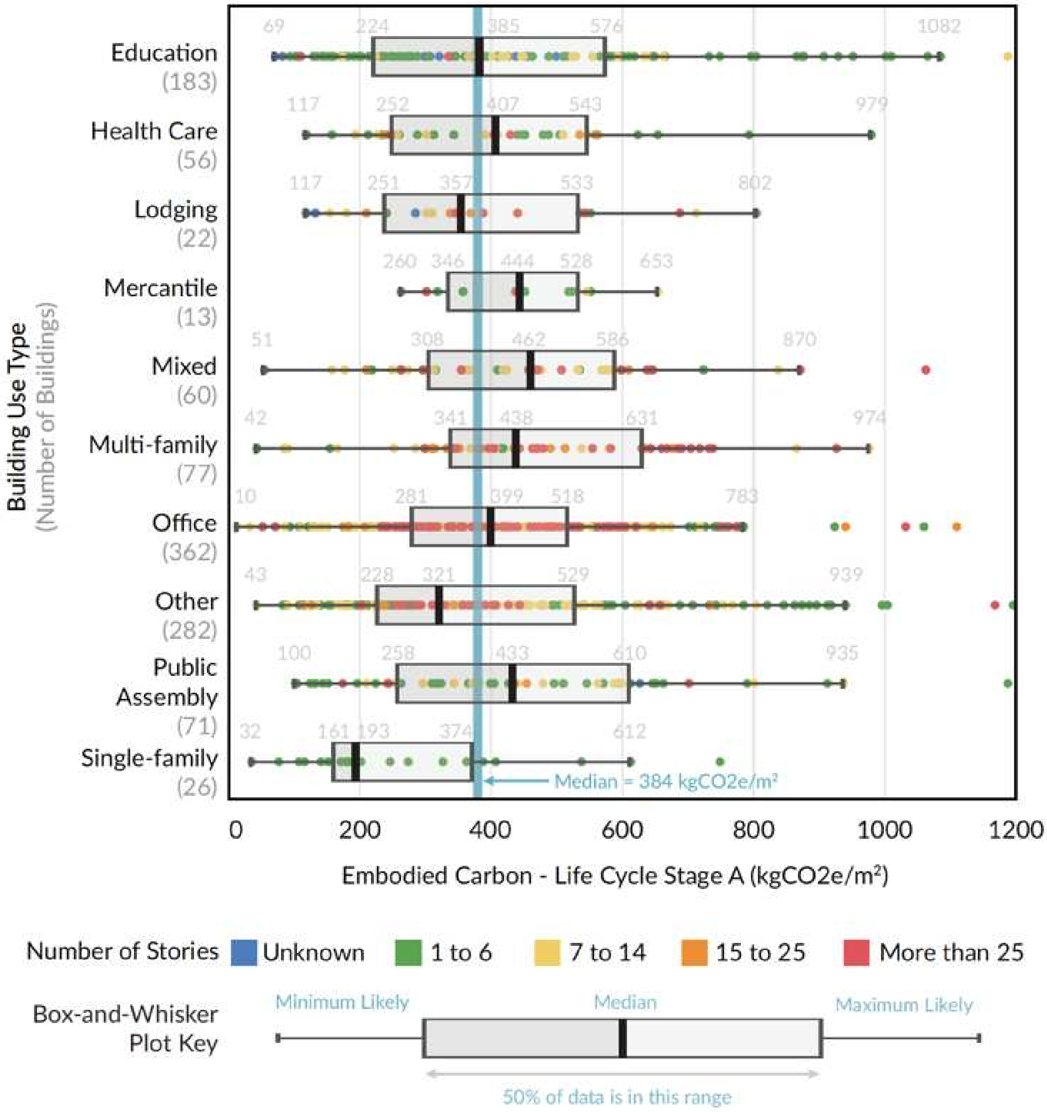


***Figure 15: Embodied Carbon per square meter – initial embodied carbon (cradle-to-practical completion) [60]***

## Sustainability Strategy for West Cambridge Site

The development of the new Civil Engineering Department on the West Cambridge Site has been a significant construction project within the University in Cambridge and Cambridge itself for many years. The operational energy requirements of the buildings are already driven down by current and future regulations, as well the need for the department to keep energy costs low. Therefore, the embodied energy of the buildings over their lifetime is a significant portion of the total energy cost of the development.

The Sustainability Strategy for the West Cambridge Site [62] introduced the concept of 12 Sustainability Principles, with aims and targets for each. Under the 'Materials' principle, the stated aim was to 'Design buildings to be material efficient, by adopting a whole life approach', and among the objectives were:

- minimise the demand for new materials through the reuse of existing buildings, structures, and components, and designing for an appropriate life, for robustness and for low maintenance,
- adopt best practice design to minimise materials use, taking into account efficient design and ensuring that components are not over-engineered.

Meeting these objectives clearly have led to a reduction in embodied impacts of the Civil Engineering Building.

The Department of Engineering considered adopting some of the following strategies to reduce the embodied energy of the construction project:

- Required all design consultants to rigorously record the quantities of the materials they specify at each stage of the design process,
- Made comparisons of these quantities with benchmark data from other similar buildings,
- Tracked the changes to the material quantity estimates throughout the design process, and compared the design quantities to the actual quantities used on site,
- Procured an embodied energy analysis in accordance with the industry recognised methodology (at this time, using the RICS methodology included in "A methodology to calculate the embodied carbon of materials – information paper" [43], based on BS EN 15978 [26]), as part of the design brief,
- Required the embodied energy analysis to consider whole life cycle embodied impacts, thus include the transportation, construction, maintenance and end-of-life impacts, as well as cradle-to-gate impacts,
- Justified all design decisions that did not take the lowest embodied energy option,
- Required all construction suppliers for the project to provide EPDs for their materials or products, that complies with the CEN/TC 350 standard (BS EN 15804 [28]),
- Published the results of embodied carbon analyses on the WRAP open access database,
- Made a condition of appointment of any concrete supplier that cement replacements will be used wherever feasible and that recycled aggregate, sourced within 30 miles of the site, wherever possible.

The redevelopment of the Department of Civil Engineering was the first large construction project to be undertaken by the University of Cambridge, managed by the Estates Management, to submit itself under the ECM. The Department had an opportunity to use this project as a live project for the many research groups within it that are looking to improve knowledge and expertise in the area of energy efficiency in the built environment, and in doing so also influence the design of future construction projects run by the University.

# CHAPTER 2:
# ENERGY DESIGN BRIEF

*prepared by David MacKay, Department of Engineering, University of Cambridge (see Appendix A1)*

"Very-low energy; pleasant; zero-bling; upgradeable; and well measured."

David MacKay, 2014

Prior to applying the ECM to the design process of the new Civil Engineering Building, a design brief was developed by the Energy Committee for the 'Move West' project. This committee, led by the late Sir David MacKay, consisted of architects, engineers, and academics. The design brief was then taken forward to guide the development of the new Department of Engineering building at the West Cambridge Development Site.

The committee summarised its views and guidelines into a 6-point design brief for the construction of a new building:

1. **Very-low energy:** The building will be an exemplar low-energy building, minimizing the sum of
    - embodied energy,
    - measured energy in-use over the intended lifetime, including the occupants' energy for transport,
    - minus an energy credit for embodied energy that will credibly be reclaimed (thanks to design for disassembly and reuse) when the building is disassembled.
2. **Pleasant:** The building should be pleasant for its occupants and should promote health and well-being.
3. **Zero-bling**: The energy solutions this exemplar building uses should be scalable and widely useable. On-site energy generation should not be specially favoured over off-site generation.
4. **Upgradeable:** The building will be designed for easy upgrade, extension, and modification.
5. **Well measured:** All aspects of energy use should be measured, so that the low-energy credentials of the design can be confirmed; so that any problems with the building's performance are identified and fixed rapidly; and because a well-measured building is likely to engage its occupants in meter-reading, which affects behaviour and enhances energy-saving.
6. **Participatory:** The design of the building should involve both engineers and architects. There should be a model of energy consumption at the heart of the design process with transparent assumptions, shared with the clients. The design process should be consultative and iterative, involving the representatives nominated by the Department, assisted by professional advisors dedicated to supporting the Department's objectives. The design process must have the buy-in not only of the building's users but also of the building's maintenance team.

The first five points refer directly to the design outcome, whereas point 6 to the design process. Very-low energy is quantified through the ECM which sums whole life energy and capital cost. Pleasant, zero-bling, upgradeable, and well-measured are captured through a linear scale which qualifies each design decision from negative to positive. This is then represented in a traffic light system, to indicate a design choice performance across the different design criteria, alongside the ECM.

It should be noted that trade-offs between different design criteria are expected. Rather than specifying a hierarchy, stakeholders are encouraged to engage in a participatory design process, facilitated through the simplicity of the design brief, to form adequate decisions. The palpable representation of the performance of different design options through the ECM and traffic light evaluations empowers laypeople to engage in meaningful discussion about energy and the overall sustainability of the project.

Stakeholder participation additionally ensures that the final design is appropriate and adopted to the needs of the occupants. This is particularly important as building performance regulations are not sufficient to guarantee occupant comfort or suitability.

By developing a common language around energy consumption, stakeholders can follow and participate in discussing the design brief in a coherent and constructive manner. This stakeholder participation is particularly important for situations where there is no clear answer. For example, occupants of the Electrical Engineering building on the West Cambridge site comment that the existing University building performance regulations do not guarantee comfort as the building tends to overheat in Summer. To avoid such outcomes, all design criteria should be reviewed as a collective and support a conscious decision process, rather than any one metric to dictate outcomes.

## Energy rather than carbon

The design brief does not mention ***carbon***. This is a conscious choice to avoid unintended consequences or accounting difficulties which result from a carbon focus. Instead a focus on energy minimisation has been selected which addresses climate change and intends for a genuinely very-low-carbon building.

A decarbonisation of the national energy supply is explicitly advocated. The government's 2011 Carbon Plan [63] envisages that decarbonisation would be achieved by (a) increasing electricity provision, to permit electrification of much of the heat and transport sectors; (b) decarbonizing electricity supply with nuclear power, carbon capture and storage, and renewables at the required scale; and (c) using sustainable bioenergy for fuel-consuming sectors that are not easily electrified.

The design brief gives no special credit for on-site generation of energy, whether low-carbon or not. The most cost-effective way to meet the bulk of a building's energy demand is considered to be served from off-site, and it is therefore aberrant to mandate on-site generation. Some on-site generation may be included in a cost-effective design, just like energy efficiency measures, on the grounds that it reduces the energy that will be imported in use. If a design includes on-site generation that may export excess electricity, these exports will earn a modest credit in the metric.

# CHAPTER 3:
# ENERGY COST METRIC

*Written by David MacKay, Department of Engineering, University of Cambridge*

## Energy Cost Metric

As opposed to the Whole-life carbon assessment method presented by RICS [9] and based on BS EN 15978 [26] and to bridge the performance gap between cost and energy considerations in a transparent and effective manner the Energy Cost Metric (ECM) was developed. The ECM relates the total energy to the building cost factored by the current or anticipated cost of energy.

It is anticipated that a well-optimized low-energy design will have the following features:

a) The building should have a near-zero heating and cooling requirement, thanks to the use of insulation; natural ventilation and perhaps (in winter) mechanical ventilation with heat recovery; and simple controls that are successfully used by real, comfortable occupants.
b) The building's construction should use reclaimed materials (especially steel) and sustainably sourced wood, and many of its components should be designed for disassembly and reuse.
c) The building should be lightweight – designed exactly to comply with the Eurocode standards, rather than unnecessarily exceeding those standards. The foundations should be designed and measured such that the building can be modified without costly or unnecessarily material-intensive foundation work.
d) The "in-use energy" definition includes the occupants' transport energy, favouring thoughtful building designs that strongly promote:
    i) low-energy transport (e.g. excellent cycle provision;
    ii) convenient and effective wet-weather drying facilities;
    iii) tight and attractive integration with public transport; and
    iv) electric vehicle charging, especially for lightweight electric vehicles); and alternatives to transport (e.g., video-conferencing).
e) The building should not make use of natural gas as an energy source, or if it does, there should be a credible, low-cost plan for the natural gas supply to be eliminated within a few decades.

All design decisions should be optimized subject to explicit constraints on occupant comfort (pleasant), which will be reviewed during the design process to confirm that the energy cost metric does not drive unwanted outcomes. These constraints should include especially:

i. provision of daylight at most or all working locations;
ii. satisfying human thermal comfort constraints;
iii. floor-area constraints determined by the number of occupants.

Thus, the objective function used in design optimization that proposes Energy Cost Metric is $F$ (given the designation $U$ in the original report) (Eq. 1)

$$F = E + C/\alpha \tag{1}$$

Objective function includes the sum of two terms:

– the approximate total whole-life energy (in kWh or MJ), $E$ defined below,
– quotient of the building cost ($C$) and a weight ($\alpha$), such as 25 p/kWh.

This weighting should be set by the client. In case of Civil Engineering Building, University or by the Department's representative. It quantifies the degree to which the client (University and Department) value an energy-minimizing design as specified in the top line of the brief.

An absolute minimum justifiable value for $\boldsymbol{\alpha}$ would be the average future expected retail price of energy to the University (e.g. 12.5 p/kWh). That might be appropriate if the client did not care about sustainable resource use or climate change action. Due to the fact that there is a missing carbon price in the global economy, and genuine carbon neutralization can be achieved only by measures that suck carbon back out of the atmosphere, it could be argued that that cost should be factored into ethical decision-making. Even without climate change, one could argue that society should put a higher price on energy, especially unsustainably-sourced energy. The multiple justifications identified a value as 25 p/kWh or higher.

## Total whole-life energy

Total whole-life energy, $\boldsymbol{E}$, is defined as the sum of five parts (Eq. 2):

$$E = E_E + E_{MT} + E_{IU} + E_T - E_R \tag{2}$$

where:

$E_E$ – embodied energy,

$E_{MT}$ – material transport energy,

$E_{IU}$ – in-use energy,

$E_T$ – occupants' energy for transport,

$E_R$ – reclaimable energy thanks to design for disassembly and reuse.

Life Cycle Energy considered under the ECM with a distinction between material energy and use-phase energy is presented on Figure 16.

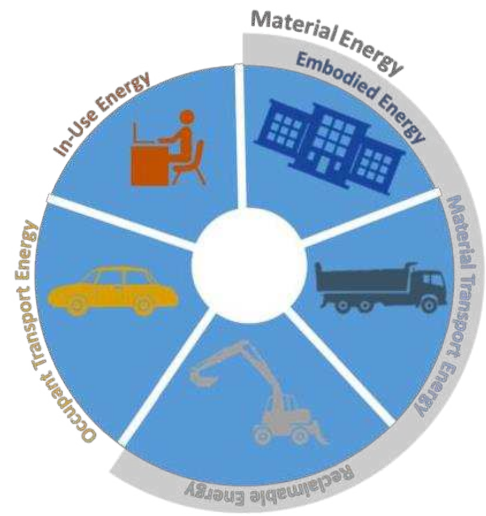


***Figure 16: Life Cycle Energy considered under the ECM with a distinction between material energy and use-phase energy.***

Each of these components is discussed in more detail in the following section.

**Embodied energy** $E_E$ – for simplicity this is be deliberately approximated (Eq. 3); the approximation should be reviewed during the design to ensure it is not producing unintended consequences. With $m$ running over materials, $i_m$ denoting the energy intensity of the $m$th material (in MJ/kg or kWh/kg), and $m_m$ the mass of the $m$th material brought to site:

$$E_E = \sum_m i_m m_m \tag{3}$$

The material list might be: glass, wood (possibly sub-categorized), aluminium, reclaimed steel, new steel, concrete, cement, brick, plastic, electronic device, other. Any item not well captured by the above list (for example a crystalline silicon solar panel) should be given individual treatment, if doing so would make a substantial difference to the optimization of the design. Embodied energy included in ECM relates to cradle-to-gate energy (Modules A1-A3) according to the BS EN 15804 [28]. Energy used in ECM measured in [J] to avoid unintended consequences or accounting difficulties which result from a carbon focus.

**Note**: Reclaimed materials should not be assigned zero energy intensity – attribution of the energy savings is arbitrary, but as a rough rule of thumb, and should be reviewed during the design. Rough assumption might be made that reclaimed materials have half the energy intensity of the new ones.

**Example**: Let's assume that we have 1000 kg of steel in a building per person and we design a building for 1000 people, thus:

1000 kg /person * 1000 people * 6 kWh / kg * 3.6 MJ/kWh = 21.6e$^6$ MJ
Express in kWh per day per person: 6000 kWh/(365.25 days/year * 50 years) = 0.33 kWh/d/p.]

**Material Transport Energy** $E_{MT}$ (Eq. 4)

$$E_{MT} = \mu(M + m_0) \tag{4}$$

Let $M$ be the total mass of materials brought to site, $m_0$ be the total mass removed from site (the sum of any discarded building materials and any other mass removed from the site during site preparation) and $\mu$ energy of transport, e.g. 3.6 MJ/ton-km (for 200 km, $\mu$ might be set to 3.6 MJ/ton-km × 200 km= 720 MJ/t). The distance should reflect the additional non-energy disbenefits associated with heavy goods vehicle movements (for CEB it was taken 200 km).

**In-use energy** $E_{IU}$ – Let $T$ be the intended life of the building (for buildings 50 years according to BS 7543:2015 [31] or 60 years according to [30] ). The in-use energy is $T$ times the estimated actual total energy consumption rate $Ec$, measured at the electricity meter and the gas meter (Eq. 5). The energy consumption of a small number of experimental facilities is excluded from this total, since it is outside the control of the building designers and constructors.

The decision that electricity and natural gas are weighted equally, MJ for MJ (rather than up-weighting electricity), should be reviewed during the design to confirm that it produces no perverse consequences. If a design needs to make use of any other fuels, the client (Department's representatives) should be consulted to confirm the weighting. The actual annual energy use will be measured for the first $Y$ years (e.g. 4 years) of occupation and the designers and constructors will be jointly incentivized (through a risk-sharing arrangement) to ensure that the actual energy use, post-commissioning, is consistent with their projections.

$$E_{IU} = TEc \tag{5}$$

**Occupants' energy for transport** $E_T$ (Eq. 6) - The design should be accompanied by a reasoned description of the predicted transport footprint of the occupants and visitors to the building, including number of car journeys, number of bus journeys, number of foot journeys, number of electric-vehicle journeys, and number of rail and air journeys per year. Typically, the energy footprint associated with transport will be much larger than the embodied energy and in-use energy of the building, so we strongly favour building designs that promote low total transport energy. This simple model will be used (with $T$ = an intended building lifetime, e.g. 50, 100, or 200 years – the duration of impact of the design choices made today):

$$E_T = T\left(\sum_m N_m c_m\right) \tag{6}$$

where $N_m$ is the rate of return trips of mode $m$, and $c_m$ is an energy cost per trip.

**Note**: For CEB, we would hope for a design that favours some switches of local travel from car to bus or bicycle, add bike parks closer to the building to encourage behaviour changes, possibly some switches of longer distance travel from car to train (through excellent interconnection to public transport), and switches of long-distance travel to videoconferencing.

**Example:**

***Table 2: Occupants' energy for transport for CEB.***

| Local travel | |
|---|---|
| mode | $c_m$(MJ/trip) |
| foot, cycle | 0 |
| car (local) | 16 x 3.6 = 57.6 (20 km in single-occupancy car at 80 kWh/100 km) |
| bus | 2*3.6 = 7.2 (20 km in bus at 10 kWh/100 p-km) |
| EV | 2*3.6 = 7.2 (20 km in EV at 10 kWh/100 p-km) |
| UEV | 0.5*3.6 = 1.8 (20 km in ultra-light electric-vehicle at 2.5 kWh/100 p-km) |

| Longer distance travel | |
|---|---|
| mode | $c_m$(MJ/trip) |
| car (long distance) | 160*3.6 =576 (200 km in single-occupancy car at 80 kWh/100 km) (for national car trip (eg return to Bath or Birmingham) |
| rail | 16*3.6 =57.6 (400 km in train at 4 kWh/100 p-km) (for national rail trip (allowing for longer route thanks to silly rail network) |
| flight | 12000*3.6 = 43200 (LA return by plane, assumed full) |

Provision of excellent attractive and convenient videoconferencing facilities could be deemed to perhaps reduce all long distance journeys by 50%. If $T$ = 50 years and there are $N$ = 1000 people in the building each taking one flight per year, then the energy benefit of videoconferencing according to this crude model, from flight reductions alone, could be 2.2e$^9$ MJ (6e$^8$ kWh). Similarly, excellent integration with an attractive bus service might be deemed to switch 100 individuals from car to bus for 200 days per year, saving 200*50*(14*3.6)*100 = 0.05e$^9$ MJ.

**Reclaimable energy thanks to design for disassembly and reuse** $E_R$ – Energy credit should be given where there is a credible account of reuse-ability of components such as steel beams. For CEB, the credit will be scaled down by [0.5], or perhaps more to allow for the material inefficiency of reuse, that is, the scrapping [virtual or actual] that is likely when a component is put to a new use for which it was not perfectly designed.

## Credit for on-site generation of energy

For avoidance of doubt, there was no credit for on-site generation of energy, nor for energy efficiency measures. Such measures are already incentivised by our metric's emphasis of energy-use by the building. If a design has on-site generation that will sometimes export electricity from the building, these exports must be scalable in the sense that there must be a credible nearby demand for that electricity at the time the excess electricity is generated (for example, an air-conditioning load in a nearby building); subject to this constraint, such net electricity exports from the building will be credited in our metric at a rate of (say) $\beta$ = 5 p/kWh.

## Alternative ways of defining ECM

Four alternative ways of representing the objective $U$ (Eq. 1), which may be useful in certain contexts:

### The energy-weighted cost (Eq. 7)

$$C_U \equiv \alpha U = C + \alpha E \tag{7}$$

### The energy-weighted cost per person per year (Eq. 8)

$$c_U \equiv \frac{C_U}{NT} \tag{8}$$

where $N$ is the average effective number of building occupants (for example, the number of employees) and $T$ is lifespan of the building (for example $T$ = 50 years);

### The cost-weighted power per person (Eq. 9)

which might be measured in kWh per day per person

$$p_U \equiv \frac{U}{NT} \tag{9}$$

**The cost-weighted power per unit area (Eq. 10)**
which might be measured in kWh per $m^2$ per year or in $W/m^2$

$$p_{UA} \equiv \frac{U}{NTA} \tag{10}$$

where $A$ is the floor area of the building.

## ECM: Questions and Answers

**Won't the uncertainties of some of the quantities in the objective function U be enormous?**

Yes, but that is not a reason for ignoring them! Good decision making should take into account all the uncertainties.

**Won't the uncertainties of some of the quantities in the objective function U be bigger than the size of potential design effects?**

Yes, but that doesn't matter. If a design change definitely reduces the total U by a material amount, then it doesn't matter that U itself is uncertain. If on the other hand it is highly uncertain what the effect of a design change is on U, then that would justify careful further thought and analysis.

**Won't the evaluation and optimization of this objective slow down the design process, which needs to be fast?**

The building, and the consequences of its design decisions, are going to last for 100 years. The objective of making a genuinely low-energy building is important, and the design process must, if necessary, be constrained to proceed at a pace consistent with achieving this objective.

**Transport is a major part of U, but it isn't something that the designers can change.**

We disagree.

1. The designers can think hard about how to design the building such that public transport, cycling, and walking are attractive to the building's users. For example, how about a design for the new Physics and Engineering buildings in West Cambridge in which elevated walkways and cycle ways provide attractive routes to avoid road-crossings? How about planning a building design that integrates with an elevated cycleway over Madingley Road? Such a design would change the transport decisions of a person who would otherwise say "I don't like crossing Madingley Road by bike – it's so busy and the traffic lights take for ever".
2. The designers can focus attention on providing videoconferencing facilities that are so user-friendly that people will videoconference instead of travel. Not only are the potential energy savings large, the potential financial savings to the University are enormous – if every researcher takes one fewer flights per year then the financial savings over 50 years are similar to the entire cost of the building! These genuine financial savings could be spent on the University's goals of teaching and research.
3. The designers can pay attention to the provision of parking and charging for lightweight electric vehicles.

**The draft energy brief sets out areas in which the whole life cost should be incorporated into the build cost. This is logical but doesn't fit into the standard budgeting of construction?**

Yes. Certain chosen elements will indeed be more expensive than "normal" solutions. It has been suggested to us that when the project gets underway an additional detailed budget needs to be clearly set out and ring-fenced to cover the costs of the expensive elements.

# CHAPTER 4:
# APPLICATION OF METRIC – THE CIVIL ENGINEERING BUILDING

## Façades and HVAC systems

*Prepared by Katie Doig and Joel Gustafsson, Max Fordham*

The façade and HVAC systems are interlinked in terms of their performance efficiency. Given this, the contribution to F for each combination of Facade and HVAC options has been considered. On the cost side, an annualised cost of the façade and HVAC systems is applied. On the energy side, the material energy of the façade ($E_M$) and the in-use energy ($E_{IU}$) associated with each combination was considered.

The façade options that have been compared under the ECM are presented in Table 3 and Appendix A2, along with their performance parameters, annualized material energy and annualized costs. For each of these options the two performance parameters are outlined; their thermal conductivity (U-value) and the air tightness. These performance parameters have been used to determine the in-use energy associated with each façade and HVAC combination by calculating a heating and cooling load.

The material energy considers embodied energy, transport to and from site, and any reclaimed energy at the end of the building lifetime. The costs presented are projected costs based on m$^2$ rates.

***Table 3: Summary of Façade options under consideration.***

| Façade Type | | Area Weighted U-Value | Air Tightness | $E_M$ | Cost |
|---|---|---|---|---|---|
| | | $W/(m^2K)$ | $m^3/(m^2h)$ at 50Pa | MWh/yr | £/yr |
| Masonry With Punched Hole Windows | *M* | 0.65 | 5 | 13 | 25,597 |
| Composite Wall System With Strip Windows | *C* | 0.95 | 4 | 13 | 54,722 |
| Rainscreen System (Proprietary) | *R(P)* | 0.95 | 3 | 8 | 25,166 |
| Rainscreen System (Bespoke) | *R(B)* | 0.65 | 3 | 8 | 28,323 |
| Double Glazed Aluminium Mullion Stick Curtain Wall | *CW(DG)AM* | 0.95 | 2 | 19 | 45,423 |
| Double Glazed Steel Mullion Stick Curtain Wall | *CW(DG)SM* | 0.95 | 2 | 13 | 45,423 |
| Double Glazed Timber Mullion Stick Curtain Wall | *CW(DG)TM* | 0.95 | 2 | 11 | 45,423 |
| Triple Glazed Aluminium Mullion Stick Curtain Wall | *CW(TG)AM* | 0.55 | 2 | 26 | 61,455 |
| Triple Glazed Aluminium Mullion Unitised Curtain Wall | *UCW(TG)AM* | 0.75 | 1 | 26 | 76,685 |
| Triple Glazed Steel Mullion Stick Curtain Wall Systems | *CW(TG)SM* | 0.55 | 2 | 21 | 61,455 |
| Triple Glazed Timber Mullion Stick Curtain Wall | *CW(TG)TM* | 0.55 | 2 | 18 | 61,455 |

All HVAC options have been appraised over 25-year plant life and a 50-year lifetime for auxiliary components (see

Table 4). The auxiliary components consist of everything associated with the HVAC system that is not the plant itself, for example pipe work (see Appendix A2). To extract the in-use energy from the raw heating and cooling loads the HVAC performance parameters were applied, which are the heating efficiency (COP), cooling efficiency (EER) and transfer efficiency (COP/EER).

For the options including heat transfer the available transfer load was determined from the hourly thermal output of the dynamic thermal model. The annualised in-use ($E_{IU}$) and material energy ($E_M$) that arise from the different HVAC and façade option combinations are presented together in Figure 17 and Appendix A2.

***Table 4: Summary of HVAC options under consideration.***

| HVAC Type | | Heating efficiency (COP) | Cooling efficiency (EER) | Transfer efficiency (COP/EER) | Cost *(£/yr)* |
|---|---|---|---|---|---|
| Ground source heat pump with heat recovery | (GSHP+r) | 5.1 | 6 | 4.66/3.66 | 42,000 |
| Air Source Heat Pump | (ASHP) | 3.3 | 3.54 | 4.15/4.15 | 34,000 |
| Boiler-VRF | (B-V) | 0.9 | 6.5 | -/- | 20,000 |
| Boiler-Chiller | (B-C) | 0.9 | 5 | -/- | 26,800 |
| Boiler-Chiller with Heat Recovery | (B-C+r) | 0.9 | 3.5 | 4.15/- | 30,000 |

The HVAC systems with heat pumps have a significant reduction in in-use energy in comparison to those with heating being supplied by a boiler. A notable consequence of this is that for the more efficient HVAC systems (the two heat pump options) the choice of façade has a smaller impact on the in-use energy. Given the embodied energy for each façade type does not change with the HVAC system, the embodied energy becomes more critical for these options. For the lower efficiency HVAC systems, the façade performance is the dominant factor in the energy ranking. This demonstrates the link between the energy savings generated by HVAC efficiency and façade performance.

Based on the ECM analysis, at the Stage 2 proposed: a ground source heat pump with heat recovery (GSHP) as the HVAC system, a bespoke rain screen as a general façade and double-glazed curtain wall with timber mullions as a feature façade. The appropriate value of α has remained undefined throughout stage 2. Setting α to a value such as 25 p/kWh or higher, the general façade sits comfortably in the acceptable range and the proposed feature option can be considered either fully agreeable or warranting consideration.

## Duckwork

*Prepared by Katie Doig and Joel Gustafsson, Max Fordham*

For the requirements of the civil engineering building, where the majority of the ductwork is relatively small in size, cardboard ductwork did not perform better than galvanised steel under the ECM within the range of α that might be of interest (Figure 18). As such it is not recommended that the Civil Engineering Building should use cardboard ductwork in place of galvanised steel ductwork. It is worth noting that this may not be the outcome for all ductwork configurations. As such it is recommended that this topic should be re-examined on future projects at CUED, particularly for situations where there is a requirement for larger ductwork systems (Appendix A3).

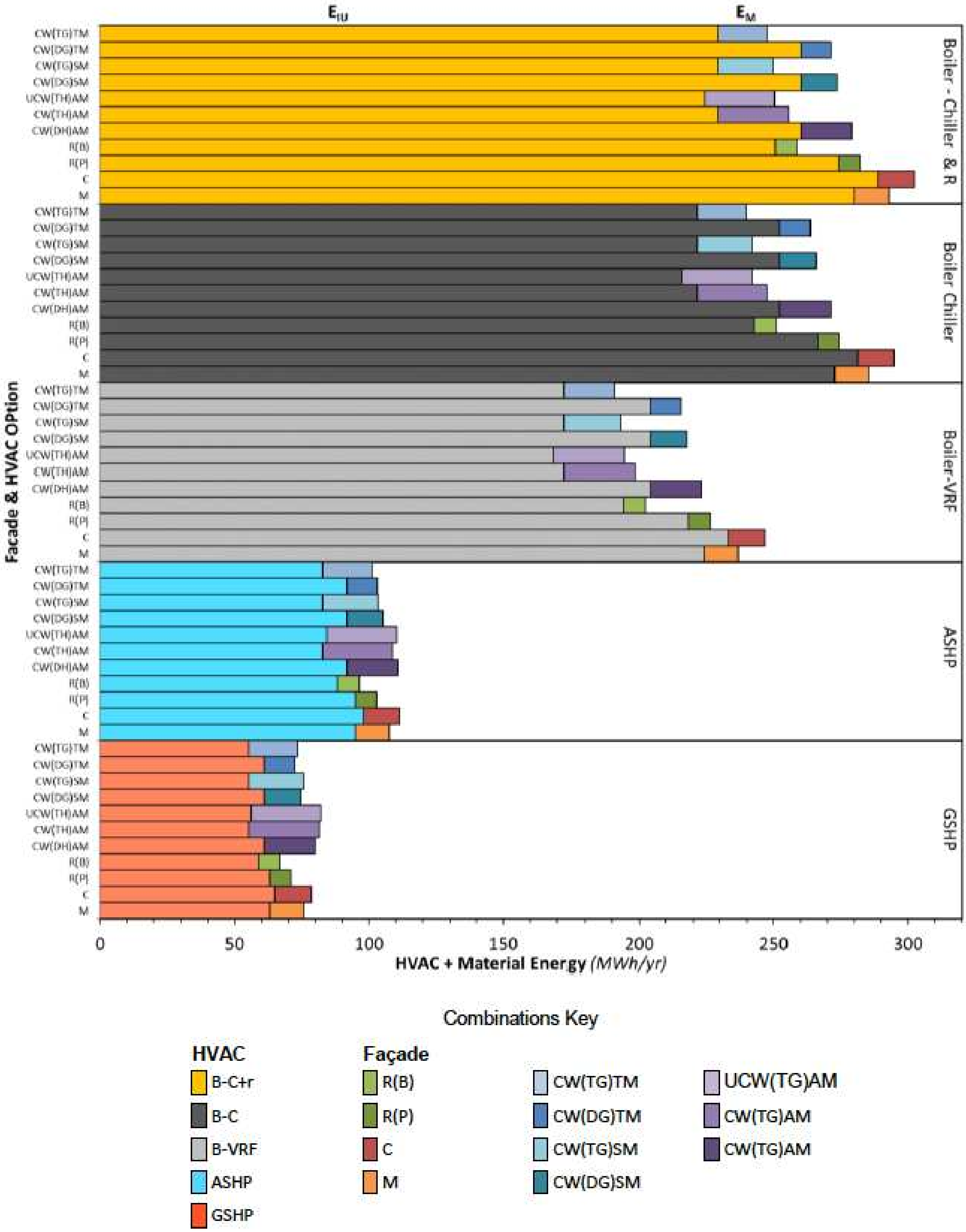


*Figure 17: In-use and embodied energy for the different façade and HVAC option combinations.*

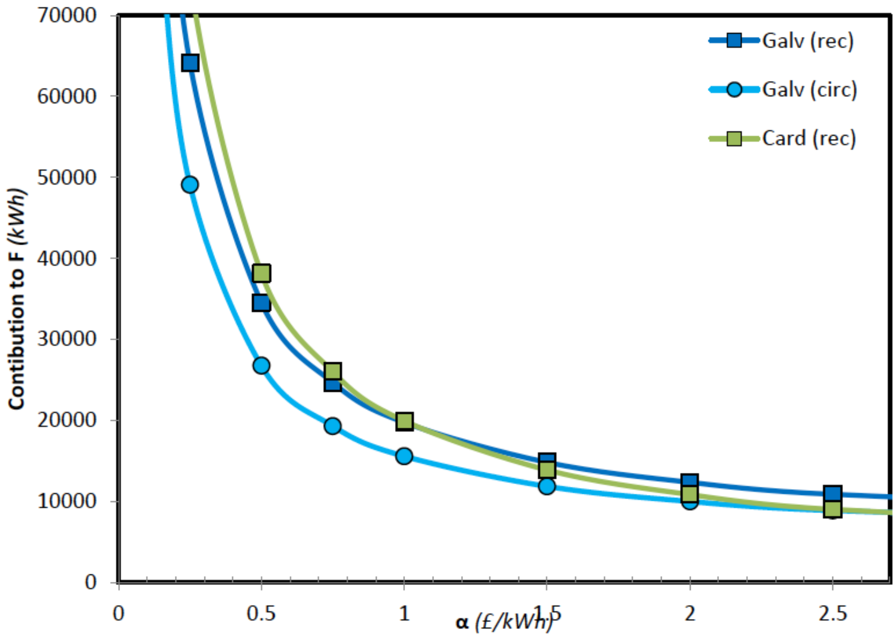


***Figure 18: Contribution to F for a range of values of α for circular and rectangular galvanised steel ductwork and for rectangular cardboard ductwork.***

## Kill Switches

*Prepared by Katie Doig and Joel Gustafsson, Max Fordham*

A large proportion of energy use of the Civil Engineering Department is caused by electrical base load overnight. The potential energy saving from kill switches is difficult to accurately predict. Whether kill switches perform well under the ECM is highly dependent on the level of cuts to the base load that are thought to be possible and on the lifetime that might be attributed to them. Both of these factors can be considered highly subjective and uncertain. The level of lighting present in the electrical gain profiles also adds an additional unknown; however, based on the examples that are available it is likely that this effect is small in comparison to the first two factors.

Given this inherent uncertainty determining the energy savings, calculating alpha breakeven ($\alpha_{BE} = -\Delta C/E$) for a range of reductions to the base load is an effective way of examining the measure's potential cost-effectiveness. Figure 19 shows $\alpha_{BE}$ for a range of percentage reductions to the base load. The grey band between 10% and 20% highlight the range that might represent a sensible minimum and maximum case for the possible reduction in the baseload. Assuming a 50-year lifetime for cabling and 25-year for all other components, with a 10-20% baseload reduction including the lighting correction, $\alpha_{BE}$ would range between 24-50p/kWh.

If assessed under a simple payback scenario (see Table 3 in Appendix A4) kill switches do not perform well unless unrealistically high levels of energy saving are assumed. To achieve a simple payback in 15 years 77% of the out-of-hours base load would have to be saved. This equates to a 30% reduction in the overall electrical load profile. This level of saving is unlikely to be achievable.

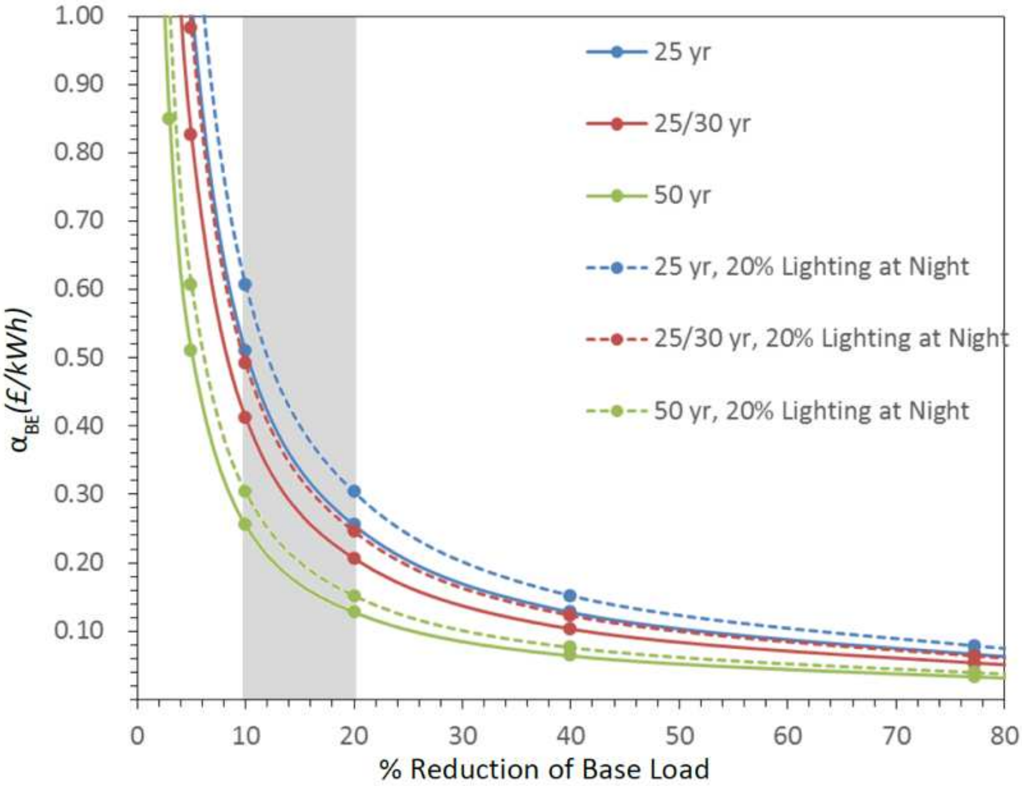


***Figure 19 αBE for different % reductions in the annual base load. The 25/30-year case is for the breakdown presented Appendix A4, while the other two cases assume a 25-year and 50-year lifetime for all components respectively.***

It is important to note that simple payback is based on the current price of energy and that one of the fundamental drivers of the ECM is to value energy in a different way. As such, although kill switches do not perform well on a simple payback metric it doesn't necessarily follow that they don't have merit under the ECM. Given the degrees of uncertainty in assigning potential base load savings and system lifetimes, it is difficult to give a definitive conclusion on kill switch performance under the ECM without further discussion to narrow the possible ranges of the savings and lifetime parameters.

Given the uncertainty over the performance of this measure a possible proposal for the civil engineering building had been that a trial installation was set up with infrastructure provision for the trial to be extended if successful, we could monitor the effectiveness of the kill-switches against a similar area without kill switches and against the same area with and without kill switches in operation. Alternatively, further research into existing schemes may provide further clarification on the effectiveness of the measure. The research on the effectiveness of the ECM is planned to be conducted in 2020.

## Thermochromic Fins

*Prepared by Katie Doig and Joel Gustafsson, Max Fordham*

Criterion 3 of part L2A of the building regulations puts limits on the amount of solar gain that rooms can experience between March and September. Here the solar gains had to comply with regulation and maximise occupants' comfort throughout the year. To address this issue, fins made of thermochromic glass were reviewed under the ECM to improve the visible light and useful solar gain availability in the winter, while blocking unwanted solar gain during the summer. Thermochromic glass has a temperature dependent transmittance of light; as the temperature increases the transmittance for optical and thermal radiation decreases.

The use of thermochromic fins results in a small energy saving in heating and cooling of a few MWh per year compared to solid fins or solar control glazing with no fins (Appendix A5). This represents a small percentage improvement of slightly under 2%. In terms of the ECM, solid fins always perform better than the thermochromic fins of equivalent size. The values of α that would be required to switch from solid fins to thermochromic fins performing better under the ECM is over £10/kWh, which is significantly higher than the range that has been under consideration.

Although the solid/thermochromic fin options do not perform better under the ECM than solar-control glazing without fins, using fins rather than solar-control glazing to control solar gain can have other less quantifiable benefits, listed below:

- Better connections with the outside
- Better access to daylighting in the winter or dull weather
- A façade that can respond to different conditions at different locations
- The addition of architectural interest to the façade

Consideration needs to be given to the level of importance associated with these aspects and how well the inclusions of fins meet other aspects of the brief.

## Photovoltaic Array

*Prepared by Jeremy Climas and Ben Leary, Max Fordham*

The masterplan objective stated that “PV [photovoltaic] panel area for each building should target at least 25% of the building’s footprint, and therefore anticipated to cover approximately 50% of the building’s roof area (allowing for space between panels).”

Photovoltaic arrays were generally arranged in a grid and spaced to minimise overshadowing at their chosen inclination. The optimum angle for the panels is dependent on if the aim is to maximise panel area for a given available area or to maximise the output for a single panel over a year. For the PV array to meet the masterplan requirements the panel area would need to be in excess of 396m². However, by reasonably accounting for over shading by both panels and chimneys it was not possible to meet this target at a 30° panel inclination (see Figure 20). By angling the panels at 10° the panel area of the array can be significantly larger but still did not meet the 25% target. Both options utilised in excess of 50% of the total roof area.

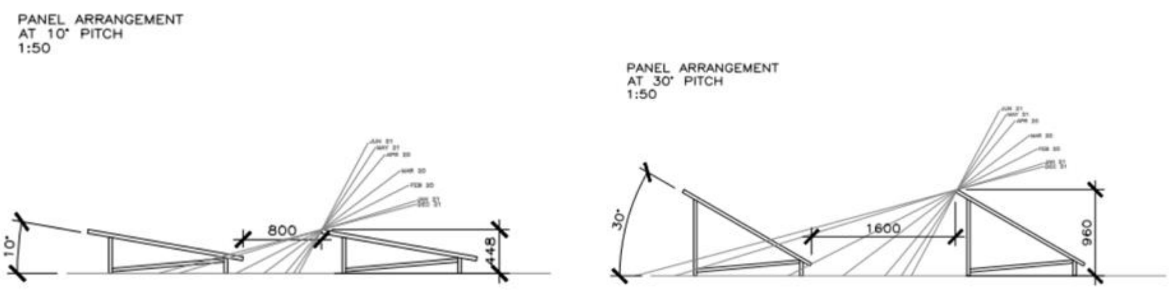


***Figure 20: Indicative Panel Spacing with 10° and 30° panel inclination.***

The embodied energy the PV panel was estimated to be 500 kWh/m$^2$ of panel and the lifespan is expected to be a minimum of 25 years. The breakeven alpha, $\alpha_{BE}$ is calculated as (Eq. 11):

$$\alpha_{BE} = \frac{-\{Cost\ (£)/Lifespan\ (Yrs)\ \}}{-\{Energy\ Generation\ (kWh/yr) - (Embodied\ Energy\ (kWh)/Lifespan\ (Yrs))\}} \tag{11}$$

The results for the different options estimate $\alpha_{BE}$ between £0.10/kWh and £0.11/kWh (see Table 2, Appendix A6). In terms of ECM, the low cost, lower efficiency panels perform better that the higher cost higher efficiency panels. Additionally, the optimised orientation option performs better against the Energy Cost Metric in both scenarios as the annual yield per panel increases. As such the best option under energy cost metric is low efficiency panels installed at 30° incline.

## Structural Frame and Floor System

*Prepared by Katie Symons and Simon Smith, Smith & Wallwork Engineers*

A number of assessment criteria have been used in developing a preferred structural frame and floor system for the phase 1 building. The requirement to adopt design for manufacture and design for de-construction principles have played a significant role in defining the extent of options reviewed within this paper. In this respect, an in-situ reinforced concrete frame has not been considered.

### Structural Frame

Three types of frame have been reviewed, steel simple beam and column, pre-cast concrete simple beam and column, and steel portal frame. A primary consideration in choosing the framing options to review has been the requirement to consider design for manufacture and design for de-construction. In this respect steel frame and precast concrete frame are considered. For the three-storey building system being considered, previous studies have indicated that the floor system (not the frame) is likely to form the dominant element of energy figures.

Energy results show that there is advantage in adopting a portal frame approach as it reduces steel frame quantities (Figure 21, see also Appendix A7). The inherent lateral stiffness of a portal frame also offers opportunity to stabilise the building, potentially omitting the requirement for braced cores. All values used for energy calculations are presented in Appendix A7, Table 2.

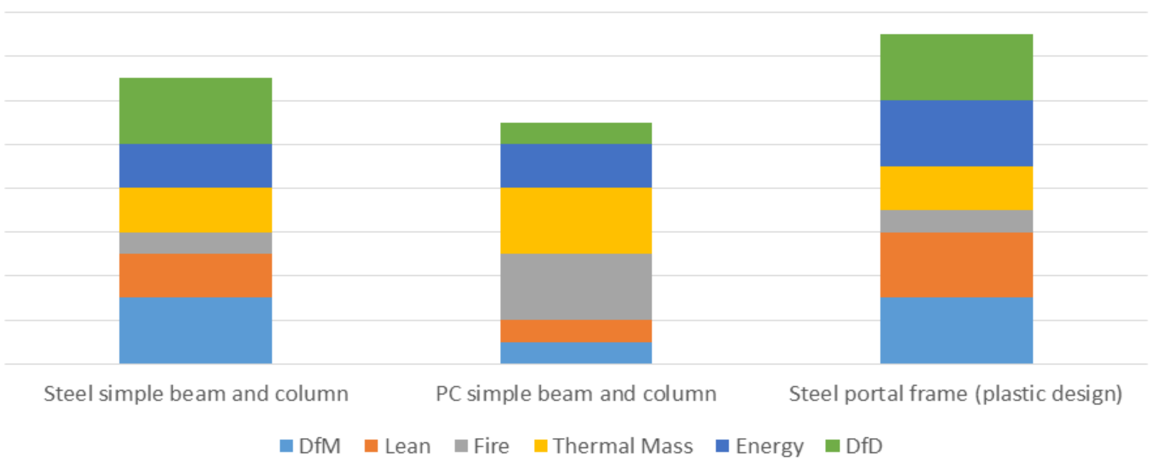


***Figure 21 Three types of frame considered.***

## Floor System

In deciding which floor system to use there were a number of assessment criteria that can be used from the client brief. These have been used in a simple scoring matrix to give an un-weighted assessment (see Figure 1 in Appendix A7). The assessment highlighted that a bespoke pre-stressed concrete floor plank would achieve most of the client brief requirements (Figure 22). With the extent of repetition of the structure at West Cambridge, developing a bespoke pre-stressed concrete floor unit makes sense. However, this approach would have to be reviewed against the requirement to competitively tender future phases of construction.

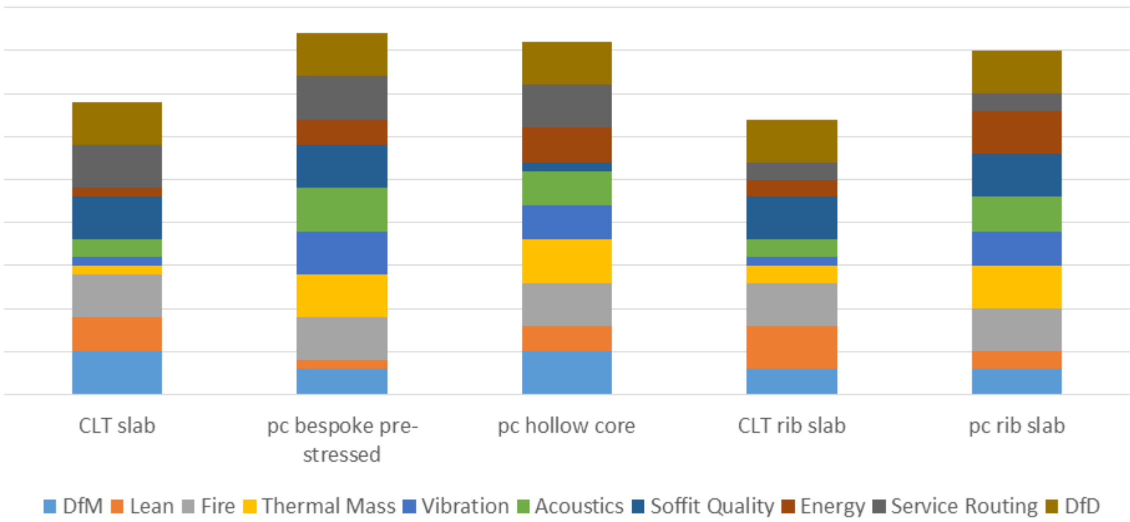


***Figure 22: Assessment of five different floor types.***

## Energy and Structural Engineering Materials

*Prepared by Petia Tzokova and Simon Smith, Smith & Wallwork Engineers*

For the first three options, a four-storey building was assumed with a 7.5m x 7.5m grid, supported on shallow foundations onto ground with an allowable bearing pressure of 150kN/m$^2$ and a 150mm thick reinforced concrete ground bearing slab. The fourth option was based on the outline structural design specification for the proposed UKCRIC building, the first phase of the Engineering Department's new campus on the West Cambridge site, issued by Smith and Wallwork in December 2015. The major difference between this option and the other 3 is the inclusion of a single storey basement and strong floor, which increases the material quantities per m$^2$ significantly.

A steel frame and cross laminated timber rib slab solution delivered a 16% increase in the energy figures compared to the steel and pre-stressed concrete solution. A concrete frame option delivered a 51% increase in the energy figures compared to the steel and pre-stressed (hollowcore) concrete solution (Figure 23). All energy assumptions are included in Appendix A8.

This study indicated that a steel frame and pre-stressed (hollowcore) plank structural scheme delivers the lowest energy option for a 4 storey building with a 7.5m column grid on shallow foundations.

Based on these considerations, it was agreed that the new Civil Engineering Building will comprise a steel frame supporting pre-cast concrete floor planks with a concrete raft foundation. The floor system is a bespoke pre-cast concrete plank. Plank bearings are bolted to steel beams and adjacent planks are bolted together.

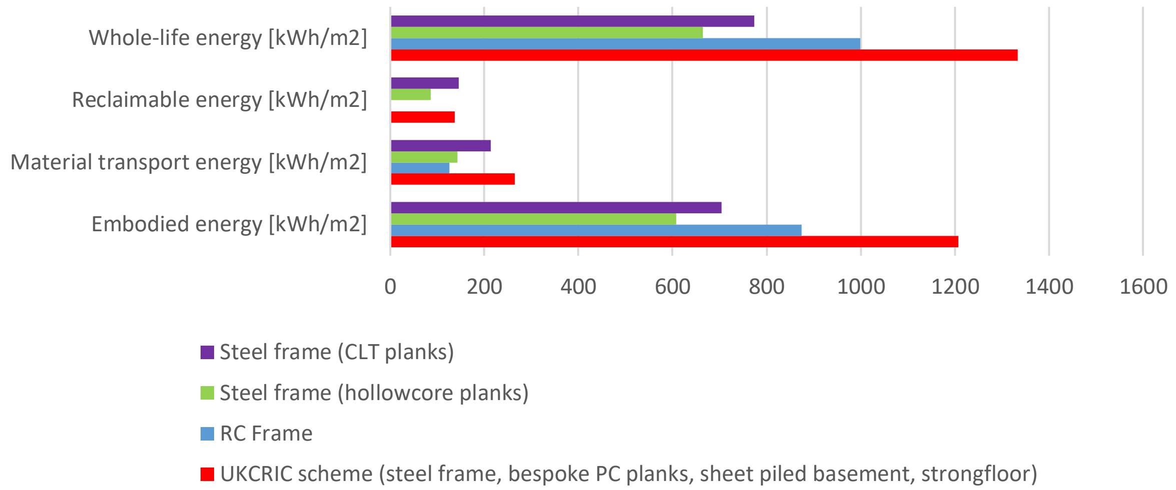


***Figure 23: Building Based Results (kWh/m²).***

## Design for Deconstruction

*Prepared by Katie Symons and Simon Smith, Smith & Wallwork Engineers*

The CUED brief for the new building included issues such as low whole life energy, design for manufacture, adaptability, embedded sensors and design for deconstruction (DfD) as well as visible engineering had to be considered. In addition to these brief requirements the design of the building must accommodate future extension, it forms the first element of a long linear building in the masterplan.

At the new Civil Engineering Building the adoption of DfD will allow both the steel frame and pre-cast concrete planks to be re-used. It has other potential benefits including the elimination of wet trades on site, it allows easier adaption of the building in the future and it gives more control over the quality of exposed concrete soffits (when compared to standard pc hollow core units). In developing a DfD pre-cast concrete floor system there is potential for an academic research paper, such a system does not yet exist, it would be a first.

The stage 3 design of the new Civil Engineering Building used approximately 270t of steel and 3800m$^2$ of 250mm thick bespoke precast planks. The embodied energy and transport energy of the stage 3 structure frame and floor system was found to be 3.2x10$^6$kWh and 0.8x10$^6$kWh respectively.

When comparing this design to an industry standard pc hollow core plank system and steel frame (assuming a 10% in steel tonnage due to lighter weight planks), the embodied energy and transport energy of the stage 3 structure frame and floor system was 2.1 x10$^6$kWh and 0.5 x10$^6$kWh respectively. This represents a saving of 1.4 x10$^6$kWh prior to any re-use scenario.

A range of re-use scenarios has been considered and is presented below.

- Option 1: Bespoke bolted pc planks & steel frame 100%/100% re-use of steel and concrete
- Option 2: Bespoke bolted pc planks & steel frame 80%/80% re-use of steel and concrete
- Option 3: PC hollow core planks & steel frame 35%/0% re-use of steel and concrete
- Option 4: PC hollow core planks & steel frame 0%/0% re-use of steel and concrete

The re-use potential for the stage 3 design with bespoke bolted planks ranged from option 1 - full re-use (i.e. 3.2 x106kWh) to option 2 - 80% steel frame and pc plank re-use (i.e. 2.5 x$10^6$kWh).

The re-use potential for the pc hollow core plank and steel frame ranged from option 3 - partial re-use of the steel frame (i.e. 0.5x$10^6$kWh) to option 4 - 0% re-use of the steel frame and planks (i.e. 0kWh). The pc hollow core plank option involves grouted and shear stud connected planks to beams and as such de-construction without damage is limited.

It was estimated that the total energy saving in adopting a DfD approached is likely to be in the region of 0.75x$10^6$kWh (i.e. option 2 vs option 3) (Figure 24).

Detailed calculations are included in the Appendix A9.

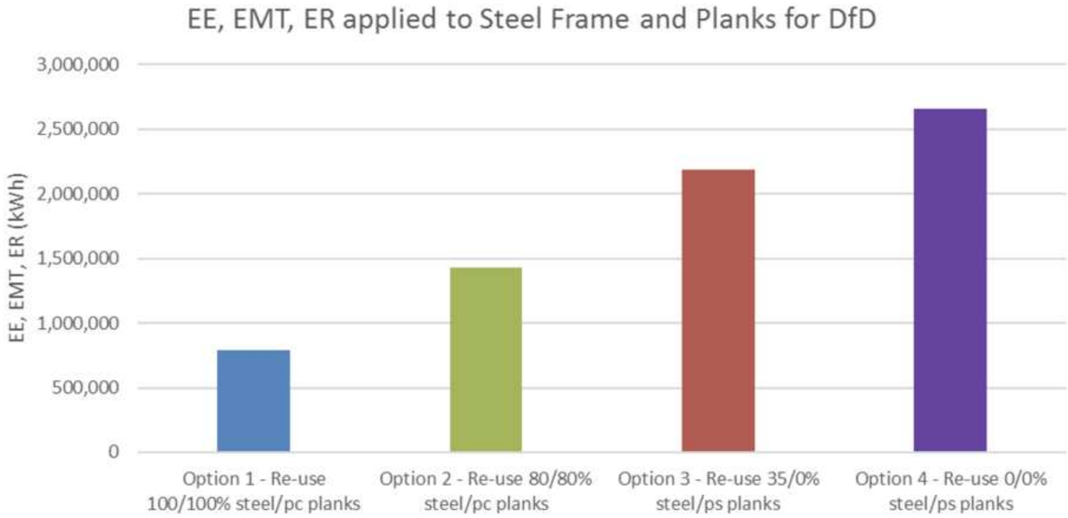


***Figure 24: DfD potential (kWh/m²).***

An ECM study had been carried out on compliant steel frame and precast floor planks and compared to an industry standard design of non-compliant steel frame and PC hollow core planks. Overall the DfD design was likely to save in the region of 750,000kWh of energy (Figure 24). However, the DfD design is likely to attract in the region of £300,000 additional construction cost when compared to an industry standard pre-cast hollow core solution (Appendix A9).

If energy cost of 25p/kWh is taken, the maximum premium fir DfD measures was in order of £33/$m^2$ or £125,000 construction cost to establish the lowest value of F (U, Eq. 1).

Using the energy cost metric it can be seen that an energy cost of 50p/kWh is required to ‘justify’ the DfD investment. It should be noted that the energy cost metric may not be the only consideration in the selection of the concrete floor plank solution. Other issues such as adaptability and soffit quality should also be considered.

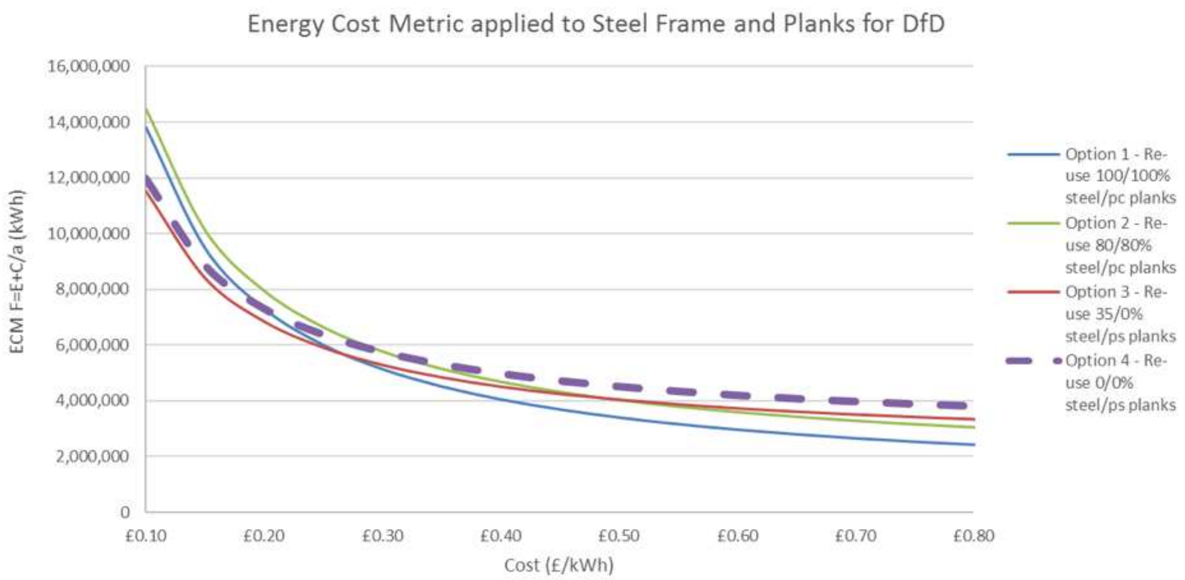


***Figure 25: Analysis of all for options has been undertaken for varying α values (10p/kWh to 80p/kWh).***

CHAPTER 5:
DISCUSSION AND CONCLUSION

The Civil Engineering Building is a two-stage design and build project undertaken in the context of finely tuned procedure developed over many years, as part of the University of Cambridge Technical Procedures Manual. In this project Grimshaw, Max Fordham and Smith & Wallwork were retained as part of the client team. The introduction of the ECM process added a further component to an already full process, but the impact was significant.

## Multi-stakeholder design guide

The greatest impact on design, both from initial and long tern cost as well as environmental impact (embodied carbon), can be found in a very early stage of design and decrease at subsequent stages of the project [64]  (Figure 26). The all effort should be therefore focused on the early stages decisions improving them during the project.

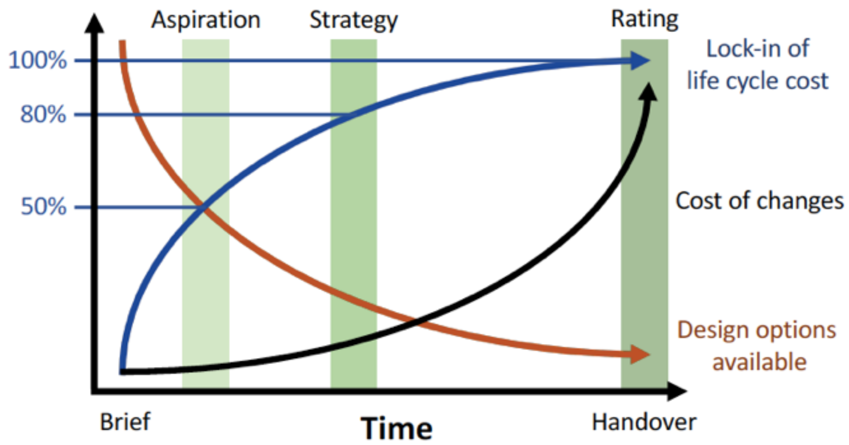


***Figure 26: Value gain (adapted from [64]).***

At the first Design Team meeting with the Contractor, the ECM was one of the first items on the agenda. The combined project team discussed how it could be used, what impact it would have on the design and the realisation dawned with the new team that for all the major components everyone will need to understand the energy performance statistics. The contractor soon got to grips with the metric and introduced a summary calculation with each “buildability” change element to show how the proposed change would impact on the current ECM assessment.

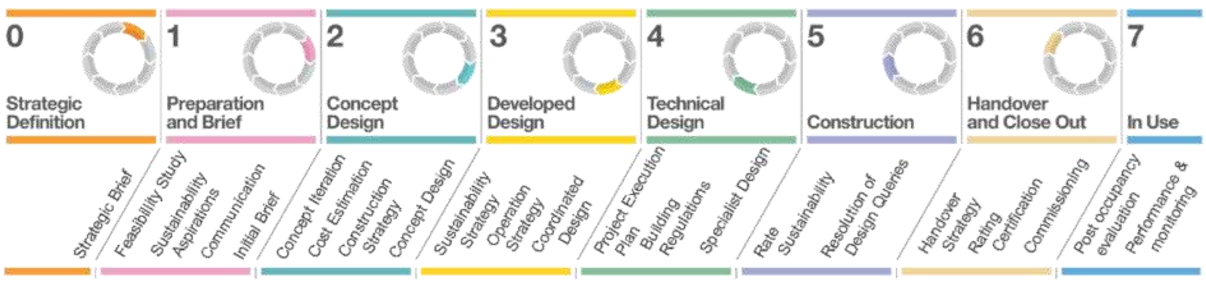


***Figure 27: RIBA 2013 work flow [24].***

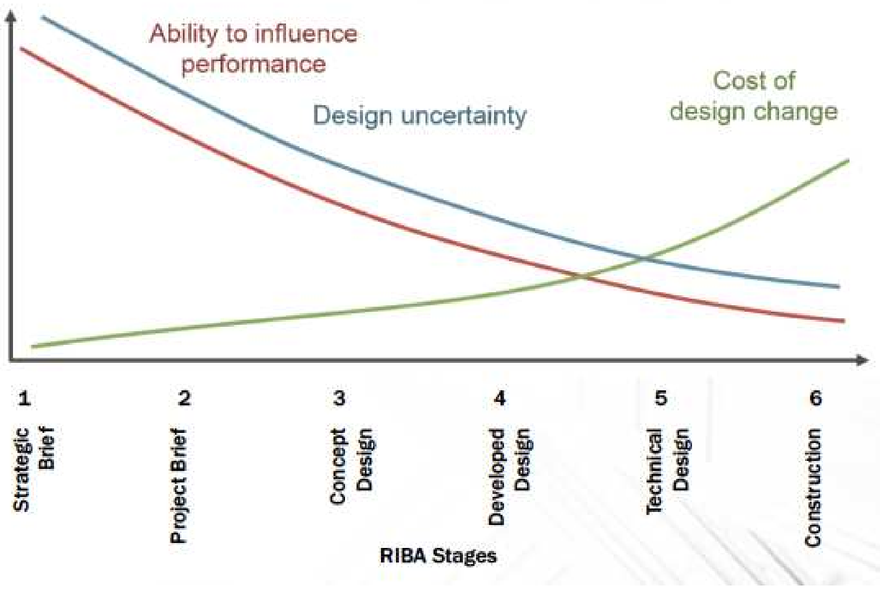


***Figure 28: Balance of ability to influence performance, design uncertainty and cost of design changes through the project life-cycle (reproduced from [65]).***

Highlighted in green (Figure 28) are the areas of relevance at each stage of the RIBA construction process (Figure 27). Compared to existing rating standards and tools, the ECM offers early stage assessments which guide the design process. Ongoing assessments are powerful to challenge new decisions in their overall impact for the project prior to their execution. This requires a collaborative approach in determining and discussing assessments at regular intervals during the project to lead to the desired effect.

## Collaborative approach in practice

Throughout the RIBA Stage 2 & 3 design process (Figure 27) the project team met regularly with both the User Project Team and the Energy Group. These meetings demonstrated the inevitable differences between separate parts of the Engineering Departments' emerging Design Brief and provided a challenge for the design team to balance these often conflicting pressures. The tendency for the User Project Team was to seek the maximum floor area for the available budget, whilst the preference of the Energy Group was to maximise energy performance opportunities in the design. Other energy group suggestions also presented challenges to the users. For example, users were uncomfortable with the concept of controlled power outlet "kill switches" (see Appendix A) which although had potential to reduce energy consumption, especially overnight, may adversely impact on the user's ability to confidently control the supply of energy to equipment used in overnight Engineering experiments.

Although this tension was evident across a number of subject areas, it reflected the breadth and multifaceted nature of the users brief in addition to the University's design standards. By specifically articulating these requirements separately in the respective meetings, the design team was clear about the potential impact of these positions and was able to act as facilitator to achieve beneficial outcomes for the different stakeholders of the project.

## Beyond numbers

The ECM provides an accurate estimate on the lowest-energy and -cost design option, excluding further design considerations such as aesthetics, stakeholder needs, and urban planning aspirations, unless indirectly accounted for in the design options themselves. On occasion, the most low-energy option led to unsustainable outcomes. In the case of the façade system, the lowest was not immediately chosen. Instead the top 6 or 12 options were selected to be reviewed against more subjective design criteria, to evaluate which would lead to the most sustainable outcome.

## Cost of innovation

This view beyond numbers is especially important when considering the cost of innovation in the construction industry, for example in the case of the building floor support structure: bespoke solutions, such as re-usable steel planks, measured against off-the-shelf, such as permanent concrete flooring, face a steep premium cost penalty. Even when factoring in their end-of-life contributions, the up-front premium cost supersedes future benefits resulting from reuse. Further adjusting the value of alpha would eventually tilt the balance, albeit at an order of magnitude greater than the set value of £0.25 in the design brief.

From this example, it can be seen that innovative solutions which have not yet benefitted from years of price optimisation, could be immediately excluded if no further thought is given to their assessment under the ECM tool. Suggestions are discussed under **Component Reuse** further on.

## Space optimisation

A key concern of the client was to maximise the space, here maximise the number of desks and seats for a fixed budget. Here the quality of the space was neglected, and minimum space requirements were applied. The maximum area per floor was set by the property, though number of floors and expansion options were set by the budget.

The ECM was used to evaluate different options, as space alterations impact cost as well as heating and cooling energy demands. It can therefore inform discussions between stakeholders with diverting views on the importance of maximising space; minimising energy consumption; ease of construction; and optimising future expansion possibilities for the building.

# CHAPTER 6:
# CIVIL ENGINEERING BUILDING IN WEST CAMBRIDGE

The following images show views of the proposed and finished CEB in West Cambridge. Post-occupancy studies to verify the effectiveness of the ECM method are in progress.

***Figure 29: Front view [66].***

***Figure 30: Front view [66].***

***Figure 31: Side  view [66].***

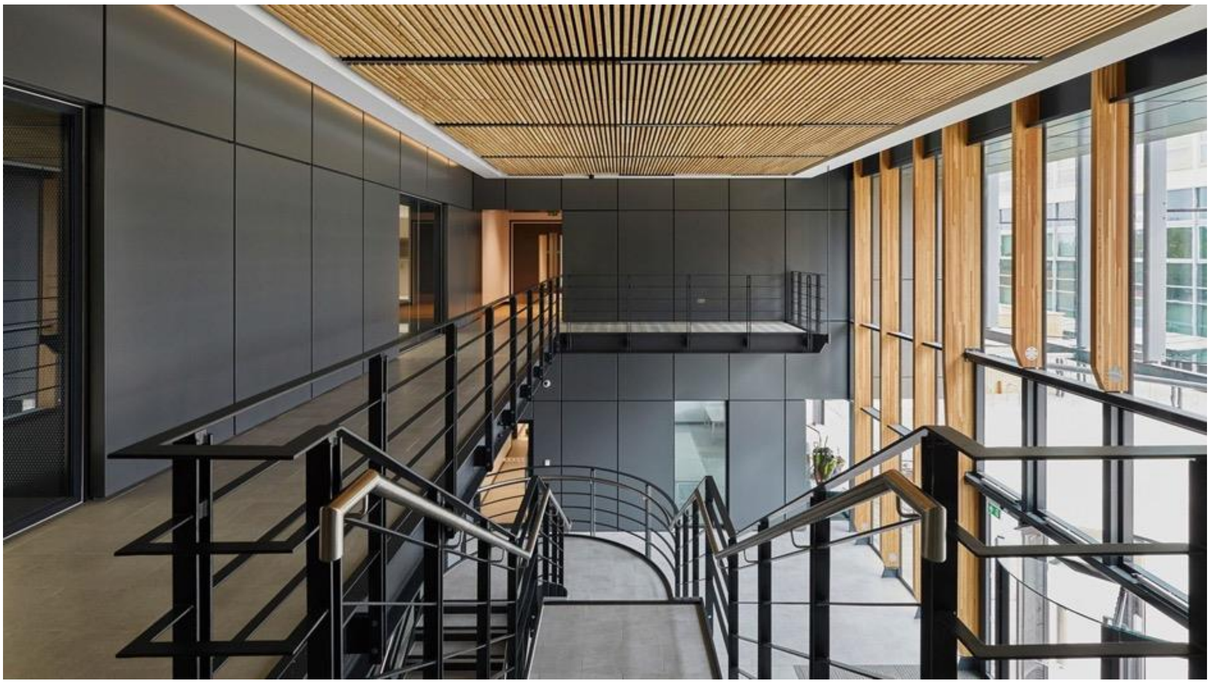

***Figure 32: Reception [66].***

# CHAPTER 7:
# FUTURE WORK AND FURTHER DEVELOPMENTS

## ECM validation

The Energy Cost Metric (ECM) was developed during the early design stages for the Civil Engineering Building and was used as a guide tool across each design stage. Based on the ECM methodology, embodied and operational energy was calculated and compared with the capital building cost. All assumptions used in the design process were accepted according to the best available knowledge, experience and using available data sources at that time (2015-2017).

Civil Engineering building was completed in June 2019 and occupied in July 2019. In 2020 ECM validation is planned against actual embodied and operational energy, and construction and operation costs. Analysing the post-constriction data will bring significant value for the commercial partners involved in the design and construction of the CEB, and for the University of Cambridge, who have adopted the ECM as part of their Environment and Energy guide for new University buildings. The results are planned for publication in the second part of this report at the end of 2020.

## Sourcing embodied energy data

The ECM relies on embodied energy data as part of the total energy contribution stemming from materials and construction products. During the application of the ECM for the design phase, sourcing an accurate value for the embodied energy has been one of the most challenging aspects.

Experts source this information through a mix of available channels, including the open Inventory of Carbon and Energy (ICE) dataset [67], proprietary database ecoinvent [68], or other, and Environmental Product Declarations (EPDs). Comparing different options with varying availability of data has pushed experts to fall back on the lowest common denominator to perform a “fair” comparison. This entails referencing embodied energy based on the material content, with a view that manufacturing and transportation only have a marginal contribution and if ignored for all options would lead to a fair evaluation. However, in cases where the manufacturing component is a significant contributor, for instance deciding on the added value between double (**EE value compared to just material contribution**) and triple glazed (**EE value compared to just material contribution**), the material content approach is misleading.

Typically, the construction product under consideration lacks a matching data record. An EPD for every construction product is still a remote reality and the process of generating a Life Cycle Assessment (LCA) is technically not feasible as the underlying information from manufacturers simply does not exist. Therefore, expert estimations continue to be a necessary tool for sourcing the embodied energy.

Future iterations of the ECM tool could feature a workflow to capture energy data points including descriptions of the underlying assumptions. Placing these on a common repository for the project or ECM community would greatly expedite the process of sourcing such information in future. Values could further be challenged and revised as new information becomes available.

## Streamlined not bespoke

The ECM is meant to be a streamlined, easy-to-use tool rather than tailor fit to specific construction projects. Simplicity and universality are especially important when enabling and comparing sustainable thinking across projects. Higher costs through bespoke tools could introduce additional barriers for adoption and gear outcomes into unwanted directions through a wrong focus or emphasis on certain aspects of the decision-making process. When expanding the tool, these design considerations should always be met.

## Subjective decisions

Initial examination of the ECM raised concerns about the nature of some of the factors contributing to the objective function. These were felt to fall into three categories:

- **Controllable factors:** There are parameters that the design team will have a good degree of control over through the design process.
- **Subjective factors:** These are parameters where either someone has to select a value to weight the credit from a particular contribution or where the predicted impact of a design is essentially a guess.
- **External factors:** These factors are out with the control of the design team either because the building is likely to have little impact on them or because they are essentially fixed parameters.

Looking more closely at subjective factors, these include:

- Pleasant environment for occupants (generous daylight and views out)
- Architectural impression (keeping an aspirational target for the overall design)
- Robustness and ease of maintenance
- Design for deconstruction
- Design for off-site manufacture

Subjective factors are not strictly speaking quantifiable by the ECM, yet are critical for the overall design of a building. These ensure that the building works well and is well liked by its occupants which is of critical importance to its true sustainability. This will ensure that the building is used and achieves if full design life.

Further development of the overall ECM tool would highlight this distinction and provide a structure to categorise factors into these groupings to support the decision workflow. Additionally, subjective factors would be captured through a weighting system and pulled into the overall ECM reporting on design decisions.

## Component reuse

Design for deconstruction and reuse is not common practice in the built environment, and off-the-shelf components which offer the most competitive pricing are designed for single use only. The ECM already includes an energy credit for embodied energy for components which will credibly be reclaimed when the building is disassembled. However, rebates for capital cost are currently being ignored, when considering components with reuse potential. This has a significant impact on the selection process of components using the ECM tool. Reusable components are typically subject to higher costs and only benefit from a scaled (0.5 or less) energy credit due to scrapping when a component is put to a new use for which it was not perfectly designed.

Future iterations of the ECM tool shall include a rebate on capital cost. The exact nature of the rebate needs to be investigated, as scarcity can drive up the value of reusable components over time, whereas changes in building practice and material preferences can render certain components inadmissible for reuse in the future.

# REFERENCES


1. *Civil Engineering Building, Estates Division, University of Cambridge* [cited 2020 19 February]; Available from: http://bit.ly/39OZFIH.
2. *Global Status Report 2019 - Towards a zero-emission, efficient, and resilient buildings and construction sector, Global Alliance for Building and Construction and International Energy Agency*. 2019, Global Alliance for Building and Construction, International Energy Agency.
3. *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015, Part two: Action taken by the Conference of the Parties at its twenty-first session*. 2016, United Nations, Framework Convention on Climate Change.
4. European Commission, *A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, in *COM(2018) 773*. 2018: Brussels.
5. *The Climate Change Act 2008 (2050 Target Amendment) Order 2019, No. 1056*. 2019, The UK Government.
6. Serrenho, A.C., et al., *The influence of UK emissions reduction targets on the emissions of the global steel industry.* Resources, Conservation and Recycling, 2016. **107**: p. 174-184.
7. Eastin, J., R. Grundmann, and A. Prakash, *The two limits debates: "Limits to Growth" and climate change.* Futures, 2011. **43**(1): p. 16-26.
8. Allwood, J.M., et al., *Sustainable materials: with both eyes open*. 2012: Citeseer.
9. *RICS professional standards and guidance: Whole life carbon assessment for the built environment, RICS*. 2017, RICS.
10. Geoffrey P. Hammond, C.I.J., *Embodied energy and carbon in construction materials.* Proceedings of the Institution of Civil Engineers 2008. **Energy 161**(May 2008 Issue EN2): p. 87–98.
11. Pullen, S.F., *Energy used in the Construction and Operation of Houses.* Architectural Science Review, 2000. **43**(2): p. 87-94.
12. *Evaluation of Embodied Energy and CO2eq for Building Construction (Annex 57) - Subtask 2: A Literature Review*. 2016, International Energy Agency, Institute for Building Environment and Energy Conservation: Tokyo.
13. Zimmermann, R.K., et al. *Categorizing Building certification systems according to the definition of sustainable building*. IOP Publishing.
14. *International Organization for Standardization - ISO*. [cited 2019 19 July]; Available from: www.iso.org.
15. *European Norms, Sustainability of Construction Works*. [cited 2019 19 July]; Available from: www.cen.eu.
16. Annunziata, E., M. Frey, and F. Rizzi, *Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe.* Energy, 2013. **57**: p. 125-133.
17. Samuel, D.G.L., S.M.S. Nagendra, and M.P. Maiya, *Passive alternatives to mechanical air conditioning of building: A review.* Building and Environment, 2013. **66**: p. 54-64.
18. van der Grijp, N., et al., *Demonstration projects of Nearly Zero Energy Buildings: Lessons from end-user experiences in Amsterdam, Helsingborg, and Lyon.* Energy Research & Social Science, 2019. **49**: p. 10-15.
19. Sartori, I. and A.G. Hestnes, *Energy use in the life cycle of conventional and low-energy buildings: A review article.* Energy and Buildings, 2007. **39**(3): p. 249-257.
20. Giordano, R., et al., *Embodied energy and operational energy assessment in the framework of nearly zero energy building and building energy rating.* Energy Procedia, 2015. **78**: p. 3204-3209.

21. De Wolf, C., F. Pomponi, and A. Moncaster, *Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice.* Energy and Buildings, 2017. **140**: p. 68-80.
22. Ding, G.K.C., *Sustainable construction—The role of environmental assessment tools.* Journal of Environmental Management, 2008. **86**(3): p. 451-464.
23. Siew, R.Y.J., *A review of corporate sustainability reporting tools (SRTs).* Journal of Environmental Management, 2015. **164**: p. 180-195.
24. RIBA, *RIBA Plan Of Work 2013*. 2013: London. p. 1-27.
25. *Net Zero Carbon Buildings: A Framework Definition*. 2019, UK GBC, Advancing Net Zero.
26. BSI, *BS EN 15978 - Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*. 2011, IBSI.
27. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* 2013, IPCC: United Kingdom and New York.
28. BSI, *BS EN 15804:2014 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products.* 2014.
29. *ISO 15686-1:2011 — Buildings and constructed assets — Service life planning — Part 1: General principles and framework*. 2011: BSi.
30. *NA to BS EN 1990: 2002+A1:2005 UK National Annex for Eurocode — Basis of structural design*. 2009: BSi.
31. *BS 7543:2015 Guide to durability of buildings and building elements, products and components*. 2015: BSi.
32. Symons, K., *CUED, Technical Report - Embodied Energy/Lean Design*. 2015, Smith and Wallwork Engineers.
33. Moynihan, M.C. and J.M. Allwood, *Utilization of structural steel in buildings.* Proc. R. Soc. A, 2014. **470**(2168): p. 20140170.
34. Dunant, C.F., et al., *Regularity and optimisation practice in steel structural frames in real design cases.* Resources, Conservation and Recycling, 2018. **134**: p. 294-302.
35. Orr, J.J., et al., *Concrete structures using fabric formwork.* Structural Engineer, 2011. **89**(9): p. 20-26.
36. *Low Carbon Construction. Innovation & Growth Team. Final Report*. 2010, HM Goverment, Department for Business Innovation and Skills. p. 231.
37. *Low Carbon Construction Action Plan: Government response to the Low Carbon Construction Innovation & Growth Team Report.* 2011, HM Goverment. p. 1-85.
38. *CEN/TC 350 - Sustainability of construction works*. [cited 2018 25 January]; Available from: http://bit.ly/2yfMMa0.
39. Moncaster, A.M., et al., *Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies.* Journal of Cleaner Production, 2019. **235**: p. 378-393.
40. *EPD Verifivation Scheme, BRE*. [cited 2020 15 January]; Available from: http://www.greenbooklive.com/search/scheme.jsp?id=260.
41. *EPD Programm, Institut Bauen und Umwelt e.V.* [cited 2020 15 January]; Available from: https://ibu-epd.com/epd-programm/.
42. *Embodied energy and carbon - The ICE database, Circular Ecology*. [cited 2019 10 August]; Available from: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.
43. RICS, *Methodology to calculate embodied carbon of materials - information paper*, in *RICS QS & Construction Standards IP32/2012*. 2012.
44. Ibn-Mohammed, T., et al., *Operational vs. embodied emissions in buildings—A review of current trends.* Energy and Buildings, 2013. **66**: p. 232-245.

45. RICS, *Professional Guidance, Global Methodology to calculate embodied carbon (1st edition)*. 2014, Royal Institution of Chartered Surveyors London.
46. UK GBC. *Tackling embodied carbon in buildings Report*. 2015; Available from: http://bit.ly/2urPQBJ.
47. Pomponi, F., A. Moncaster, and C. De Wolf, *Furthering embodied carbon assessment in practice: Results of an industry-academia collaborative research project.* Energy and Buildings, 2018. **167**: p. 177-186.
48. *Construction 2025: Industrial Strategy for Construction - Government and Industry in Partnership*. 2013, Department for Business, Innovation & Skills.
49. dcarbon8. *Case studies - footprint measurement and reduction*. 2007 [cited 2016]; Available from: http://bit.ly/39lkcnW.
50. Hammong G. and Jones C. *A BSRIA guide. Embodied Carbon. The Inventory of Carbon and Energy (ICE)*. 2011; Available from: http://bit.ly/2tQNAUe.
51. *EN 1990: Eurocode: Basis of Structural Design*. 2002, EC.
52. Nadoushani, Z.S.M. and A. Akbarnezhad, *Effects of structural system on the life cycle carbon footprint of buildings.* Energy and Buildings, 2015. **102**: p. 337-346.
53. Dimoudi, A. and C. Tompa, *Energy and environmental indicators related to construction of office buildings.* Resources, Conservation and Recycling, 2008. **53**(1): p. 86-95.
54. Luo, Z., L. Yang, and J. Liu, *Embodied carbon emissions of office building: a case study of China's 78 office buildings.* Building and Environment, 2016. **95**: p. 365-371.
55. Eleftheriadis S., et al., *Comparative numerical analysis for cost and embodied carbon optimisation of steel building structures.* Advances in Computational Design, 2018. **3**(4 Special Issue): p. 385-404.
56. *The Embodied Carbon Task Force, Embodied Carbon Industry Task Force Recommendations*. 2014; Available from: http://bit.ly/2vpcESs.
57. *One Click LCA*. [cited 2020 February 19]; Available from: https://www.oneclicklca.com.
58. *WRAP Embodied Carbon Database, UK GBC*. [cited 2020 February 16]; Available from: http://ecdb.wrap.org.uk.
59. *Embodied Carbon Benchmark Study - University of Washington*. [cited 2019 July 19]; Available from: www.carbonleadershipforum.org/projects/embodied-carbon-benchmark-study/.
60. Simonen, K., B.X. Rodriguez, and C. De Wolf, *Benchmarking the Embodied Carbon of Buildings.* Technology|Architecture + Design, 2017. **1**(2): p. 208-218.
61. *deQo - database of embodied Quantity outputs*. [cited 2020 19 February]; Available from: https://www.carbondeqo.com.
62. AECOM. *West Cambridge Site Masterplanning. Sustainability Strategy*. 2015 [cited 2016]; Available from: http://www.aecom.com/projects/north-west-cambridge/.
63. *The Carbon Plan - reducing greenhouse gas emissions. Department of Energy & Climate Change, HM Goverment*. 2011.
64. Bias, R.G. and D.J. Mayhew, *Cost-justifying Usability*. The Morgan Kaufmann Series in Interactive Technologies Series. 1994: Academic Press.
65. Hester J., Gregory J., and Kirchain R. *Guiding Early Building Design with Streamlined Life Cycle Analysis*. MIT Concrete Sustainability Hub, Massachusetts Institute of Technology, 2017.
66. *sdc - Civil Engineering Building* [cited 2020 19 February]; Available from: https://www.sdc.co.uk/portfolio/civil-engineering-building/.
67. *Embodied energy and carbon - The ICE database, Circular Ecology / Bath University*. 2019; V3.0 - 7 Nov 2019:[Available from: http://bit.ly/2HbJfOe.
68. *ecoinvent - life cycle inventory database*. [cited 2020 15 January]; Available from: https://www.ecoinvent.org.

APPENDICES

Appendix A1

# Energy Brief for Design of new Engineering Department Buildings in West Cambridge

by David MacKay

# Energy Brief for Design of new Engineering Department Buildings in West Cambridge

David MacKay

March 19, 2015 – **Rough Draft Number 2.0**

"Very-low-energy; pleasant; zero-bling; upgradeable; and well measured."

1. The building will be an exemplar low-energy building, minimizing the sum of
   - embodied energy,
   - measured energy in-use over the intended lifetime,
     - including the occupants' energy for transport,
   - minus an energy credit for embodied energy that will credibly be reclaimed (thanks to design for disassembly and reuse) when the building is disassembled.

   (subject to overall cost-effectiveness, as sketched below in Annex 1).
2. The building should be pleasant for its occupants, and should promote health and well-being.[1]
3. The design should be zero-bling. The energy solutions this exemplar building uses should be scaleable and widely useable. On-site energy generation should not be specially favoured over off-site generation.
4. The building will be designed for easy upgrade, extension, and modification.
5. All aspects of energy use should be measured – so that the low-energy credentials of the design can be confirmed; so that any problems with the building's performance are identified and fixed rapidly; and because a well-measured building is likely to engage its occupants in meter-reading, which affects behaviour and enhances energy-saving.
6. *[The design of the building should involve both engineers and architects.]* There should be a model of energy consumption at the heart of the design process with transparent assumptions, shared with the clients. The design process should be consultative and iterative, involving the representatives nominated by the Department, assisted by professional advisors dedicated to supporting the Department's objectives. The design process must have the buy-in not only of the building's users but also of the building's maintenance team.

**Comments:** this brief has not mentioned **carbon**; we do care about climate change and intend that the building be genuinely very-low-carbon; we judge the best way to achieve this objective without unintended consequences or accounting difficulties is to focus on energy minimization, and explicitly to advocate the decarbonization of the national energy supply. The government's 2011 Carbon Plan

[1] According to occupants of the EE building on the West Cambridge site, the current regulations that the University applies to its buildings do not guarantee comfort. There are issues to do with uncomfortable high temperatures in summer. We should also stipulate that the comfort of *equipment* should be maintained – for example, equipment that should be at 20±0.5C.

envisages that decarbonization would be achieved by (a) increasing electricity provision (to permit electrification of much of the heat and transport sectors); (b) decarbonizing electricity supply with nuclear power, carbon capture and storage, and renewables (especially wind power) at the required scale; and (c) using sustainable bioenergy for fuel-consuming sectors that are not easily electrified.

We give no special credit for **on-site generation of energy**, whether low-carbon or not. It is our expectation that it is always going to be most cost-effective for the *bulk* of a building's energy demand to be served from off-site, and it is therefore perverse to mandate on-site generation. Some on-site generation may be included in a cost-effective design, just like energy efficiency measures, on the grounds that it reduces the energy that will be imported in use. If a design includes on-site generation that sometimes exports excess electricity, these exports will earn a modest credit in our metric.

## Annex 1: The low-energy metric

1. It is anticipated that a well-optimized low-energy design will have the following features:
   (a) The building should have a **near-zero heating and cooling requirement**, thanks to the use of insulation; natural ventilation and perhaps (in winter) mechanical ventilation with heat recovery; and simple controls that are successfully used by real comfortable occupants.
   (b) The building's construction should use reclaimed materials (especially steel) and sustainably-sourced wood, and many of its components should be designed for disassembly and reuse.
   (c) The building should be lightweight – designed exactly to comply with the Eurocode standards, rather than unnecessarily exceeding those standards. The foundations should be designed and measured such that the building can be modified without costly or unnecessarily-material-intensive foundation work.
   (d) The "in-use energy" definition includes the occupants' transport energy, favouring thoughtful building designs that strongly promote:
      i. low-energy transport (eg. excellent cycle provision; convenient and effective wet-weather drying facilities; tight and attractive integration with public transport; and electric vehicle charging, especially for lightweight electric vehicles); and
      ii. alternatives to transport (eg, video-conferencing).
   (e) The building should not make use of natural gas as an energy source, or if it does, there should be a credible, low-cost plan for the natural gas supply to be eliminated within a few decades.
2. The low-energy metric should be optimized subject to explicit constraints on occupant comfort, which will be reviewed during the design process to confirm that the low-energy metric does not drive unwanted outcomes. These constraints might include:
   (a) provision of daylight at most or all working locations;
   (b) satisfying human thermal comfort constraints (add a reference to the best guidance);
   (c) floor-area constraints determined by the number of occupants.
3. The objective function $U$ to be used in design optimization decisions is the sum of two terms,

$$U = E + C/\alpha, \tag{1}$$

   where $E$ is the approximate total whole-life energy (in kWh or MJ), defined below, $C$ is the building cost, and $\alpha$ is a weight such as 25 p/kWh. (This weighting should be set by the University or by the Department's representatives: it quantifies the degree to which the University and Department value an energy-minimizing design, as specified in the top line of the brief.) [An absolute minimum justifiable value for $\alpha$ would be the average future expected retail price of energy to the University (eg 12.5 p/kWh or so); that might be appropriate if we did not care about sustainable resource use or climate change action; in fact, there is a missing carbon price in the global economy, and genuine carbon neutralization can be achieved only by measures that suck carbon back out of the atmosphere, and it could be argued that that cost should be factored into ethical decision-making; even without climate change, one could argue that society should put a higher price on energy, especially unsustainably-sourced energy. There are thus multiple justifications for setting $\alpha$ to a value such as 25 p/kWh or higher.]

4. $E$ is the sum of five parts:

$$E = E_E + E_{MT} + E_{IU} + E_T - E_R \tag{2}$$

**Embodied energy** $E_E$ – for simplicity this will be deliberately approximated; the approximation will be reviewed during the design to ensure it is not producing unintended consequences. With $m$ running over materials, $i_m$ denoting the energy intensity of the $m$th material (in MJ/kg or kWh/kg), and $m_m$ the mass of the $m$th material brought to site:

$$E_{EE} = \sum_m i_m m_m$$

The material list might be: glass, wood (possibly sub-categorized), aluminium, reclaimed steel, new steel, concrete, cement, brick, plastic, electronic device, other. Any item not well captured by the above list (for example a crystalline silicon solar panel) should be given individual treatment, if doing so would make a substantial difference to the optimization of the design. Note: Reclaimed materials should not be assigned zero energy intensity – attribution of the energy savings is arbitrary, but as a rough rule of thumb, to be reviewed during the design, we might let reclaimed materials have half the energy intensity of fresh ones.

[Let's roughly estimate how this will come out – How many tonnes of steel in a building? Plausible that it might be one tonne per person, like a car? 1000 kg /person * 1000 people * 6 kWh / kg * 3.6 MJ/kWh = 21.6e6 MJ. Express in kWh per day per person: 6000 kWh/(365.25 days/year * 50 years) = 0.33 kWh/d/p.]

**Material Transport Energy** $E_{MT}$ – Let $M$ be the total mass of materials brought to site. Let $m_0$ be the total mass removed from site (the sum of any discarded building materials and any other mass removed from the site during site preparation). Material transport energy $E_{MT} = \mu(M + m0)$, where $\mu$ might be set to 3.6 MJ/t-km $\times$ 200 km = 720 MJ/t. (The transport distance is set on the high side (200 km) to reflect the additional non-energy disbenefits associated with heavy goods vehicle movements.)

**In-use energy** $E_{IU}$ – Let $T$ be the intended life of the building (say 50 or 100 years).

The in-use energy is $T$ times the estimated actual total energy consumption rate, measured at the electricity meter and the gas meter. (The energy consumption of a small number of experimental facilities is excluded from this total, since it is outside the control of the building designers and constructors.)

The decision that electricity and natural gas are weighted equally, MJ for MJ (rather than up-weighting electricity), will be reviewed during the design to confirm that it produces no perverse consequences. If a design needs to make use of any other fuels, the Department's representatives should be consulted to confirm the weighting.

The actual annual energy use will be measured for the first $Y$ years (eg 4 years?) of occupation and the designers and constructors will be jointly incentivized (through a risk-sharing

| Local travel | |
|---|---|
| mode | $c_m$ (MJ/trip) |
| foot, cycle | 0 |
| car (local) | $16 \times 3.6 = 57.6$ (20 km in single-occupancy car at 80 kWh/100 km) |
| bus | 2*3.6 = 7.2 (20 km in bus at 10 kWh/100 p-km) |
| EV | 2*3.6 = 7.2 (20 km in EV at 10 kWh/100 p-km) |
| UEV | 0.5*3.6 = 1.8 (20 km in ultra-light electric-vehicle at 2.5 kWh/100 p-km) |

| Longer -distance travel | |
|---|---|
| mode | $c_m$ (MJ/trip) |
| carLD | 160*3.6 =576 (200 km in single-occupancy car at 80 kWh/100 km) (for national car trip (eg return to Bath or Birmingham)) |
| Rail | 16*3.6 =57.6 (400 km in train at 4 kWh/100 p-km) (for national rail trip (allowing for longer route thanks to silly rail network)) |
| Flight | 12000*3.6 = 43200 (LA return by plane, assumed full) |

arrangement) to ensure that the actual energy use, post-commissioning, is consistent with their projections.

**Occupants' energy for transport** $E_T$ – The design should be accompanied by a reasoned description of the predicted transport footprint of the occupants and visitors to the building, including number of car journeys, number of bus journeys, number of foot journeys, number of electric-vehicle journeys, and number of rail and air journeys per year. Typically the energy footprint associated with transport will be much larger than the embodied energy and in-use energy of the building, so we strongly favour building designs that promote low total transport energy. This simple model will be used (with $T$ = an intended building lifetime, eg 50, 100, or 200 years – the duration of impact of the design choices made today):

$$E_T = T\left(\sum_m N_m c_m\right)$$

where $N_m$ is the rate of return trips of mode $m$, and $c_m$ is an energy cost per trip. We would hope for a design that favours some switches of local travel from car to bus or bicycle, possibly some switches of longer distance travel from car to train (through excellent interconnection to public transport), and switches of long-distance travel to videoconferencing.

Example approximate energy costs are as follows:

Provision of excellent attractive and convenient videoconferencing facilities could be deemed to perhaps reduce all long distance journeys by 50%. If $T = 50$ years and there are $N = 1000$ people in the building each taking one flight per year, then the energy benefit of videoconferencing according to this crude model, from flight reductions alone, could be 2.2e9 MJ (6e8 kWh). Similarly, excellent integration with an attractive bus service might be deemed to switch 100 individuals from car to bus for 200 days per year, saving 200*50*(14*3.6)*100 = 0.05e9 MJ.

**Reclaimable energy thanks to design for disassembly and reuse** $E_R$ – Energy credit will be given where there is a credible account of reuseability of components such as steel beams. The credit will be scaled down by [0.5], or perhaps more to allow for the material inefficiency of reuse, that is, the scrapping [virtual or actual] that is likely when a component is put to a new use for which it was not perfectly designed.

5. For avoidance of doubt, there is no credit for on-site generation of energy, nor for energy efficiency measures. Such measures are already incentivised by our metric's emphasis of energy-use by the building. If a design has on-site generation that will sometimes export electricity from the building, these exports must be scaleable in the sense that there must be a credible nearby demand for that electricity at the time the excess electricity is generated (for example, an air-conditioning load in a nearby building); subject to this constraint, such net electricity exports from the building will be credited in our metric at a rate of (say) $\beta = 5\,\mathrm{p/kWh}$.

6. Four trivial alternative ways of defining the objective $U$ (1), which may be useful in certain contexts, are: the energy-weighted cost

$$C_U \equiv \alpha U = C + \alpha E;$$

the energy-weighted cost per person per year,

$$c_U \equiv C_U/(NT),$$

where $N$ is the average effective number of building occupants (for example, the number of employees) and $T$ is lifespan of the building (for example $T = 50$ years); the cost-weighted power per person (which might be measured in kWh per day per person),

$$p_U \equiv U/(NT);$$

and the cost-weighted power per unit area, (which might be measured in kWh per m$^2$ per year or in W/m$^2$),

$$p_{UA} \equiv U/(NTA),$$

where $A$ is the floor area of the building.

In the next draft of this note I will spell out a few examples of how these alternative metrics might be useful for different aspects of the design.

## Annex 2: Questions and Answers

***Won't the uncertainties of some of the quantities in the objective function U be enormous?***

Yes, but that is not a reason for ignoring them! Good decision making should take into account all the uncertainties.

***Won't the uncertainties of some of the quantities in the objective function U be bigger than the size of potential design effects?***

Yes, but that doesn't matter. If a design change definitely reduces the total $U$ by a material amount, then it doesn't matter that $U$ itself is uncertain. If on the other hand it is highly uncertain what the effect of a design change is on $U$, then that would justify careful further thought and analysis.

***Won't the evaluation and optimization of this objective slow down the design process, which needs to be fast?***

The building, and the consequences of its design decisions, are going to last for 100 years. **The objective of making a genuinely low-energy building is important, and the design process must if necessary be constrained to proceed at a pace consistent with achieving this objective.**

***Transport is a major part of $U$, but it isn't something that the designers can change.***

We disagree.

1. The designers can think hard about how to design the building such that public transport, cycling, and walking are attractive to the building's users. For example, how about a design for the new Physics and Engineering buildings in West Cambridge in which elevated walkways and cycleways provide attractive routes to avoid road-crossings? How about planning a building design that integrates with a an elevated cycleway over Madingley Road? Such a design would change the transport decisions of a person who would otherwise say "I don't like crossing Madingley Road by bike – it's so busy and the traffic lights take for ever".

2. The designers can focus attention on providing videoconferencing facilities that are so user-friendly that people will videoconference instead of travel. Not only are the potential energy savings large, the potential financial savings to the University are enormous – if every researcher takes one less flight per year then the financial savings over 50 years are similar to the entire cost of the building! These genuine financial savings could be spent on the University's goals of teaching and research.

3. The designers can pay attention to the provision of parking and charging for lightweight electric vehicles.

***The draft energy brief sets out areas in which the whole life cost should be incorporated into the build cost. This is logical but doesnt fit into the standard budgeting of construction?***

Yes. Certain chosen elements will indeed be more expensive than "normal" solutions. It has been suggested to us that when the project gets underway an additional detailed budget needs to be clearly set out and ring-fenced to cover the costs of the expensive elements.

**Acknowledgements**

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**Notes**

Target: 15 kWh/m$^2$ /year for heating. 1 kWh/day/person for all energy? too small... Assume 15m$^2$ per person, then (1/15) kWh/d/m$^2$ $\longrightarrow$ 24 kWh/m$^2$ /year.

Target: 1 kWh/d/p embodied energy, 1.5 kWh/d/p use (heating, lighting, computers).... target roughly 2 kWh/d/p for those.

Check: If the building cost ends up being $C$ = 100 M pounds then $C/\alpha/N/Y = 100\,\mathrm{M}$ pounds / ( 0.24 pounds per kWh ) / 1000 people / (50 $\times$ 365 d) = 23 kWh/d/p.

$C = 100\,\mathrm{M}$ pounds could also be thought of as (100 k pounds per person; 2k pounds per person per year – similar to the potential avoided cost of the air travel!)

Should we include an explicit financial opex too? Perhaps so, because we could justify the cost of an extra member of staff whose role is to run around fixing things, checking, etc. Could even justify them being on the payroll of the constructor and builder?

Should we allow the design to be influenced by any government incentives such as feed in tariffs or renewable heat incentive? I'd like a methodology that leads to long-term rational buildings. It could be argued that it is rational to exploit incentives. But we know what this leads to – it leads to a school in Impington carefully NOT insulating their leaky structure, but instead installing a biomass boiler, to maximize the subsidy cash they receive. So I'd say that the objective should take into account running costs but not government incentives.

Appendix A2

# Façades and HVAC systems

prepared by Katie Doig and Joel Gustafsson, Max Fordham

MAX FORDHAM

# ECM – FAÇADE AND HVAC OPTIONS

Rev A - 21/03/2016

The façade and HVAC systems are interlinked in terms of their cost effective performance efficiency. As such the combinations need to be examined in conjunction with each other. This is achieved by considering the contribution to the objective *F* for each of the Façade and HVAC combinations under consideration. In terms of cost this assessment needs to take into account the annualized cost of the façade and HVAC systems and in energy terms the material energy of the façade ($E_M$) and the in-use energy ($E_{IU}$) associated with each commination needs to be considered.

## 1 Façade Options

The selection of a suitable façade option for the UKCRIC building takes a range of criteria into consideration, energy performance is a key driver. The different façade options will have different embodied energies and in-use energies associated with them. The façade options that have been compared under the ECM are presented in Table 1 along with their performance parameters, annualized material energy and annualized costs. To aid comparison the annualized material energy and cost are also presented in Figure 1.

| Façade Type | | Area Weighted U-Value *W/(m²K)* | Air Tightness *m³/(m²h) at 50Pa* | $E_M$ *MWh/yr* | Cost *£/yr* |
|---|---|---|---|---|---|
| Masonry With Punched Hole Windows | *M* | 0.65 | 5 | 13 | 25,597 |
| Composite Wall System With Strip Windows | *C* | 0.95 | 4 | 13 | 54,722 |
| Rainscreen System (Proprietary) | *R(P)* | 0.95 | 3 | 8 | 25,166 |
| Rainscreen System (Bespoke) | *R(B)* | 0.65 | 3 | 8 | 28,323 |
| Double Glazed Aluminium Mullion Stick Curtain Wall | *CW(DG)AM* | 0.95 | 2 | 19 | 45,423 |
| Double Glazed Steel Mullion Stick Curtain Wall | *CW(DG)SM* | 0.95 | 2 | 13 | 45,423 |
| Double Glazed Timber Mullion Stick Curtain Wall | *CW(DG)TM* | 0.95 | 2 | 11 | 45,423 |
| Triple Glazed Aluminium Mullion Stick Curtain Wall | *CW(TG)AM* | 0.55 | 2 | 26 | 61,455 |
| Triple Glazed Aluminium Mullion Unitised Curtain Wall | *UCW(TG)AM* | 0.75 | 1 | 26 | 76,685 |
| Triple Glazed Steel Mullion Stick Curtain Wall Systems | *CW(TG)SM* | 0.55 | 2 | 21 | 61,455 |
| Triple Glazed Timber Mullion Stick Curtain Wall | *CW(TG)TM* | 0.55 | 2 | 18 | 61,455 |

**Table 1** Summary of Façade options under consideration for UKCRIC.

**Performance Parameters**

For each of these options the two performance parameters are outlined; their thermal conductivity (U-value) and the air tightness. The values that have been assigned were advised by the façade consultant, Montresor Partnership. These performance parameters have been used to determine the in-use energy associated with each façade and HVAC combination. The process by which the in-use energy was extracted from these is discussed in Section 0.

**Embodied Energy**

The annualized material energy for each façade option is also presented. The material energy is defined by:

$$E_M = E_E + E_{MT} - E_R$$

where $E_E$ is the embodied energy, $E_{MT}$ is the energy associated with transporting materials to and from the site and $E_R$ is the energy that can be reclaimed at the point of deconstruction. The annualized material energy takes into account the required replacement cycle of the different components making up each façade options. The annualized embodied energy was evaluated by Smith and Wallwork in conjunction Grimshaw and advice on component lifetime was provided by Montresor partnerships. Further details on the material energy analysis undertaken can be found in the architectural design section of the Stage 2 report.

**Cost**

The annualized cost has been examined over the same component and lifetime break down as the embodied energy. The cost presented are project costs and the rates were provided by AECOM Quantity Surveyors.

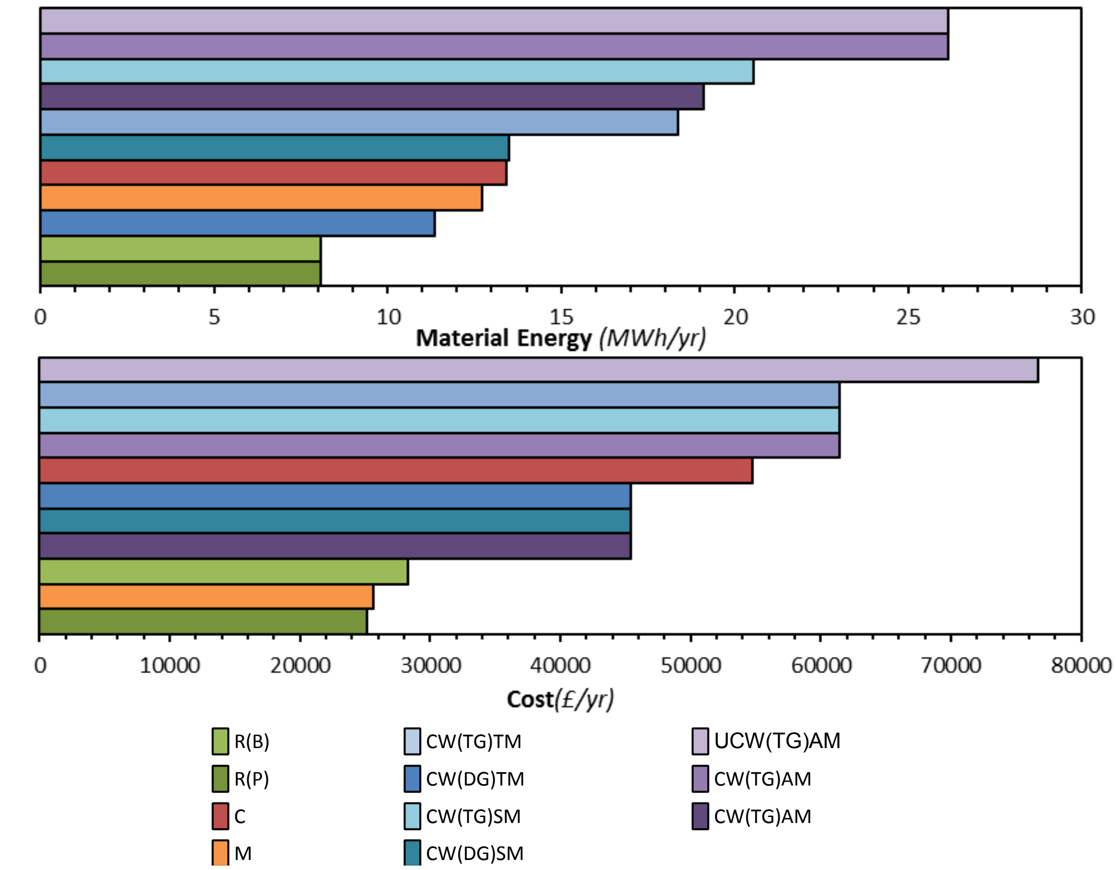



**Figure 1** Annualized Material energy and Cost for the proposed facade options.

## 2 HVAC Options

There are a range of HVAC systems with different performance parameters and costs under consideration for UKCRIC; these are outlined in the table below.

| HVAC Type | | Heating efficiency (COP) | Cooling efficiency (EER) | Transfer efficiency (COP/EER) | Cost *(£/yr)* |
|---|---|---|---|---|---|
| Ground source heat pump with heat recovery | (GSHP+r) | 5.1 | 6 | 4.66/3.66 | 42,000 |
| Air Source Heat Pump | (ASHP) | 3.3 | 3.54 | 4.15/4.15 | 34,000 |
| Boiler-VRF | (B-V) | 0.9 | 6.5 | -/- | 20,000 |
| Boiler-Chiller | (B-C) | 0.9 | 5 | -/- | 26,800 |
| Boiler-Chiller with Heat Recovery | (B-C+r) | 0.9 | 3.5 | 4.15/- | 30,000 |

**Table 2** Summary of HVAC options under consideration for UKCRIC.

All HVAC options have been appraised over 25 year plant life and a 50 year lifetime for auxiliary components. The auxiliary components consist of everything associated with the HVAC system that is not the plant itself, for example, the GSHP ground array, pipe work etc. The cost presented are project costs provided by AECOM.

## 3 In-Use Energy

The aspect of the in-use energy that is affected by both the façade and HVAC performance is the required heating and cooling load. The heating and cooling requirements for a range of façade performances were determined using a dynamic thermal model (IES – Virtual Environment). Further details on how the heating and cooling loads were determined can be found in the *"ECM - In-Use Energy and Thermal Model"* report. The raw heating and cooling demand loads for each façade option can be seen in Figure 2. The parameters corresponding to the specific façade options under consideration have been highlighted. As the advised thermal properties for each of the double and triple glazed stick curtain wall options are the same these options have the same heating and cooling loads shown for the Aluminium mullion options.

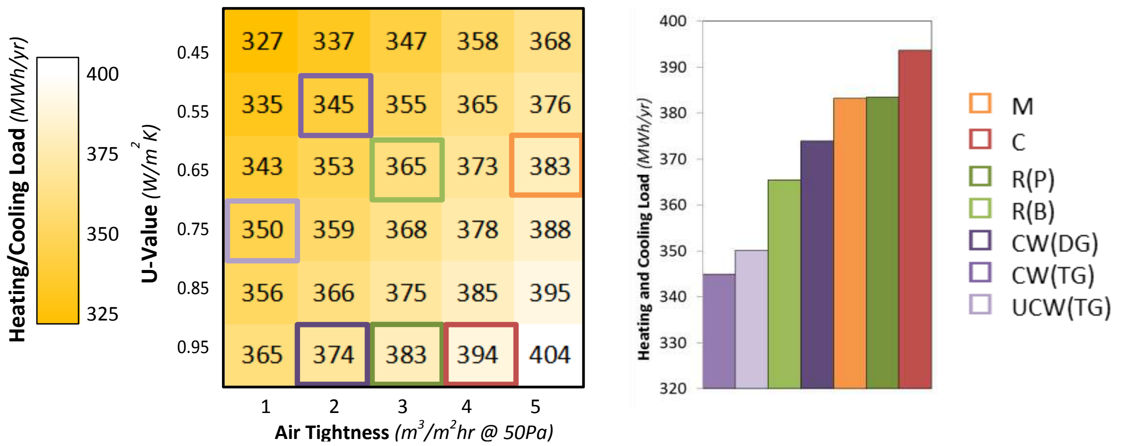



**Figure 2** Heating and cooling loads predicted by a dynamic thermal model for a range of U-values and Air tightness.

It can be seen that improving the air tightness and U-values reduces in the annual heating and cooling requirement.

To extract the in-use energy from the raw heating and cooling loads the HVAC performance parameters outlined in Table 2 were applied to the heating and cooling loads. For the options including heat transfer the available transfer load was determined from the hourly thermal output of the dynamic thermal model.

## 4 Energy Contribution

The in-use energy associated with façade option and the HVAC system are intrinsically linked. This is because the façade will alter the demand while the HVAC system will determine the efficiency with which this demand is met.

The annualised in-use ($E_{IU}$) and material energy ($E_M$) that arise from the different HVAC and façade option comninations are presented together in Figure 3. The colouring of the two components has been used to highlight the Façade-HVAC combination; $E_{IU}$ indicates the HVAC system and $E_M$ indicates the facade type. The HVAC systems with heat pumps have a significant reduction in in-use energy in comparison to those with heating being supplied by a boiler. A notable consequence of this is that for the more efficient HVAC systems (the two heat pump options) the choice of façade has a smaller impact on the in-use energy. Given the embodied energy for each façade type does not change with the HVAC system, the embodied energy becomes slightly more critical for these options. For the lower efficiency HVAC systems the façade performance is the dominant factor in the energy ranking. This demonstrates the link between the energy savings generated by HVAC efficiency and façade performance.

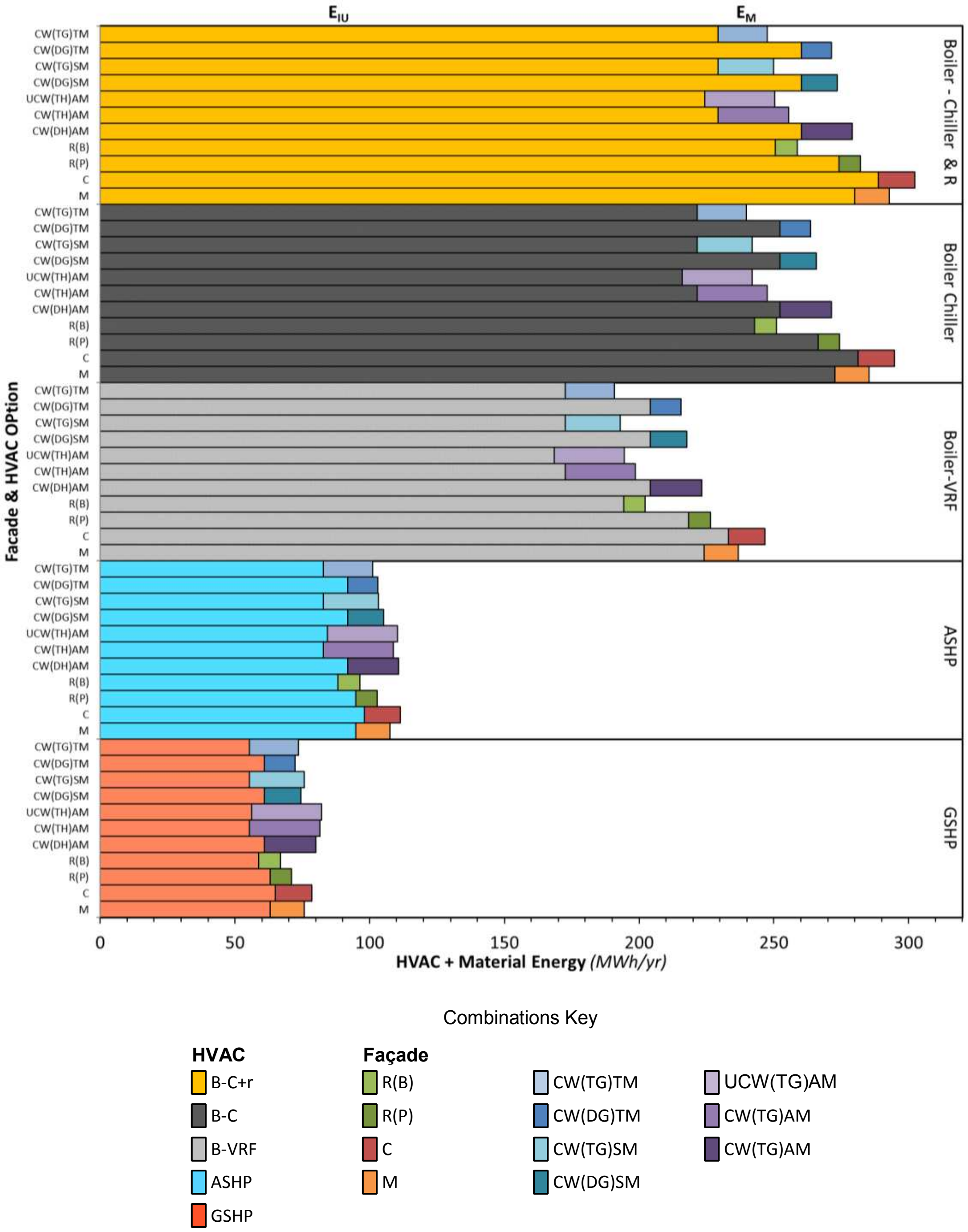



**Figure 3** In-use and embodied energy for the different façade and HVAC option combinations.

## 5 Cost Contribution

The annualised project cost for each of the different façade and HVAC option combinations are presented in Figure 4. The colouring of the two components has been used to highlight the Façade-HVAC combination; The HVAC cost indicates the HVAC system and façade indicates the façade type. Comparing the cost with the total energy cases shown in Figure 3 it can be seen that while there is a degree of correlation between in-use energy and HVAC cost, there is not a straightforward relationship between facade cost and energy. This reflects the fact that optimisation in HVAC systems is specifically targeted towards improving efficiency, while façade design takes into consideration a wide range of factors, only one of which is energy performance.

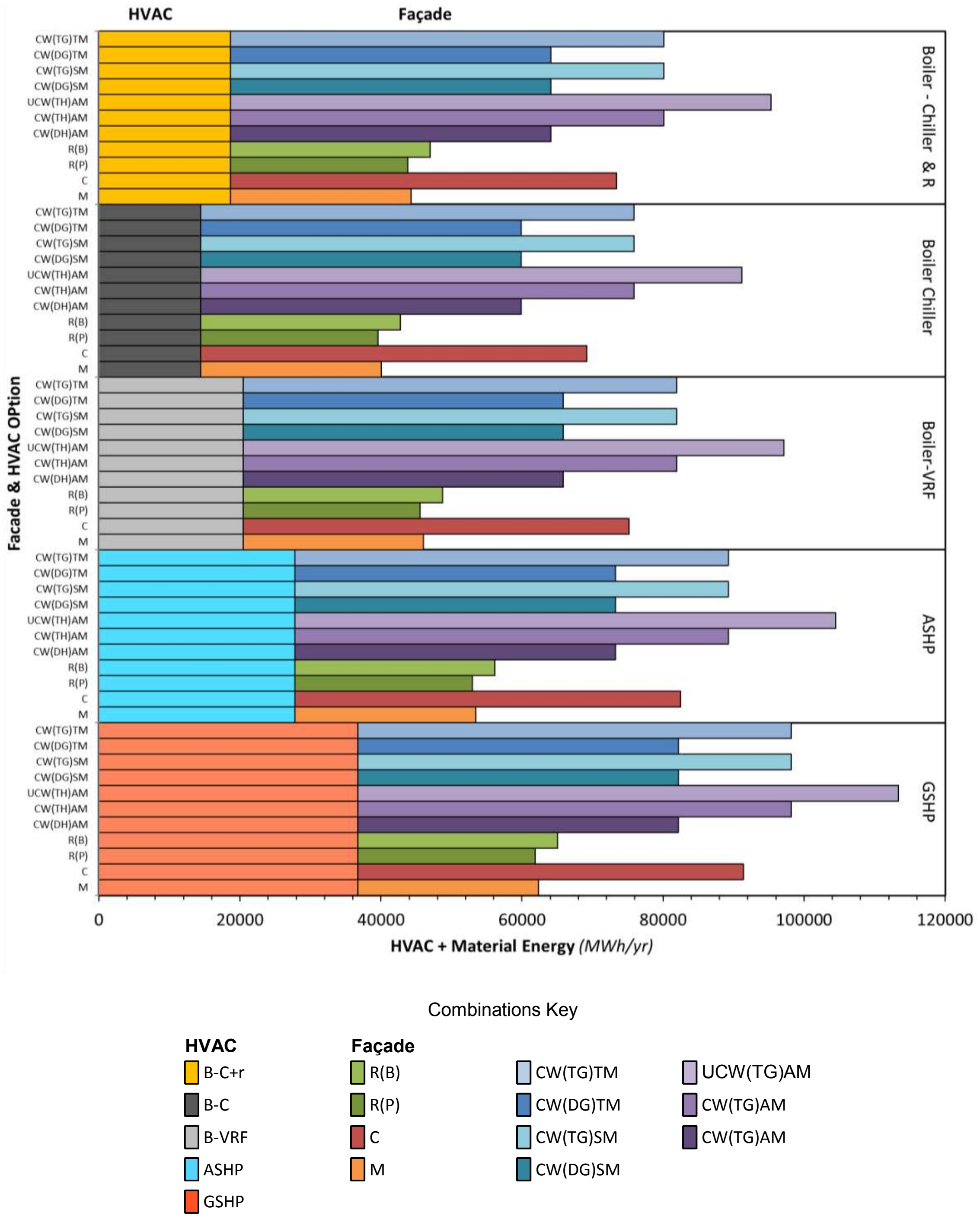



**Figure 4** Annualised cost for the different façade and HVAC option combinations.

## 6 Combined Contribution to *F*

The energy and cost data presented in Figure 3 and Figure 4 respectively has been used to determine the contribution to *F* for each of the option combination across a range of values of $\alpha$. Given that the facade and HVAC performance are intrinsically linked, this approach, where both are examined simultaneously is particularly beneficial. The resulting contributions to *F* are presented in Figure 5. This allows the options with the lowest contribution to F for a given α to be easily distinguished.

It can be seen that the combinations contributing the least to the objective function vary depending on the specific value of α. In general, the best performing HVAC options are those with either air source heat pump at lower $\alpha$ or ground source heat pump with heat recovery at medium to higher $\alpha$ and for the Façade the best performing options are the rainscreen options at lower α, the double glazed curtain wall options are viable contenders at medium to higher $\alpha$.

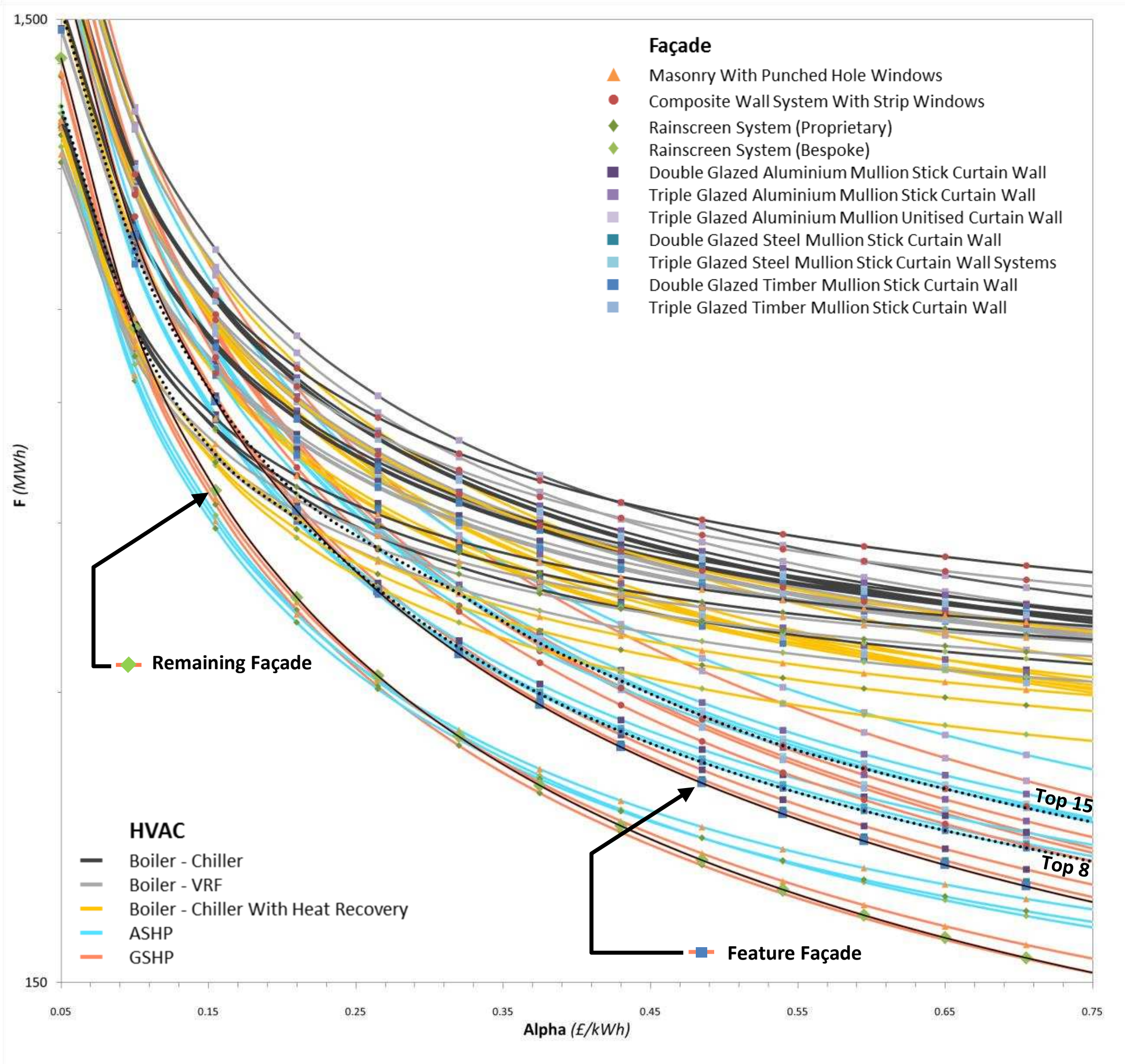



**Figure 5** The objective function, F, for all of the façade and HVAC combinations under consideration. The line colour indicates the HVAC option while the markers indicate the façade option. The dotted black lines indicate the top 8 and 15 viable options and the two proposed façade-HVAC options are indicated and highlighted by solid black lines.

To highlight how the value of $\alpha$ effects the ranking of different options and the relative importance of cost versus energy Figure 6 shows the contribution to the objective function, $F$, at discrete values of $\alpha$ of 15, 25, 35 and 50 p/kWh along with a cost and energy only ranking. In the graphs showing the ranking of the $F$ for discrete values of $\alpha$, for each scenario the lower bar highlights the energy contribution, $E$, while the upper bar shows the contribution from $C/\alpha$. In the cost ranking case the lower bar is the cost associated with the HVAC and the upper bar the cost associated with the façade while in the energy ranking case the lower bar is the in-use energy and the upper bar is the material energy associated with each combination. In all cases the colour highlighting for the lower bar follows that set out in Table 1 to indicate the façade option while the highlighting for the upper bar follows that set out in Table 2 to indicate the HVAC option.

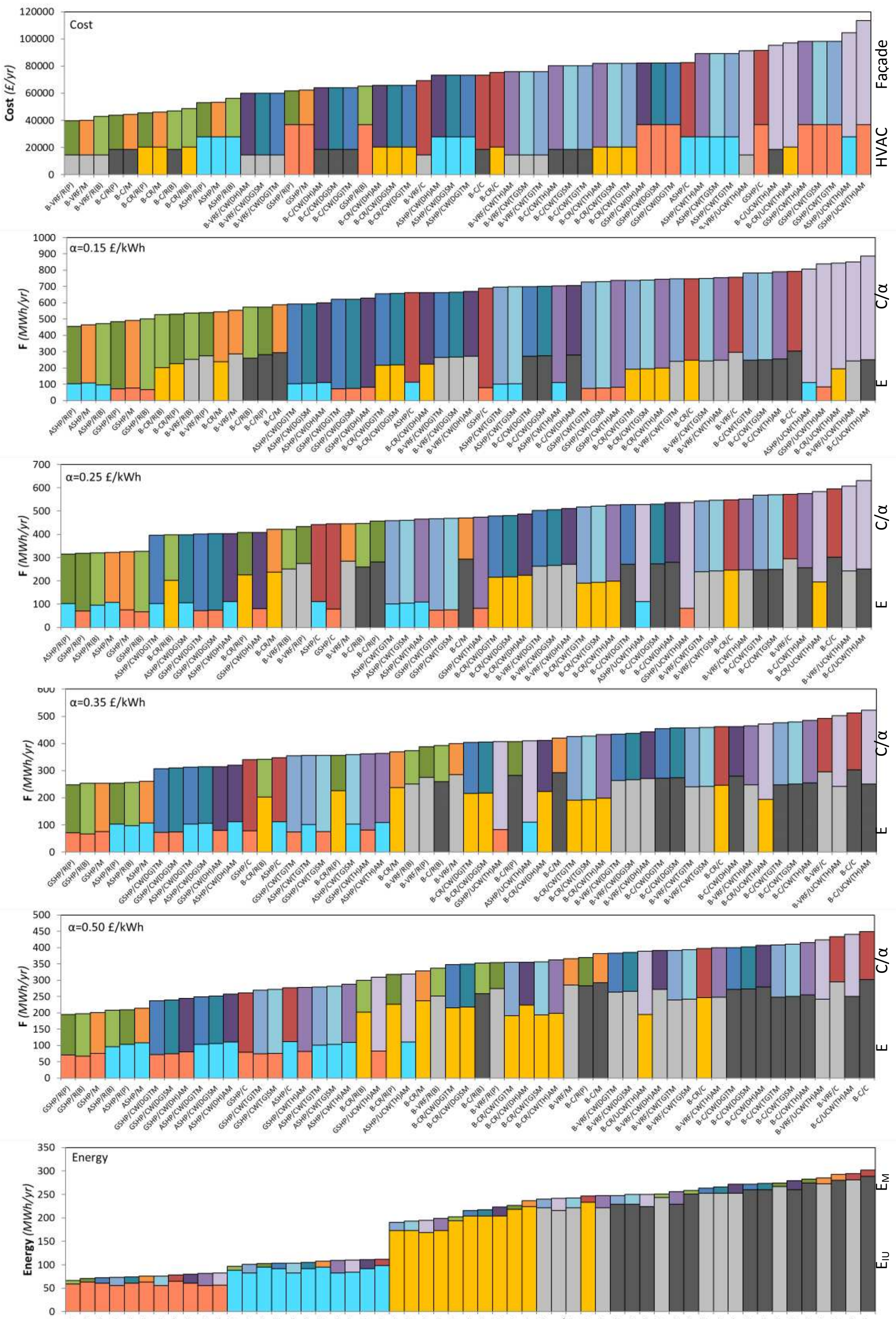



**Figure 6** Ranking of the annualised cost, contribution to the objective function, *F*, for the different façade and HVAC options combinations for discrete values of *α* (α=15, 25, 35 and 50 p/kWh) and energy. In call cases the colour highlighting for the lower bar follows that set out in **Table 1** to indicate the façade option while the highlighting for the upper bar follows that set out in **Table 2** to indicate the HVAC option. The graph labelled "Cost" shows the ranking for the annualised cost, where the lower bar is the cost associated with the HVAC and the upper bar the cost associated with the façade. For the contribution to alpha cross-sections labelled with their discrete value of *α* the lower bar is the energy contribution (*E*) while the upper bar shows the contribution from *C/ α*. The graph labelled "Energy" shows the ranking for the annualised energy, where the lower bar is the in-use energy and the upper bar is the embodied energy of the façade option.

A number of conclusions can be drawn from these sets of data:

- The cost ranking is driven by the façade cost.
- Façade is the dominant contributor to cost.
- The energy ranking is driven by the efficiency of the HVAC system
- Efficiency of the HVAC system drives the energy ranking.
- At low values of $\alpha$ the cost term ($C/\alpha$) is the dominant contributor to the objective function F. This can be seen by comparing the cost ranking with the ranking for $\alpha$=0.15£/kWh, where it can be seen that the ranking is not significantly altered.

## 7 Proposed Options

The conclusion of the energy group discussions is that any of the viable options ranked in the top 8 are agreeable and those within the top 15 may warrant further discussion if under consideration. This acknowledges the importance of the other factors as set out below. The only façade option considered not viable for this project is the masonry option. The black dotted lines in Figure 5 highlight the top 8 and 15 viable options across the range of $\alpha$.

The Stage 2 proposal is summarised as follows:

- **HVAC system** - ground source heat pump with heat recovery (GSHP).
- **General Façade** – bespoke rainscreen
- **Feature façade** - double glazed curtain wall with timber mullions

These options are highlighted by solid black lines in Figure 5 and arrows in Figure 6. The values of $\alpha$ where the proposed options enter the top 8 or 15 for all options and only the viable options are as follows:

<table>
<tr><th>HVAC Proposal</th><th>Façade Proposal</th><th>$\alpha_{Top\ 8}$ (p/kWh)</th><th>$\alpha_{Top\ 15}$ (p/kWh)</th></tr>
<tr><td rowspan="2">GSHP</td><td>Feature Façade<br>(Double glazed timber mullion curtain wall)</td><td>>24</td><td>>12</td></tr>
<tr><td>Remaining Façade<br>(Bespoke Rainscreen)</td><td>>10</td><td>All Values</td></tr>
</table>

**Table 3** Summary of range of alpha for which the chosen façade types fit with the acceptable range.

**Value of Alpha**

The appropriate value of α has remained undefined throughout stage 2. For context the original brief stated that an absolute minimum justifiable value for $\alpha$ would be the average future expected retail price of energy to the University (the University's electricity price for the current finial year is 10.85 p/kWh and a CPI indexed price is used for future planning) but that there are multiple justifications for setting α to a value such as 25 p/kWh or higher. On this basis the general façade sits comfortably in the acceptable range and the proposed feature option can be considered either fully agreeable or warranting consideration.

## 8 Considerations Beyond the ECM

As well as the ECM there are other factors that drive the choice of particular design options. Other important factors include:

- Pleasant Environment for occupants – Generous daylight and views out
- Architectural impression: In keeping with the aspirational engineering target
- Robustness and ease of maintenance
- Design for de-construction
- Design for off-site manufacture

Although not directly measurable by the ECM these factors could should still be considered of critical importance in the context of the ECM. These more subjective qualities ensure that the building works well and is well liked by its occupants. This is of critical importance to the overall sustainability of the building as these factors will play an overwhelming role in ensuring that the building achieves its full design life.

Appendix A3

# Cardboard ductwork

prepared by Katie Doig and Joel Gustafsson, Max Fordham

# CARDBOARD DUCTWORK

Rev A - 05/08/2016

This briefing note examines how cardboard ductwork performs on the energy cost metric (ECM) compared to galvanised steel ductwork for the Civil Engineering Building. The reason for examining cardboard ductwork is that there is potential to reduce the embodied and material transport energy, while improving the potential for flexibility by using cardboard ductwork rather than the more traditional metal ductwork [3].

## 1 Cardboard Ductwork

There is currently one manufacture of cardboard ductwork in the UK, GatorDuct [4]. GatorDuct is coated Tri-wall cardboard ductwork system. To form the duct the tri-wall cardboard is folded, either at three points to form a rectangular cross section or at multiple points to form a round cross section. The duct is sealed along the open edge by an angled plastic strip. As the surface of GatorDuct is printable the visual appearance of the GatorDuct cardboard ductwork is reasonably versatile, it can be designed with graphics, patterns and colour to suit a given project [4]. Some examples of GatorDuct cardboard ductwork installations can be seen in Figure 1. In terms of performance GatorDuct and traditional galvanised steel ductwork should be relatively similar.


**Figure 1** Examples of GatorDuct installations in a manufacturing building (left) and an office space (right). Images taken from [4].

## 2 Issues

**Procurement**

Currently there is only one supplier of cardboard ductwork available (GatorDuct). This means that cardboard ductwork cannot be specifically specified in the procurement process. If cardboard ductwork is of interest it could be requested that it be considered alongside galvanised steel ductwork and a performance target against the ECM given.

**FM-Maintenance**
The university FM team has expressed concern around maintenance. Primarily the concern stems from the use of an unfamiliar system. According to GatorDuct there is little difference in terms of the maintenance procedure required for traditional galvanised steel ductwork and for their cardboard ductwork. This issue could potentially be resolved with further consultation.

## 3 Cost

A sample section of a work in progress design for the ductwork in the Civil Engineering Building was costed for circular galvanised steel ductwork, rectangular galvanised steel ductwork and rectangular cardboard ductwork (the sample section in question can be seen in Appendix A). This section is fairly typical of the ductwork layout thought the building, which predominantly requires small diameter ductwork because individual spaces are treated separately. The main exceptions to this are the WC facilities and the main seminar, which both require larger ductwork because of their higher ventilation rate requirements. Some of the natural ventilation ductwork may also require larger ductwork. Table 1 summarises the cost for the sample section of ductwork for the three ductwork options. The detailed costing can be seen in Appendix B.

| Ductwork Option | Project Cost | % Cheapest |
|---|---|---|
| Circular Galvanised Steel Ductwork | £11,165 | 100% |
| Rectangular Galvanised Steel Ductwork | £14,778 | 132% |
| Rectangular Cardboard Ductwork | £18,194 | 163% |

**Table 1** Summery of ductwork cost comparison. See Appendix B for further details.

For the sample section considered the cardboard ductwork is more expensive than the galvanised steel options. Whether Cardboard ductwork is likely to be competitive in price with galvanised steel ductwork is highly dependent on the size of the ductwork, with larger sizes being more competitive in cardboard, cardboard ductwork also is cheaper as rectangular duct, whereas galvanised steel ductwork tends to be cheaper for round ductwork.

## 4 Energy

There are two energy components in the ECM that are relevant to the consideration of cardboard v galvanised steel ductwork:

- Embodied energy
- Material transport energy

**Embodied Energy**
Cardboard ductwork has a reduced embodied energy compared to galvanised steel ductwork. GatorDuct reports that it is difficult to calculate the comparative embodied energy of cardboard verses galvanised steel ductwork but that the fractions of their relative weights provides a reasonable approximation [3, 4]. This approach has been used to assess the embodied energy of the sample ductwork section shown in Appendix A for the three ductwork systems. Table 2 summarises the embodied energy for the sample section of ductwork for the three ductwork options. Further details on how the embodied energy for each system was calculated can be found in Appendix C.

| Parameter | Embodied Energy *(kWh)* | % Highest |
|---|---|---|
| Circular Galvanised Steel Ductwork | 4395 | 100% |
| Rectangular Galvanised Steel Ductwork | 4952 | 89% |
| Rectangular Cardboard Ductwork | 1730 | 35% |

**Table 2** Summery of ductwork embodied energy comparison. See Appendix C for further details.

**Material Transport Energy**

It is possible that cardboard ductwork could have a reduced material transport energy compared to galvanised steel ductwork. The reason for this is twofold. Firstly its lightweight nature should reduce the amount of energy that is required to transport it. Secondly as cardboard ductwork can be designed in collapsible formats it can be shipped flat and constructed meaning that it only requires 12% of the space of traditional steel ductwork [3, 4].

However, given that the amount of ductwork required for the civil engineering building is anticipated to be relatively small, it could be reasonably assumed that it would only require one shipment whether galvanised steel or cardboard ductwork is used. There should still be a weight benefit for cardboard ductwork, however, if it is assumed that a similar type of vehicle is used to transport either option then it is anticipated that the energy difference will be minimal. Given this the contribution from the material transport energy has not been included in the ECM analysis.

## 5 ECM Analysis

The cost and energy values presented in Table 1 and Table 2 have been used to determine the contribution to the objective function, F, for a range of values of α. This is presented in Figure 2.

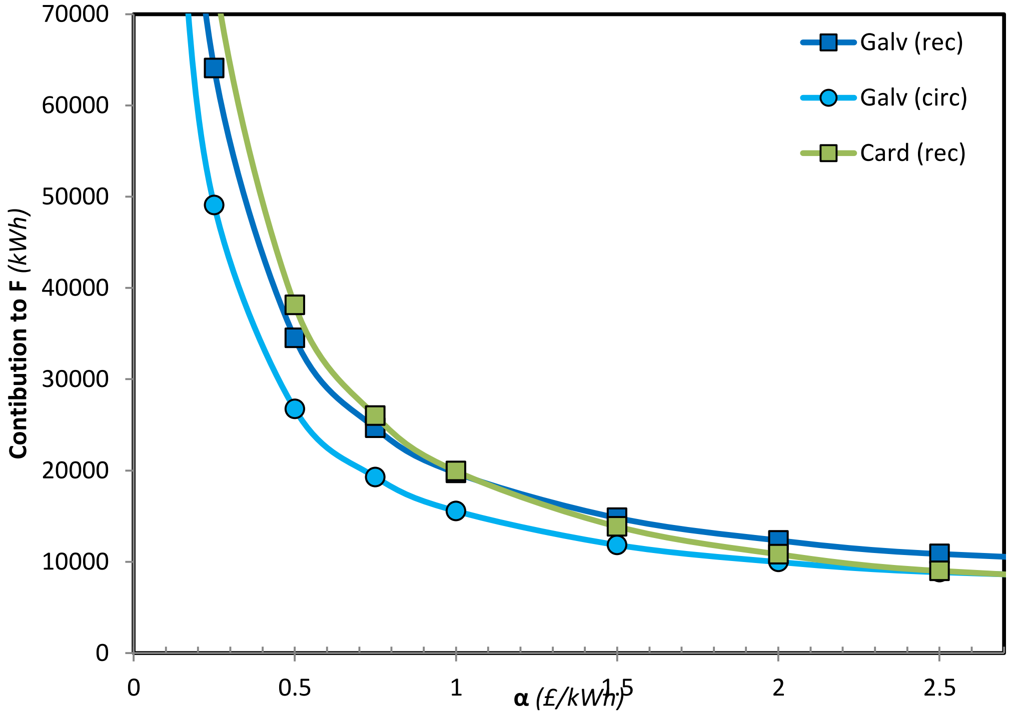



**Figure 2** Contribution to F for a range of values of α for circular and rectangular galvanised steel ductwork and for rectangular cardboard ductwork.

MAX FORDHAM

Figure 2 shows that for the sample section considered that cardboard ductwork only outperforms galvanised steel ductwork at relatively high values of α. Rectangular cardboard ductwork starts to outperform circular and rectangular galvanised steel ductwork at £2.64 and £1.06 respectively.

**Consideration of When Cardboard may Perform Better Under the ECM**
It is worth noting that although in the example considered cardboard ductwork does not perform well on the ECM that there are scenarios where its performance may be better. Cardboard ductwork should have a more competitive cost against galvanised steel for larger sizes. As such if a larger proportion of ductwork than anticipated were to require having a significantly larger sizes than that in the sample section considered then cardboard ductwork may have a more favourable cost performance compared to galvanised steel. This is a consideration that should be taken into account when assessing future projects.

Another factor in the cost effectiveness of the product is that at the moment there is one supplier producing small amounts of the cardboard ductwork whereas galvanised steel is widely produced and has an established market. It might be that in the future larger runs of cardboard ductwork are produced and this brings costs down.

## 6 Conclusions

For the requirements of the civil engineering building, where the majority of the ductwork is relatively small in size, cardboard ductwork does not perform better than galvanised steel under the ECM within the range of α that might be of interest. As such it is not recommended that the Civil Engineering Building should use cardboard ductwork in place of galvanised steel ductwork. It is worth noting that this may not be the outcome for all ductwork configurations. As such it is recommended that this topic should be re-examined on future projects at CUED, particularly for situations where there is a requirement for larger ductwork systems.

## References

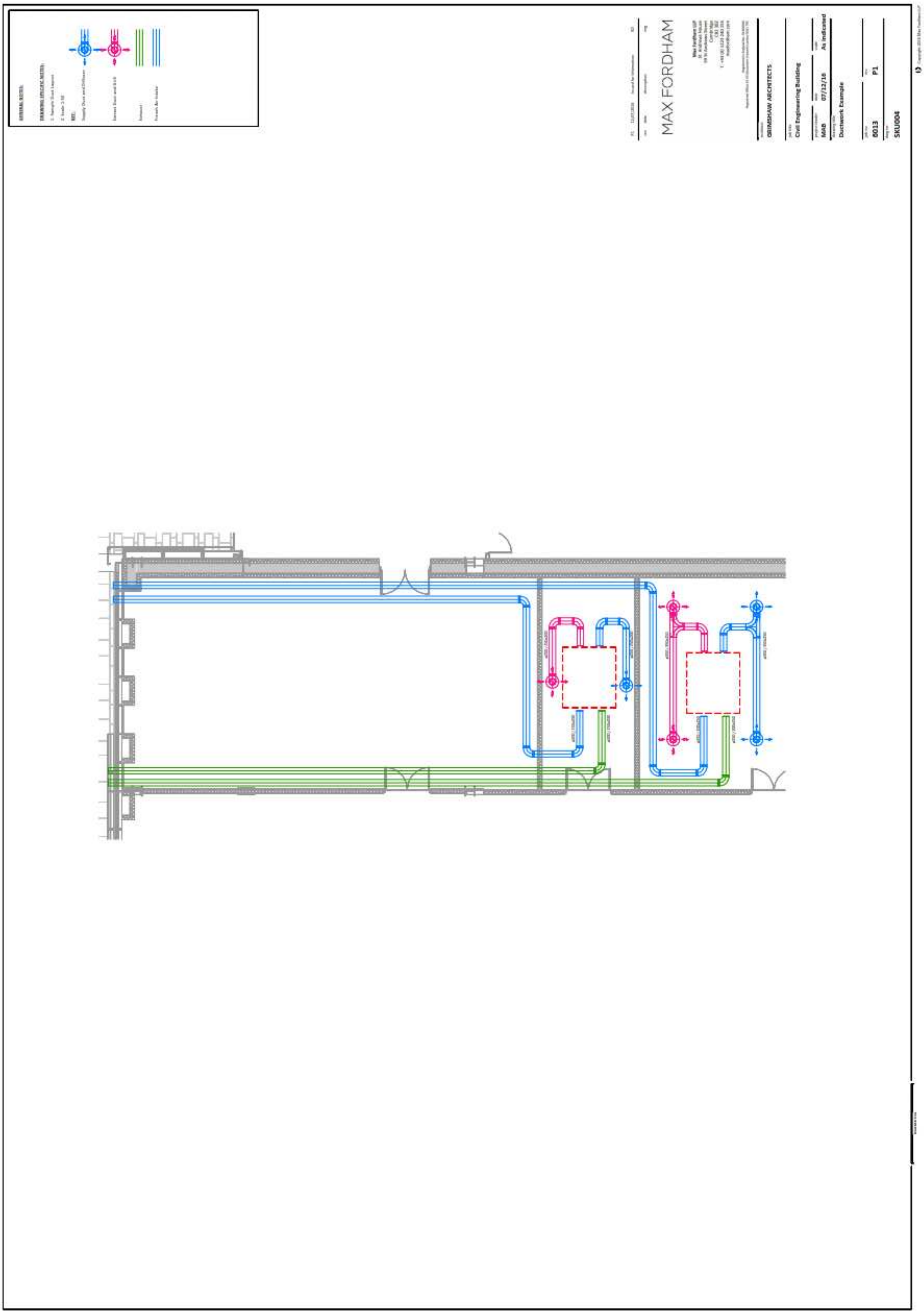

[1] D. Cheshire, "Lean Machines," *CIBSE Journal,* p. 12, March 2014.

[2] "GatorDuct," [Online]. Available: http://www.gatorduct.com/. [Accessed 4 December 2015].

[3] "Thyssenkrupp," [Online]. Available: http://www.thyssenkruppaerospace.com/materials/steel/steel-sheet-plate/weight-calculations.html. [Accessed 2016 July 20].

[4] [Online]. Available: http://www.yourhome.gov.au/materials/embodied-energy.

# APPENDIX B – EXAMPLE DUCT LAYOUT



# APPENDIX B – COST REPORT

AECOM

**University of Cambridge; Civil Engineering Building**
**Ductwork Material Capital Cost Comparison**

| Ref | Description | Qty | Unit | Supply Rate | Supply Total | Install Rate | Install Total | Total |
|---|---|---|---|---|---|---|---|---|
| **1.0** | **Circular Ductwork** | | | | | | | |
| 1.1 | 350 dia ductwork | 10 | m | 15 | 150 | 41 | 410 | 560 |
| 1.2 | 350 dia bend | 2 | nr | 11 | 22 | 30 | 60 | 82 |
| 1.3 | 350 dia tee | 1 | nr | 50 | 50 | 60 | 60 | 110 |
| 1.4 | 250 dia ductwork | 50 | m | 9 | 450 | 41 | 2,050 | 2,500 |
| 1.5 | 250 dia bend | 7 | nr | 9 | 63 | 20 | 140 | 203 |
| 1.6 | 200 dia ductwork | 35 | m | 7 | 245 | 30 | 1,050 | 1,295 |
| 1.7 | 200 dia bend | 4 | nr | 7 | 28 | 15 | 60 | 88 |
| | **Sub-Total Package Cost** | | | | 1,008 | | 3,830 | **4,838** |
| 1.8 | Construction On-costs; | 1 | item | | 473 | | 1,796 | 2,269 |
| 1.9 | Project On-costs; | 1 | item | | 846 | | 3,213 | 4,058 |
| | **Total Project Cost** | | | | 2,326 | | 8,839 | **11,165** |
| **2.0** | **Rectangular Ductwork** | | | | | | | |
| 2.1 | 350 x 250 ductwork | 10 | m | 16 | 160 | 43 | 430 | 590 |
| 2.2 | 350 x 250 ductwork bend | 2 | nr | 34 | 68 | 44 | 88 | 156 |
| 2.3 | 350 x 250 ductwork tee | 1 | nr | 66 | 66 | 53 | 53 | 119 |
| 2.4 | 250 x 200 ductwork | 50 | m | 17 | 850 | 40 | 2,000 | 2,850 |
| 2.5 | 250 x 200 ductwork bend | 7 | nr | 30 | 210 | 42 | 294 | 504 |
| 2.6 | 200 x 150 ductwork | 35 | m | 16 | 560 | 39 | 1,365 | 1,925 |
| 2.7 | 200 x 150 ductwork bend | 4 | nr | 24 | 96 | 41 | 164 | 260 |
| | **Sub-Total Package Cost** | | | | 2,010 | | 4,394 | 6,404 |
| 2.8 | Construction On-costs; | 1 | item | | 943 | | 2,061 | 3,003 |
| 2.9 | Project On-costs; | 1 | item | | 1,686 | | 3,685 | 5,371 |
| | **Total Project Cost** | | | | 4,639 | | 10,139 | **14,778** |
| **3.0** | **Cardboard Ductwork (Gatorduct)** | | | | | | | |
| 3.1 | 350 x 250 ductwork | 10 | m | | | 43 | 430 | 430 |
| 3.2 | 350 x 250 ductwork bend | 2 | nr | | | 44 | 88 | 88 |
| 3.3 | 350 x 250 ductwork tee | 1 | nr | | | 53 | 53 | 53 |
| 3.4 | 250 x 200 ductwork | 50 | m | | | 40 | 2,000 | 2,000 |
| 3.5 | 250 x 200 ductwork bend | 7 | nr | | | 42 | 294 | 294 |
| 3.6 | 200 x 150 ductwork | 35 | m | | | 39 | 1,365 | 1,365 |
| 3.7 | 200 x 150 ductwork bend | 4 | nr | | | 41 | 164 | 164 |
| | **Sub-Total Package Cost** | | | | 3,490 | | 4,394 | 7,884 |
| 3.8 | Construction On-costs; | 1 | item | | 1,637 | | 2,061 | 3,697 |
| 3.9 | Project On-costs; | 1 | item | | 2,927 | | 3,685 | 6,613 |
| | **Total Project Cost** | | | | 8,054 | | 10,139 | **18,194** |

**4.0 Notes**
4.1 Cost exercise based on Max Fordham ductwork example drawing ref. SKU004 P1
4.2 Circular ductwork is based on Class B galvanised spiral round ductwork including supports
4.3 Rectangular ductwork is based on Class B galvanised sheet ductwork including supports
4.4 Gatorduct is based on supply only quote on email to Max Fordham dated 20-07-16, plus allowance for delivery
4.5 Allowance is included for construction and project on-costs to enable a project cost comparison
4.6 If the cardboard solution is pursued, contractor warranties would need to be considered

**5.0 Assumptions;**
5.1 Gatorduct quote includes support material
5.2 Gatorduct installation time similar to rectangular galvanised ductwork. Potential reduced cost resulting from lighter material would be offset by unfamiliarity of system and susceptibility to damage

**6.0 Exclusions;**
6.1 Dampers, grilles, louvres and thermal insulation
6.2 Transformation pieces to connect to grilles, louvres and fan coil units
6.3 Fire rating to ductwork or enhanced fire protection measures between systems
6.4 Consideration of whole life costs

1

## APPENDIX C – EMBODIED ENERGY CALULATION

The embodied energy of the sample ductwork section shown in Appendix A was determined from the volume of material required using the parameters outlined in Table 1C.

| Parameter | Value | Unit |
|---|---|---|
| Density of Galvanised Steel **[6]** | 7850 | kg/m³ |
| Embodied energy of Galvanised Steel **[7]** | 38 | MJ/kg |
| Weight per surface area of GatorDuct**[3]** | 1.95 | kg/m² |

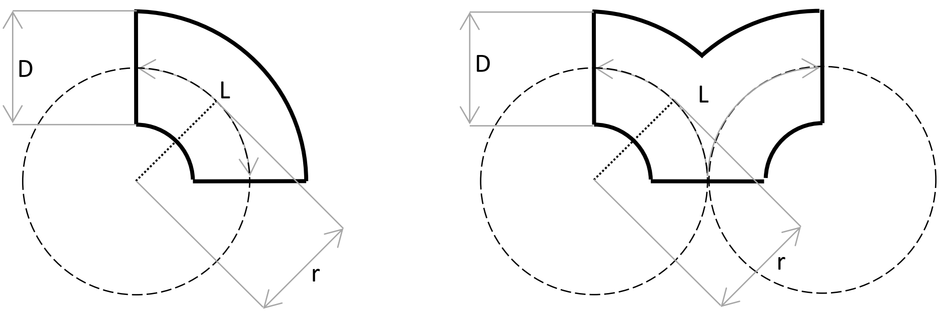
**Table C1** Parameters for calculations ductwork embodied energy.

Table 2C schedules out the ductwork comports from the sample section shown in Appendix A. Equivalent lengths for the duct fittings were based on long radius bends where the turning radius r is equal to the duct diameter D and were calculated as outlined in Figure 1C . The embodied energy for the galvanised steel options were calculated from the volume of material using the density and embodied energy of galvanised steel as outlined in Table1C. The volume of material for galvanised steel ducts was based on a thickness of 0.7mm for all duct diameters.

| Component | Diameter / Dimensions (rec) | Quantity | Length | Surface Area *(m2/m)* | $E_E$ Galv-circ (kWh) | $E_E$ Galv-rec (kWh) | $E_E$ Card-rec (kWh) |
|---|---|---|---|---|---|---|---|
| Ductwork | 350 / 350x250 | 1 | 10 | 1.10 | 638 | 696 | 23.4 |
| Bend | 350 / 350x250 | 2 | 0.55* | 1.10 | 70 | 77 | 1.3 |
| Tee | 350 / 350x250 | 1 | 1.10* | 1.10 | 70 | 77 | 2.6 |
| Ductwork | 250 / 250x200 | 1 | 50 | 0.79 | 2278 | 2610 | 87.8 |
| Bend | 250 / 250x200 | 1 | 0.39* | 0.79 | 18 | 20 | 0.7 |
| Ductwork | 200 / 200x150 | 1 | 35 | 0.63 | 1276 | 1421 | 47.8 |
| Bend | 200 / 200x150 | 4 | 0.31* | 0.63 | 46 | 51 | 0.4 |
| | | | | | 4395 | 4952 | 1730 |

**Table C2** Ductwork dimensions and embodied energy. *Refer to Figure1C for

**Bend** **Tee**




$$L = \frac{1}{4} \times \pi 2r \qquad L = 2 \times \frac{1}{4} \times \pi 2r$$

**Figure C1** Equivalent length calculations for ductwork fittings

GatorDuct reports that it is difficult to calculate the comparative embodied energy of cardboard verses galvanised steel ductwork but that the fractions of their relative weights provides a reasonable approximation [3, 4]. Using the weight per surface area of GatorDuct of 1.95kg/m² the weight of cardboard for this example was found to be 35% of the equivalent rectangular galvanised steel ductwork system. As such the embodied energy of the rectangular cardboard duct option is taken as 35% of the embodied energy of the rectangular galvanised steel ductwork option.

Appendix A4

# Kill Switches

prepared by Katie Doig and Joel Gustafsson, Max Fordham

## KILL SWITCHES

Rev A - 08/06/2016

### 1.1 Background

A large amount of the energy use of the department at the moment is caused by electrical base load overnight. Across the current department as a whole this is approximately 7W/m², while the current predictions for The Civil Engineering Building put this at approximately 6W/m². One way to reduce this base load is to provide electrical sockets that cut-out outside occupied hours. This approach to building energy efficiency has taken by a number of major American codes and standers including California's Title 24 *2013*, IgCC 2012 and ASHRAE 90.1 2010. This requires a proportion of power outlets in new developments to be controlled power outlets with automatic shutoff capability.

Installing kill switches involves the installation of contactors on many of the outgoing ways to provide a roughly 50:50 split of 24 hour sockets and cut-out sockets. The predicted cost uplift of this measure is £185,000.

### 1.2 Size of Base Load

Figure 1 shows weekday and weekend energy use profiles based on metered data for different space types in the current engineering department. Details in how these profiles were constructed can be found in the "*ECM - In-use Energy and Thermal Model*" appendix to the stage 2 report.

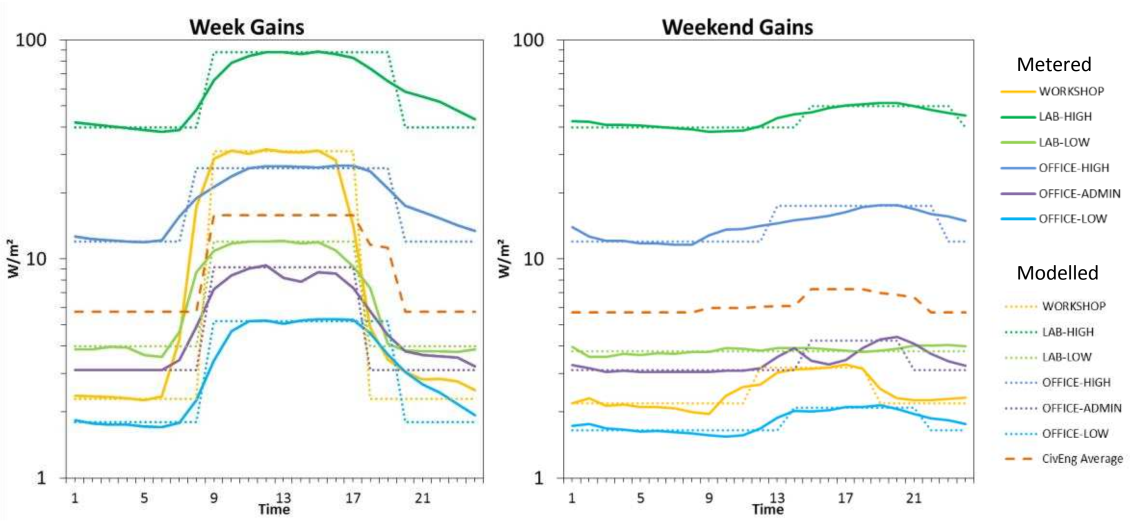



**Figure 1** Space-type power loads from CUED measured data along with the predicted UKCRIC wide load

**The total profile for the civil engineering building gives an electrical load of 376 MWh/yr[1]. It can be seen that all of the electricity load profiles have baseloads, some of which are relatively large.**

Table 1 outlines the weekday and weekend base loads for each of the space types. These have been used to determine an annual out-of-hours base load. The out-of-hours time period has been taken as 16 hours (8 hours occupied/active). From the profiles in Figure 1 it can be seen that this duration corresponds reasonably well with the load profiles. This leads to an annual out of hours base load of 145

[1] This included the metered data profiles (321 MWh/yr) shown in Figure 1 as well as a small number of constructed profiles (55 MWh/yr). Further details about all of the profiles and how they were assigned to the Civil Engineering Building can be found in the "*ECM - In-use Energy and Thermal Model*" appendix to the stage 2 report.

MWh, which is 45% of the metered data profiles. The aim of introducing kill switched would be to reduce the level of this base load.

| | Workshop | Lab-Low | Lab-High | Office-Low | Office-Admin | Office-High | Total |
|---|---|---|---|---|---|---|---|
| Floor Area *(m2)* | 453 | 684 | 418 | 1345 | 145 | 132 | 3176 |
| Annual Load *(kWh)* | 39,587 | 36436 | 206408 | 11,981 | 6574 | 20376 | 321,361 |
| Weekday Base load *(W/m2)* | 2.3 | 4 | 40 | 1.8 | 3.1 | 12 | - |
| Weekend Base load *(W/m2)* | 2.2 | 3.8 | 40 | 1.65 | 3.1 | 12 | - |
| Annual Base Load *(kWh)* | 6,008 | 15,748 | 97,696 | 13,801 | 2,618 | 9,247 | 145,188 |

**Table 1** Base load analysis for the metered data profiles.

## 1.3 ECM Analysis

The potential energy saving that this measure may achieve is difficult accurately predict; a sensible estimate could put this at 10% of the base load. Given this inherent uncertainty determining the energy savings, calculating alpha breakeven ($\alpha_{BE} = -\Delta C/E$) for a range of reductions to the base load is an effective way of examining the measure's potential cost-effectiveness.

Figure 2 shows $\alpha_{BE}$ for a range of % reductions to the base load. The grey band between 10% and 20% highlight the range that might represent a sensible minimum and maximum case for the possible reduction in the baseload.

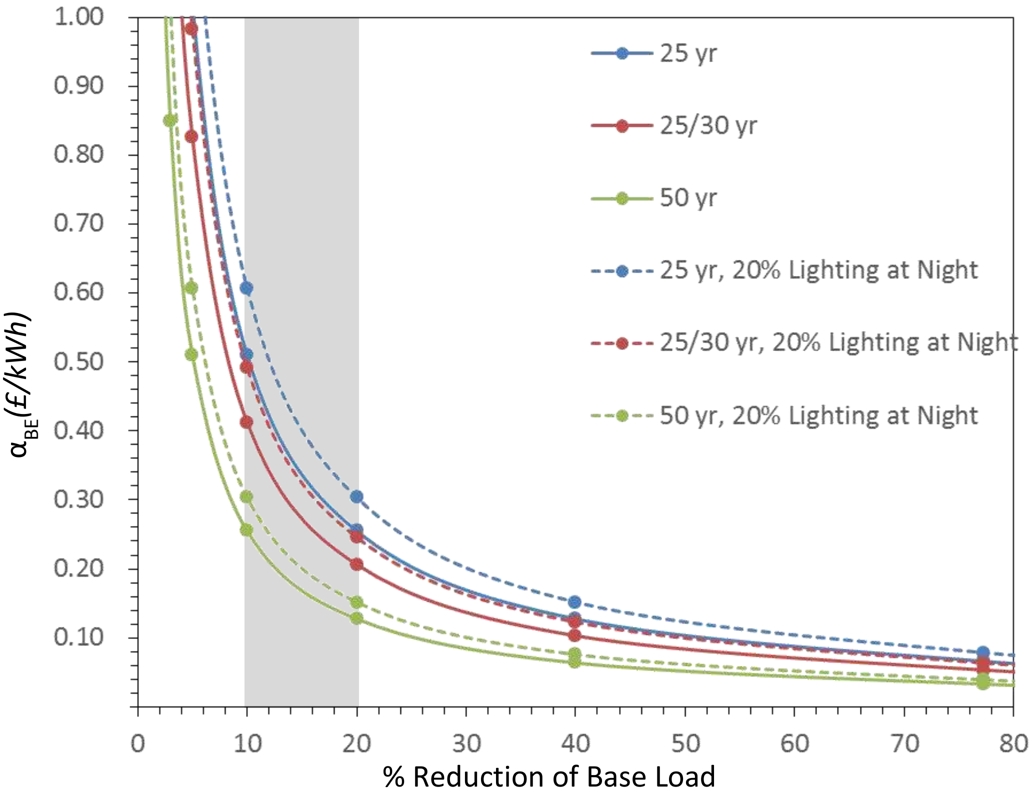


**Figure 2** $\alpha_{BE}$ for different % reductions in the annual base load. The 25/30 yr case is for the breakdown presented in Table 2, while the other two cases assume a 25 year and 50 year lifetime for all components respectively.

The three solid curves show the show the effect on $\alpha_{BE}$ if different assumptions are made about the lifetime of the kill circuits. The effect of assuming an increased lifetime of the kill circuits reduces the annualised cost meaning that the option performs more favourably under the ECM. Predicting the most suitable lifetime to assign to the kill circuits is uncertain. A reasonable estimate could be 50 years for the cabling and 25 years for the contactors and control systems. Table 2 outlines the annualised cost for kill circuits based on this breakdown and is presented along with examples for all components lasting 25 years and 50 years in Figure 2.

| | Additional Project Cost | Lifetime | Annualised Cost |
|---|---|---|---|
| | *£* | *yr* | *£/yr* |
| Increase capacity of distribution boards | 53,298 | 25 | 2132 |
| Increase quantity of final small power circuits by 25% | 71,062 | 50 | 1421 |
| Addition of kill switch enclosure including contactors and simple controls | 60,910 | 25 | 2436 |
| | 185,270 | | 5,990 |

**Table 2** Annualised cost of kill switches

## 1.4 Lighting

The plugin power and lighting were not metered separately in the data sets used to create the space type electrical load profiles. As such part of the electricity load profiles is lighting rather than plug-in load. It is important to consider how much of the base load might be lighting rather than other electrical use as the kill circuit system will not save lighting energy. An energy audit of the current engineering buildings, carried out by AECOM in June 2015 [1], had been used to establish what proportion of the base load might be lighting[2]. Based on this the estimated energy density of lighting for the electrical load profiles is 26.5 kWh/m$^2$.

Given that the floor area is 4358m$^2$ this gives 116 MWh/yr of lighting. This is the maximum range assumption that has been used in the energy use prediction. To give some context to this value a reasonable estimate of the installed lighting capacity in the current engineering buildings is 15 W/m$^2$; to give 116 MWh/yr this level of installed would be equivalent to an average daily running time of 5 hours.

Given that the majority of metered data used did not have lighting sub metered it is difficult to determine what proportion of the lighting load that is used during the night and will thus contribute to the out of hours base load. Figure 3 shows an example of the lighting and non-lighting load for a lab where lighting and non-lighting energy use were separately sub metered. For this example, the lighting load out of normal working hours is approximately 20% of the lighting during the day. If this scenario is typical of the out of hours lighting use then this would mean that 20% of the 116 MWh/yr lighting load (23 MWh/yr) would occur out of hours and contribute to the out of hours base load. The dotted curves in Figure 2 show a modification to the effect on $\alpha_{BE}$ taking into account that 23 MWh/yr lighting contribution is removed from the out of hours baseload before analysis.

[2] Further detail on how the 26.6 kWh/m$^2$ energy density figure has been arrived at from the AECOM energy audit can be found in the Energy Use Prediction note.

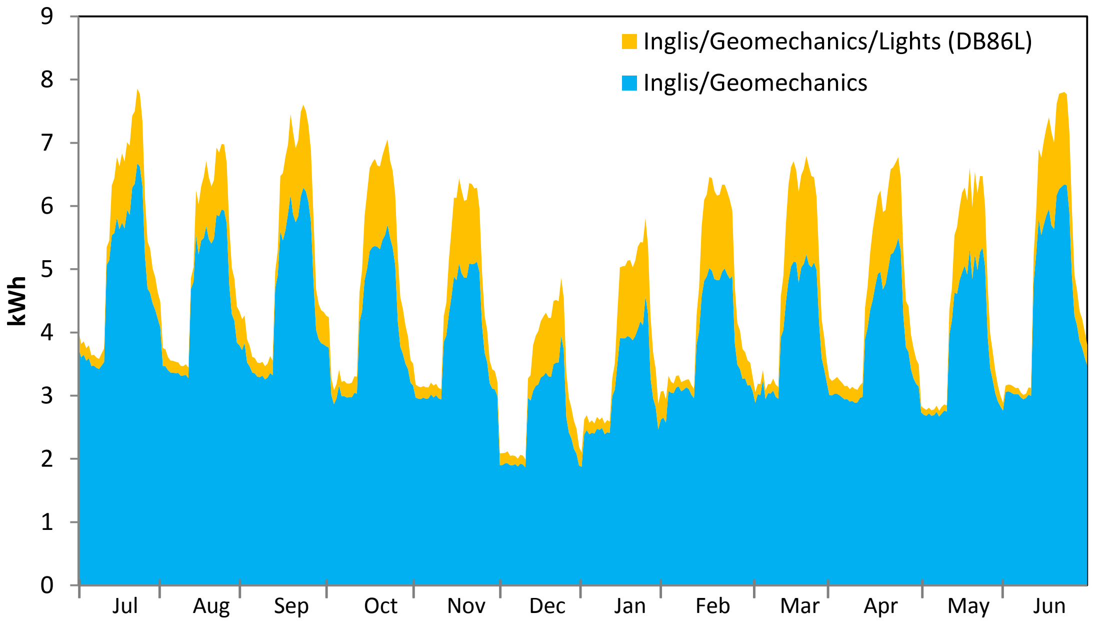



**Figure 3** An example of the electrical power and lighting energy use where the lighting and electrical power were metered separately. An average energy profile for each month is shown.

## 1.5 Simple Payback

**The performance of kill switches has also been examined in terms of simple payback.**
Table 3 outline the payback periods for a range of potential baseload savings:

| **Base Load** | | **Electricity Cost** | **Capital Cost Uplift** | **Total Electrical Load** |
|---|---|---|---|---|
| *kWh* | | *£/kWh* | *£* | *kWh/yr* |
| 145,118 | | 0.11 | 185,000 | 375,919 |
| **% Base saved** | **Annual Energy Saving** | **Annual saving** | **Years to Payback** | **% Total Saved** |
| | *kWh/yr* | *£/yr* | *Yr* | |
| 1% | 1,451 | 160 | 1,159 | 0% |
| 3% | 4,354 | 479 | 386 | 1% |
| 5% | 7,256 | 798 | 232 | 2% |
| 10% | 14,512 | 1,596 | 116 | 4% |
| 20% | 29,024 | 3,193 | 58 | 8% |
| 40% | 58,047 | 6,385 | 29 | 15% |
| 77% | 112,121 | 12,333 | 15 | 30% |

**Table 3** Payback periods for a range of potential energy savings.

If assessed under a simple payback scenario kill switched do not perform well unless unrealistically high levels of energy saving are assumed. To achieve a simple payback in 15 years 77% of the out-of-hours base load would have to be saved. This equates to a 30% reduction in the overall electrical load profile. This level of saving is almost certainly not possible.

## 1.6 Conclusions

Whether kill switches perform well under the ECM is highly dependent on the level of cuts to the base load that are thought to be possible and on the lifetime that might be attributed to them. Both of these factors can be considered highly subjective and uncertain. The level of lighting present in the electrical gain profiles also adds an additional unknown; however based on the examples that are available it is likely that this effect is small in comparison to the first two factors. If a 50 year assumption for cabling and 25 years for the other components with a 10-20% baseload reduction including the lighting correction is assumes this would give a 24-50p/kWh range of values for $\alpha_{BE}$.

If assessed under a simple payback scenario kill switched do not perform well unless unrealistically high levels of energy saving are assumed.

It is important to note that simple payback is based on the current price of energy and that one of the fundamental drivers of the ECM is to value energy in a different way. As such, although kill switches do not perform well on a simple payback metric it doesn't necessarily follow that they don't have merit under the ECM. Given the degrees of uncertainty in assigning potential base load savings and system lifetimes it is difficult to give a definitive conclusion on kill switch performance under the ECM without further discussion to narrow the possible ranges of the parameters saving and lifetime parameters.

Given the uncertainty over this performance of this measure a possible proposal for the civil engineering building could be that a trial installation is set up with infrastructure provision for the trial to be extended if successful, we could monitor the effectiveness of the kill-switches against a similar area without kill switches and against the same area with and without kill switches in operation. Alternatively further research into existing schemes may provide further clarification on the effectiveness of the measure.

[1] . R. Tetlow, "University of Cambridge Carbon Management – Baker & Inglis Buildings Energy Audit," AECOM, 2015.

MAX FORDHAM

Appendix A5

# Thermochromic Fins

prepared by Katie Doig and Joel Gustafsson, Max Fordham

# ECM – THERMOCHROMIC FINS

Rev A - 25/07/2016

Criterion 3 of part L2A of the building regulations put limits on the amount of solar gain solar that rooms can experience between March and September. This means that solar control measured need to be taken into consideration from a regulatory perspective as well as from the perspective of maximising the comfort of the occupants. For the Civil Engineering Building the options to reduce solar gain in order to pass criterion 3 that have been considered are the use of:

**Solar Control Glazing**

This essentially means using a glass with reduced solar transmittance of thermal energy (i.e. a reduced g-value). This option has the drawback that the reduced thermal transition also results in reduces transition of visible light (VLT). This can be considered as a negative drawback, particularly in the winter when lighting levels are low, which as well as being undesirable in terms of building pleasantness may also contribute to an increase in energy required for lighting in the winter months.

Modelling has shown that for the Civil Engineering Building can meet criterion 3 using 50-25 solar control glazing (50% VLT and thermal transmission of 25%) is necessary.

**Shading Fins**

An alternative approach is to use non-solar control with the addition of shading fins. The use of shading fins. This approach has the benefit that the VLT of the glazing need not be reduced, although can impact on vies out of the building.

Modelling has shown that the Civil Engineering Building can meet criterion 3 using 70-40 non-solar control glazing (70% VLT and thermal transmission of 40%) with the addition of shading fins. It has been shown to be possible to pass criterion 3 sing solid and partially transparent fin options.

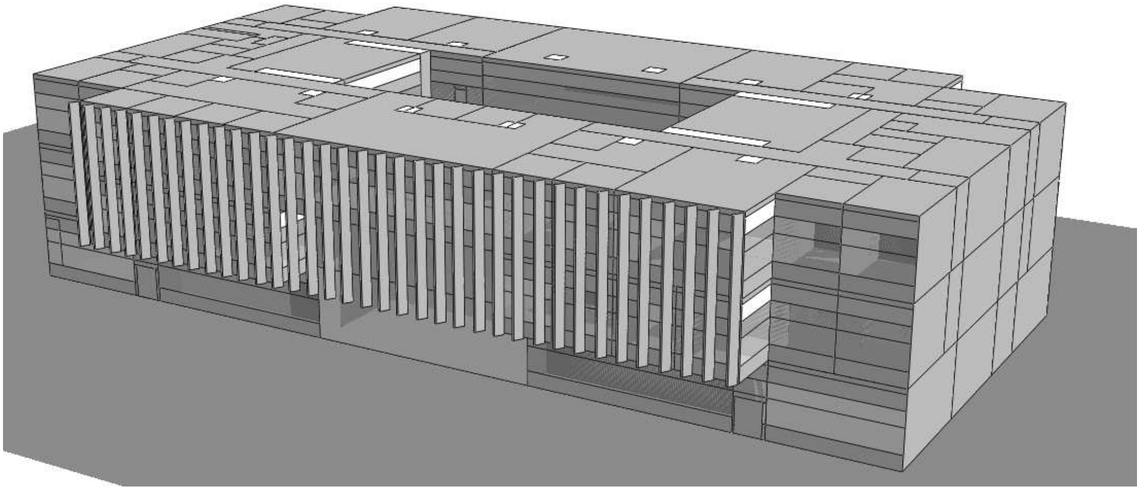


**Figure 1** Model of UKCRIC Building with fins.

# 1 Thermochromics Fins

A drawback of both of the methods described above is that they proved the same level of shading all year round. In terms of energy use and the level of daylighting this may not be the optimal situation in the winter months, where additional solar gain can help to offset heating loads and where increased daylighting will be highly appreciated by the occupants as well as help to displace artificial lighting.

Thermochroic glass has a temperature dependent transmittance of light; as the temperature increases the transmittance for optical and thermal radiation decreases. As such fins made of thermochroic glass should improve the visible light and useful solar gain availability in the winter, while blocking unwanted solar gain during the summer. These effects should mean that in addition to more subjective measures such as pleasantness of improves winter daylighting, the ability of the façade to respond to differing conditions at different locations and the addition of architectural interest to the façade thermochromic shading fins should also have a benefits in reduction winter heating loads and potentially displacing some lighting loads.

# 2 In-Use Energy Model

To test the impact shading fins on the energy use for heating and cooling for the Civil Engineering Building two cases have been compared:

**No Fins** Solar contol glazing (g=0.25) everywhere.

**Fins** Thermochomic/Solid fins with higher transmission glazing (g=0.4) under fins.
Solar contol glazing (g=0.25) elswhere.

In the case with fins, the fins were located over the proposed region on the eastern façade, as is depicted in Figure 1. The fins were modelled such that they were offset by 60° and 90° from the façade and were 300, 600, 900 and 1200mm in width. There are 36 fins which are 9m in height in the model; this is equivalent to a fin spacing of 1.2m.

The proposed glazing system for the thermochromic fins is Suntuitive self-tinting glass which has the following transmission properties:

| | 5°C | 47°C |
|---|---|---|
| Visible Light Transmission | 69% | 32% |
| Thermal Transmission | 61% | 42% |

**Table 1**Thermochromic glass transitions properties.

Reliably modelling the energy use response to varying fin VLT and g-value has presented some simulation difficulties. As such to approximate the difference in transmissions of the fins at different temperatures in the model two extreme cases have been used:

**High-T (≥18°C)** Solid fins
Higher transmission glazing (g=0.4) under fins.
Solar control glazing (g=0.25) everywhere.

**Low-T (<18°C)** No fins
Higher transmission glazing (g=0.4) where fins would be.
Solar control glazing (g=0.25) elsewhere.

These two cases should provide an over estimation of the fins true performance in terms of energy use as for cold conditions they allow 100% transmission of solar radiation, maximising the heating contribution from solar gain, while for warm conditions they are fully opaque, minimising the need to remove unwanted solar gains with active cooling systems. The High-T/Low-T switch over point has been chosen as 17.5°C as below this temperature additional heating from solar gains could be considered to add beneficial heating to the building.

## 3 Heating and Cooling Loads/Energy Use

Figure 2 shows the annual building heating, cooling and combined heating/cooling loads for Thermochromic Fins (TC), Solid Fins (S) and No Fins (NF) for the range of fin widths and angles examined.

Figure 2 (a) shows that for solid fins, the larger the fin the higher the heating load. For the thermochromic fins the heating load is constant across different fin lengths and is lower than the no fins with solar control glazing case. This comes about because the chosen High-T/Low-T temperature point of 17.5°C minimises the heating load such that it is equivalent to the heating load for the Low-T case (i.e no fins and non-solar control glazing used where the fins would have been). This means that the approach is providing an optimal situation for minimising the fins reduction of useful solar gain in cold weather where heating may be required.

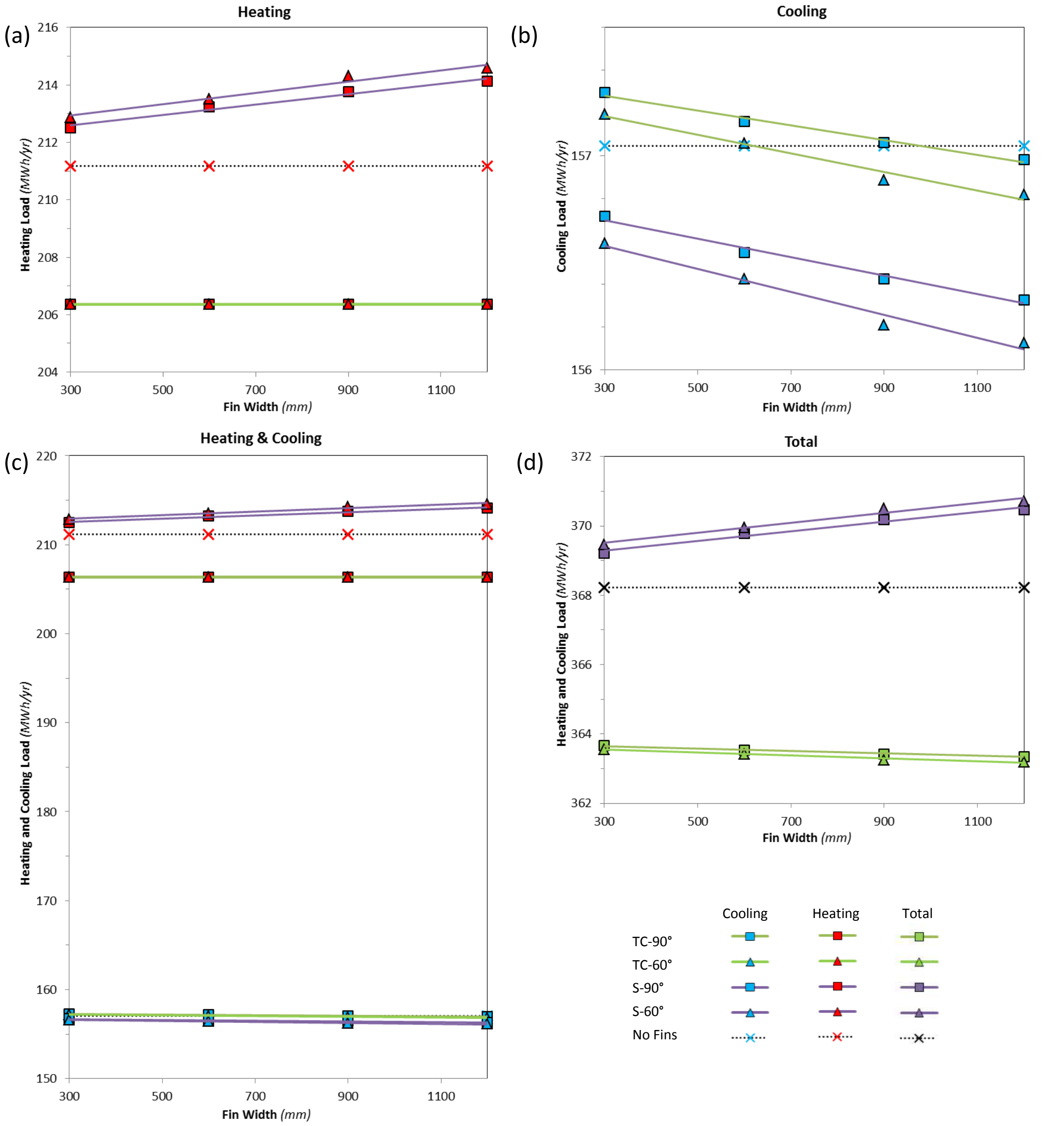



**Figure 2** Heating, Cooling and combined Heating/Cooling loads for Thermochromic Fins (TC), Solid Fins and No Fins at 60° and 90° for a range of fin widths.

From Figure 2 (b) it can be seen that the larger the fin the lower the cooling load. For the thermochromic fins the magnitude of the cooling load's offset from the solid case depends on the High-T/Low-T crossover point. For the minimum heating load the average magnitude the cooling load for the cases examined is similar to the case with no fins and solar control glazing. The lower the High-T/Low-T crossover temperature that is chosen, the smaller the difference between the solid and thermochromics cooling loads as the lower this limit the more time the fins will be considered as fully opaque. The reason for the offset between the thermochromic and solid fins cases is likely to be as a result of a slightluy different level of solar gain arising from the

As the magnitudes of the heating loads are significantly larger than the cooling the heating load dominates the overall result meaning that the reduced heating load from the thermochromics fins option results in it being the lower energy approach compared to solid fins/no fins. However, the size of the reduction in heating/cooling loads brought about by thermochromic fins is relatively small, constituting at most a few MWh per year. The average annual percentage load increases/savings across the fin width and angle options were as follows:

| | Cooling | Heating | Total |
|---|---|---|---|
| Thermochromic/Solid | 100.4% | 96.6% | 98.2% |
| Thermochromic/None | 100.0% | 97.7% | 98.7% |
| Solid/None | 99.6% | 101.2% | 100.5% |

**Table 2** Relative heating and cooling loads.

**Loads and Energy Use**
The energy used in order to meet the required heating and cooling load depends on the efficiency of the HVAC system. For the Civil Engineering building the heating and cooling will be supplied by a ground source heat pump with heat recovery (GSHP). In the loads and HVAC analysis undertaken in the stage 2 assessments of façade and HVAC (see "ECM – Façade and HVAC Options" appendix to the stage 2 report) the energy required to meet the heating and cooling load with the GSHP system was approximately 16.5%. For the analysis of the fin's performance a conservative estimate of the energy required to meet the load of 33% has been chosen. This in essentially assumes that the HVAC system is half as efficient as the manufacturer's specifications.

## 4 Lighting Energy Use

Switching from solid to thermochromic fins should also have a benefit in terms of increasing the level of daylight available in the winter and thus reducing the requirement for artificial lighting. This aspect has not been taken into consideration in the current ECM analysis.

## 5 Cost

| Fin Option | Cost Plan Project Cost | Area in Cost Plan | Rate |
|---|---|---|---|
| Thermochromic Fins | £3256,000 | 320 m² | 800 £/m² |
| Solid Fins | TC - £90,000 | Assumed ≡ TC | 520 £/m² |
| No Fins | 0 | | 0 |

**Table 3** Fin cost rates set out in the stage 2 cost estimate rev 6 and the post stage 2 VE options. See Appendix A.

The difference in cost between using solar-control and non-solar-control glazing has not been accounted for in this study.

## 6 ECM Analysis

For the ECM analysis the area cost rates were applied to the area of fin required for each option. The contribution to the objective function F for each of the options is presented in Figure 3 for the heating/cooling energy use. The 90° and 60° options were almost identical in contribution to F so the fractionally lower of the two has been shown. Figure 3 shows that for equivalent fin demotions that the solid fin case always has a lower contribution to F than the thermochromic case. It is worth noting that the ranking that the ECM analysis does not start to change within the range presented in Figure 3. Table 4 outlines the breakeven alpha ($\alpha_{BE}$) values for switching from a solid fin to a thermochromic fin of equivalent dimensions. In terms of the ECM none of the fin options performs better than using solar glazing without fins.

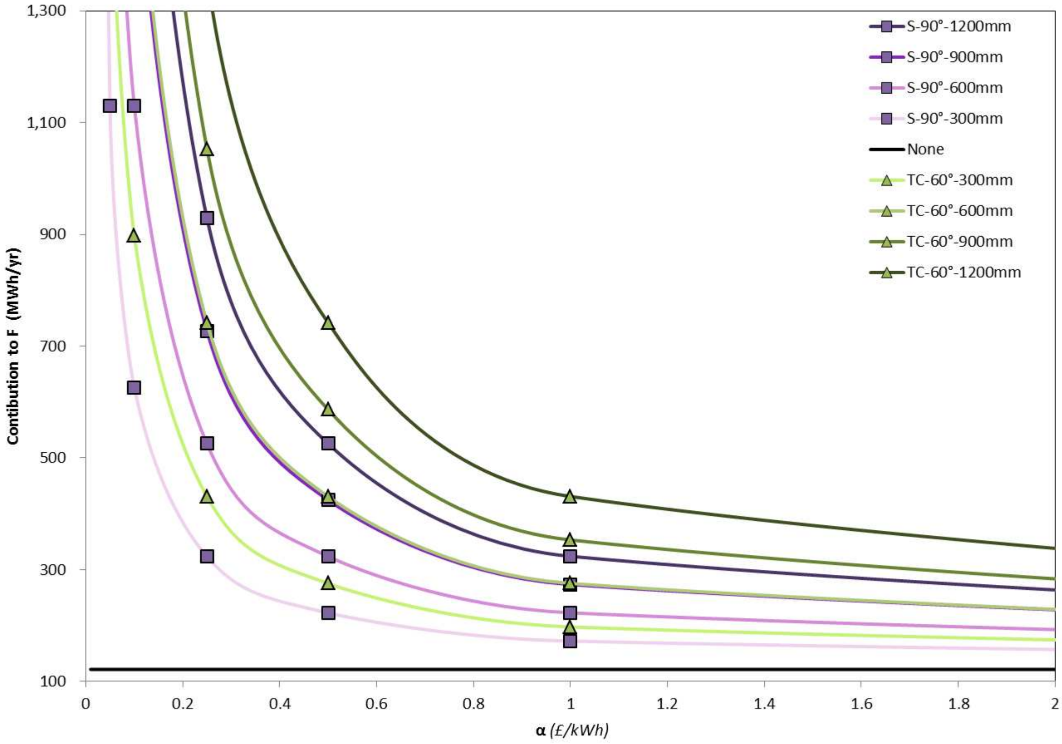



**Figure 3** Contribution to the objective function F for different thermochromic (TC) and solid (S) fin configurations.

| Fin Length (mm) | $\alpha_{BE}$ |
|---|---|
| 300 | £14.17 |
| 600 | £26.06 |
| 900 | £37.74 |
| 1200 | £49.15 |

**Table 4** Break even alpha ($\alpha_{BE}$) for switching from a solid fin to a thermochromic fin of equivalent dimensions.

## 7 Conclusions

The use of thermochroic fins results in a small energy saving in heating and cooling of a few MWh per year compared to solid fins or no fins. This represents a small percentage improvement of slightly under 2%. In terms of the ECM solid fins always perform better than then thermochromic fins of equivalent size. The values of α that would be required to switch from solid fins to thermochromic fins performing better under the ECM is in the 10s of £/kWh, which is significantly higher than the range that has been under consideration.

Although none of the fin options perform better under the ECM than the solid/thermochromic fin options, using fins rather than solar-control glazing to control solar gain can have other less quantifiable benefits as:

- Better connections with the outside
- Better access to daylighting in the winter or dull weather
- A façade that can respond to different conditions at different locations
- The addition of architectural interest to the façade

Consideration needs to be given to the level of importance associated with these aspects and how well the inclusions of fins meet other aspects of the brief.

In conclusion, the incorporation of fins has minimal energy benefits and does not perform well under the ECM but may bring other benefits and meet other aspects of the building's brief. As such the inclusion of fins should not be considered as an ECM matter and should be judged on its other benefits alone.

## APPENDIX A – COST PLAN ITEMS EXERPTS

University of Cambridge
Department of Engineering
Civil Engineering Building
Post Stage 2 VE - 02 June 2016

AECOM

**Potential Value Engineering**

| Ref. | Description | Total Project Cost Potential Saving (£) | Priority level |
|---|---|---|---|
| | **Stage 2 Cost Plan Rev 6 dated 07 April 2016** | **30,624,000** | |
| 1 | Omission of PV Panels | n/a | 0 |
| 2 | Omission of external access gantry | -260,000 | 1 |
| 3 | Omit curtain wall cladding system, add rainscreen system in lieu (Type CT01 and CT03) | n/a | 0 |
| 4 | Omit curtain wall cladding system, add brickwork with punchole windows in lieu (Type CT01 and CT03) | n/a | 0 |
| 5 | Omission of covered walkway to roof terrace | -40,000 | 1 |
| 6 | Omit thermochromic solar shading, add extruded aluminium in lieu | -90,000 | 2 |
| 7 | Omit GSHP; add ASHP in lieu | n/a | 3 |
| 8 | Omit GSHP; add Gas Fired Condensing Boiler - VRF Conditioning in lieu | n/a | 0 |
| 9 | Omit GSHP; Gas Fired Condensing Boiler - Chiller (Heat Recovery) in lieu | n/a | 0 |
| 10 | Omit 1nr lift; add office accommodation in lieu | n/a | 1 |
| 11 | Addition of smoke extract and smoke ventilation to the basement beneath the strong floor. | 340,000 | 1 |
| 12 | Addition of kill switches - Only to be implemented if additional funding made available | 0 | 1 |
| 13 | Introduction of grey water recycling | 150,000 | 2 |
| 14 | Allowance for 1% for Art - Resultant from stand alone planning application | 220,000 | 1 |
| 15 | Introduction of external gantry escape stair | 45,000 | 1 |
| 16 | Introduction of sprinkler system | 1,000,000 | 2 |
| 17 | Revised Infrastructure Levy | TBC | 1 |
| 18 | Requirement for contractor to develop BIM Model beyond level 2 | TBC | 2 |
| 19 | Monitoring of structure - BMS links/interface | TBC | 1 |
| | **Revised Stage 2 Cost Plan Total Project Cost** | **31,989,000** | |

Priority Level
0 - Not viable, no longer under consideration
1 - Favoured option, to be adopted in RIBA Stage 3 subject to conclusion of design and UoC/Dept sign off
2 - Desirable, requires further design development and testing of viability in RIBA Stage 3
3 - Unlikely to be accepted, further design development and testing of viability in RIBA Stage 3

University of Cambridge
Department of Engineering
Civil Engineering Building
Stage 2 Cost Estimate Rev 6

AECOM

**2.0 Detailed Cost Estimate**

| Ref. | Description | Qty | Unit | Rate (£) | Total (£) |
|---|---|---|---|---|---|
| **2.5** | **External Walls** | | | | |
| | External double glazed curtain wall system. Timber mullions and transoms. Integrated manual opening windows (2x per 7.2m bay per floor) and continuous insulated al. panel (300mm deep) at floor slab above continuous band of louvres (900mm deep) with 50% actuated dampers and 50% insulated panel behind. Glass to Solid = 40 : 60 (average) | 1,088 | $m^2$ | 1,000 | 1,088,000 |
| | Thermochromic glass louvres with al.support framing fixed back to external double glazed curtain wall. (Glass cost data to be verified with supplier) | 320 | $m^2$ | 800 | 256,000 |

Appendix A6

# Photovoltaic Array

prepared by Jeremy Climas and Ben Leary, Max Fordham

## ECM – PHOTOVOLTAIC ARRAY

19/07/16

**West Cambridge Energy Strategy - Aecom**

*"PV panel area for each building should target at least 25% of the building's footprint, and therefore anticipated to cover approximately 50% of the building's roof area (allowing for space between panels). Benchmark PV performance is 850 kWh / kWp and a module efficiency of at least 15%."*

*"PV systems operate best when located on a roof within 30 degrees of due south at around 30- 40 degrees inclination. The systems will work with a small drop in output for other orientations within circa 30- 40 degrees of south, and other inclination angles."*

**PV Panel Arrangement**

PV arrays are generally arranged in grid and spaced to minimise overshadowing at their chosen inclination. The optimum angle for the panels is dependent on if the aim is to maximise panel area for a given available area or to maximise the output for a single panel over a year.

The reason for the two values is simply that for a given orientation and latitude there is an inclination for which over the course of a year a panel will receive the maximum amount of direct sunlight. However, as the inclination of panel increases from horizontal, the distance between two panels must increase to avoid overshadowing, therefore limiting the total installed PV capacity for a given area. For the UK these two inclinations are approximately 10° for maximum panel area and 30° for maximum panel output. The diagram below illustrated this for an indicative PV panel.

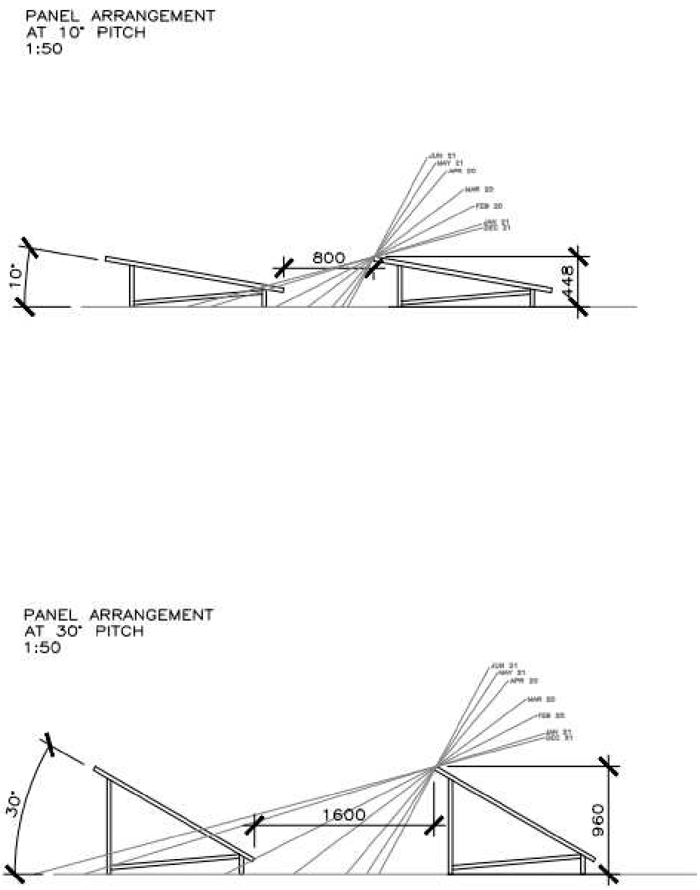
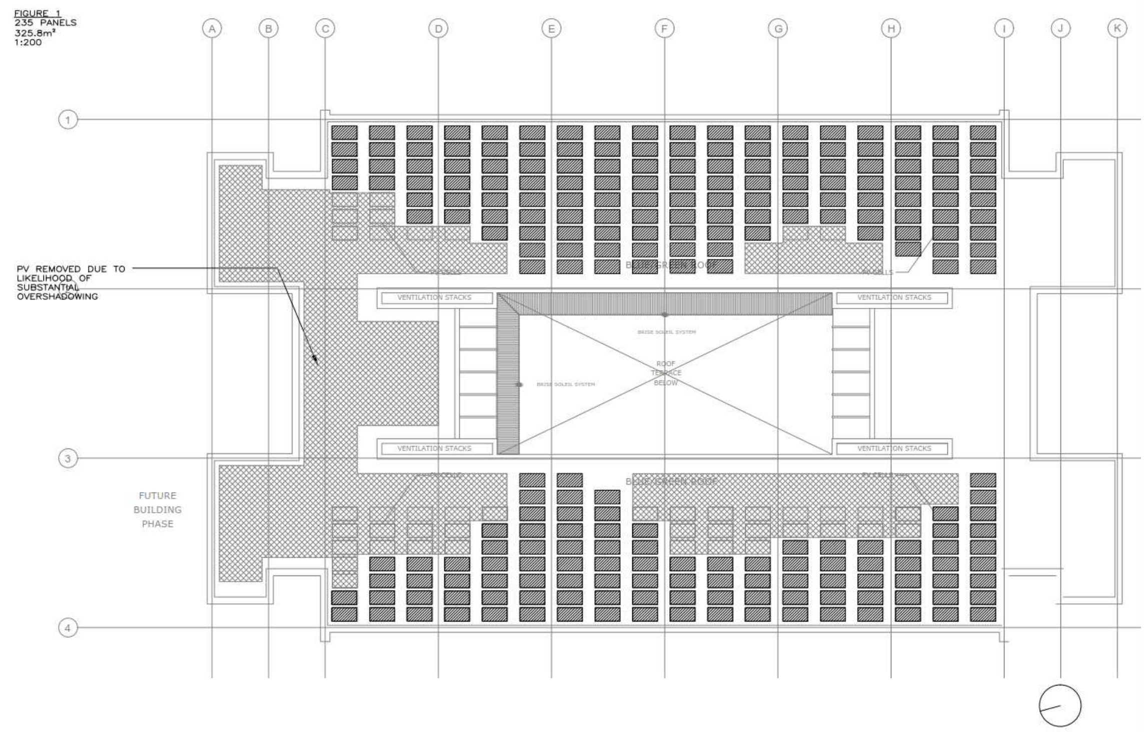
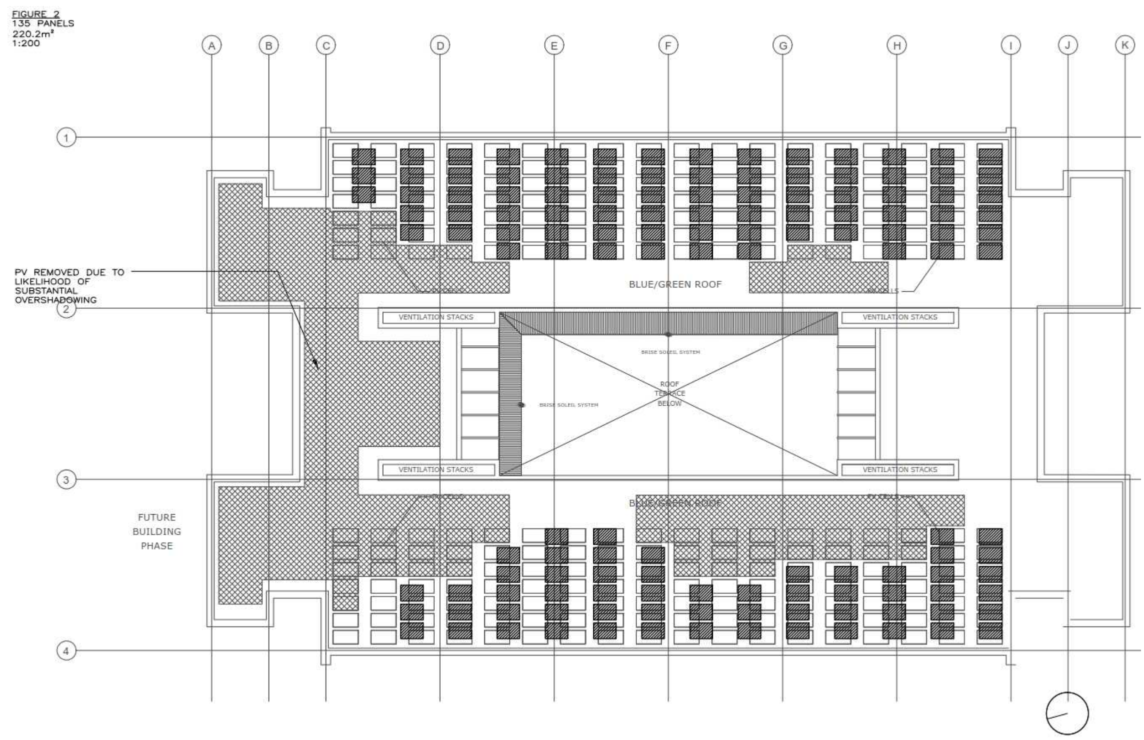



**Figure 1: Indicative Panel Spacing**

For the PV array to meet the masterplan requirements the panel area would need to be excess of 396m². However, by reasonably accounting for over shading by both panels and chimneys it is not possible to meet this target at a 30° panel inclination. By angling the panels at 10° the panel area of the array can be significantly larger but still does not meet the 25% target. Both options utilise in excess of 50% of the total roof area and are detailed below




**Option 1: Maximum practical size of PV array**




**Option 2: Energy Efficient**

The two array options were costed for both high and low efficiency PV Panels by Playfords, a PV supplier and contractor, and uplifted by 50% to give a total project cost.

| Panel Efficiency | Option 1 - 326m² @ 10° | | | Option 2 - 220m² @ 30° | | |
|---|---|---|---|---|---|---|
| | Peak Output (kWp) | Annual Yield (MWh) | Cost (£) | Peak Output (kWp) | Annual Yield (MWh) | Cost (£) |
| 15% | 58.8 | 52.5 | £123,000 | 33.8 | 33.8 | £75,000 |
| 20% | 77.6 | 69.3 | £175,500 | 44.6 | 43.3 | £106,500 |

The embodied energy the PV panel is estimated to be 500 kWh/m$^2$ of panel and the Lifespan is expected to be a minimum of 25 years.

The breakeven alpha, $\alpha_{BE}$ is calculated as:

$$\alpha_{BE} = \frac{-\{Cost\ (£)/Lifespan\ (Yrs)\ \}}{-\{Energy\ Generation\ (kWh/yr) - (Embodied\ Energy\ (kWh)/Lifespan\ (Yrs))\}}$$

The results are tabulated below.

| Panel Efficiency | Option 1 $\alpha_{BE}$ | Option 2 $\alpha_{BE}$ |
|---|---|---|
| 15% | £0.1070 /kWh | £0.1020 /kWh |
| 20% | £0.1115 /kWh | £0.1095 /kWh |

**Conclusion**
In terms of Energy/Cost metric the low cost, lower efficiency panels perform better that the higher cost higher efficiency panels. Additionally the optimised orientation option performs better against the Energy/Cost Metric in both scenarios as the annual yield per panel increases. As such the best option under energy cost metric is low efficiency panels arranged installed at 30° incline.

**Recent Developments**
From recent discussions with UKPN in relation to new PV installations, it has become apparent that their infrastructure is under a large amount of strain and restrictions are being placed on new grid linked arrays.

- All new PV installations are to be installed with an Export limiter. (Approx. £8,000 cost)
- Export limiters are to be set to zero, so no electricity is exported to the grid.
- Installations over 11kWp will not be allowed to connect to the grid infrastructure, with or without an export limiter.

The implications of the above requirements will not only impact the inset masterplan, but the entirety of the West Cambridge Development. As it stands the Civil Engineering building would be unable to meet its PV area targets with an 11kWp array. Leaving the department and masterplan with several options:

- Present a reduced PV capacity to the planners, highlighting the issues to them.
- Keep the larger PV array and wait for UKPN to carry out the required infrastructure upgrades.

Appendix A7

Structural Frame and Floor System

prepared by Katie Symons and Simon Smith, Smith & Wallwork Engineers

# Frame Study 7.2x11.2m

*Discussion Paper*

This paper is written at outline design stage of the Department of Engineering Move West project. The Engineering Department at Cambridge University aims to be a 100,000m$^2$ department by 2025. This will require 60,000m$^2$ of new building on West Cambridge. Buildings will be delivered in a phased manner adopting principles of low energy design.

This document reviews structural frame and floor options for the phase 1 building which forms the first element of a modular and extendable development of the CUED Move West. The phase 1 building provides some 4500m$^2$ of floor space over three storeys and will accommodate the main structures lab including strong floor with associated basement.

This study focuses on reviewing structural frame and floors options for the phase 1 building and makes a recommendation to take forward in completing the stage 2 design. This focus has been inform by previous studies on a range of subjects:

- Energy (embodied energy, materials transport, reclaimable)
- Design for manufacture
- Design for de-construction

| | | | |
|---|---|---|---|
| Author: | *Simon Smith* | | |
| Review: | *Katie Symons* | | |
| Revision history: | *Rev 0* | *Draft issue* | *14.12.2015* |
| | | | |

## Summary

A number of assessment criteria have been used in developing a preferred structural frame and floor system for the phase 1 building. The requirement to adopt design for manufacture and design for de-construction principles have played a significant role in defining the extent of options reviewed within this paper. In this respect insitu reinforced concrete frame has not been considered.

A building structural grid of 7.2m by 11.2m has been adopted. The preferred structural solution comprises a series of steel portal frames spanning 11.2m. Bespoke pre-stressed concrete floor planks will span the 7.2m between steel portal frames.

Further detailed review of this preferred structure will be required including of a number of technical design issues as well as supply chain capability. These reviews should be carried out during the stage 2 design.

## Floor Structure

A review of floor construction options is presented below. The requirement to consider design for manufacture and design for de-construction restricts the options for floor construction to 'dry' systems that are secured to the main frame using demountable fixings. This requirement also precludes the use of floor screeds and as such a raised floor system has been assumed. This will allow floor cambers and construction tolerances to be accommodated.

Design data is listed below:

- Floor live load 4kN/m$^2$ (allows for 3.2kN/m$^2$ floor load and 0.8kN/m$^2$ partitions)
- Floor finishes and ceiling allowance 75kg/m$^2$
- Floor structure NRF 8Hz
- Fire rating 1hr

Two types of floor soffit have been considered. A flat soffit provides uninterrupted routing of services and free air flow across the slab soffit. It also allows flexibility in the installation of partitions. However, unless the floor structure is voided, flat soffit construction tends to lead to heavier structures and potentially goes against the principle of lean design.

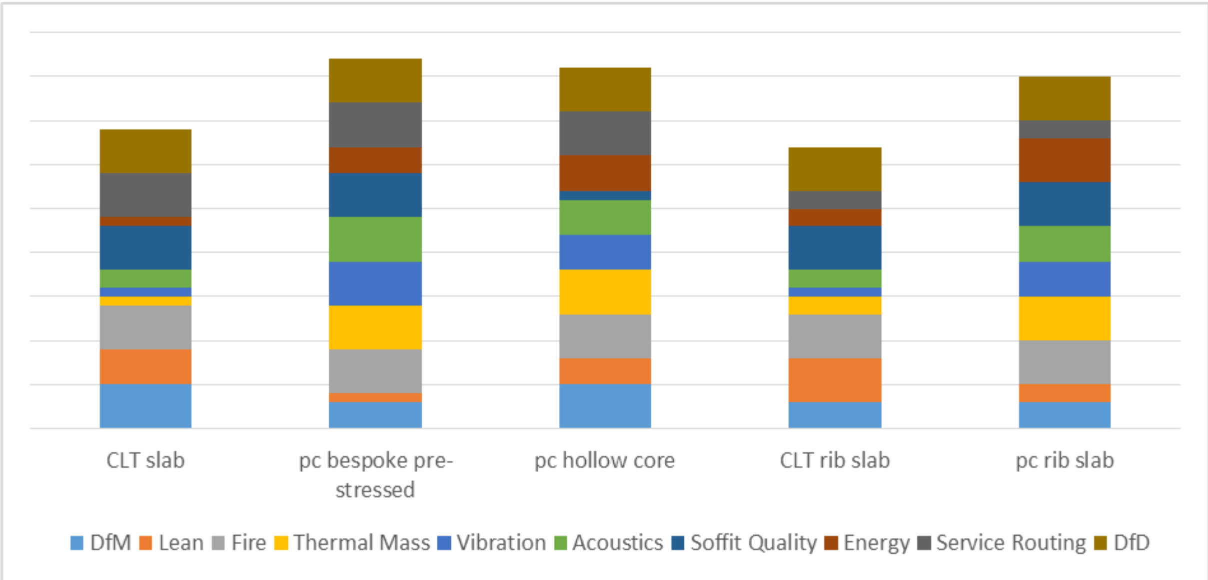
A rib soffit floor construction provides an opportunity to reduce structure weight but challenges of service routing and adaptability will need to be resolved. The added advantage of the rib slab is an increased surface area for thermal mass consideration. However in this instance the ribs run parallel to the facades and as such potentially interrupt air flow.

| | **depth** | **weight** | **embodied energy $E_E$** | **materials transport energy $E_{MT}$** | **reclaimable energy $E_R$** | **$E_E$+$E_{MT}$+$E_R$** |
|---|---|---|---|---|---|---|
| | **(mm)** | **(kg/m$^2$)** | **(kWh/m$^2$)** | **(kWh/m$^2$)** | **(kWh/m$^2$)** | **(kWh/m$^2$)** |
| **Flat soffit** | | | | | | |
| *CLT slab* | *260* | *130* | *433* | *260* | *108* | *585* |
| *pc bespoke pre-stressed* | *225* | *550* | *263* | *165* | *26* | *402* |
| *pc hollow core* | *200* | *400* | *191* | *120* | *19* | *292* |
| **Rib soffit** | | | | | | |
| *CLT rib slab* | *460* | *100* | *333* | *200* | *83* | *450* |
| *pc rib slab* | *425* | *325* | *155* | *98* | *16* | *237* |

The energy figures presented above do not take in to account the frame and foundation requirements for each floor system. These will need to be considered if a decision based on energy is to be made. For the three storey building system being considered previous studies have indicated that the floor system is likely to form the dominant element of energy figures.

In deciding which floor system to use there are a number of assessment criteria that can be used from the client brief. These have been used in a simple scoring matrix presented below to give an un-weighted assessment.

The assessment highlights that a bespoke pre-stressed concrete floor plank would achieve most of the client brief requirements. With the extent of repetition of the structure at West Cambridge, developing a bespoke pre-stressed concrete floor unit makes sense. However, this approach would need to be reviewed against the requirement to competitively tender future phases of construction.




| | DfM | Lean | Fire | Thermal Mass | Vibration | Acoustics | Soffit Quality | Energy | Service Routing | DfD | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *CLT slab* | *5* | *4* | *5* | *1* | *1* | *2* | *5* | *1* | *5* | *5* | *34* |
| *pc bespoke pre-stressed* | *3* | *1* | *5* | *5* | *5* | *5* | *5* | *3* | *5* | *5* | *42* |
| *pc hollow core* | *5* | *3* | *5* | *5* | *4* | *4* | *1* | *4* | *5* | *5* | *41* |
| *CLT rib slab* | *3* | *5* | *5* | *2* | *1* | *2* | *5* | *2* | *2* | *5* | *32* |
| *pc rib slab* | *3* | *2* | *5* | *5* | *4* | *4* | *5* | *5* | *2* | *5* | *40* |

There are a number of issues that will need to be addressed as part of the development of a bespoke pre-stressed plank system:

- Supply chain availability
- Cost
- Demountable fixing to main frame (note disproportionate collapse forces)
- Vibration and dynamic response characteristics (in combination with main frame)
- Opportunities
- Architectural soffit finish

The proposal to pre-stress the plank follows the principles of lean design and reduces plank depth by 30%, reducing frame and foundation loading and potentially offering the opportunity to reduce storey heights.

## Structural Frame

A review of frame options is presented below. The review is based on pc bespoke pre-stressed floor construction and the quantities shown below relate to a simple bay study. The steel quantities shown exclude allowances for connections and secondary steelwork.

Design data is listed below:

- Floor live load 4kN/m$^2$ (allows for 3.2kN/m$^2$ floor load and 0.8kN/m$^2$ partitions)
- Bespoke pre-stressed floor plank assumed at 5.6kN/m$^2$
- Floor finishes and ceiling allowance 75kg/m$^2$
- Frame primary span 11.2m
- Frame spacing 7.2m

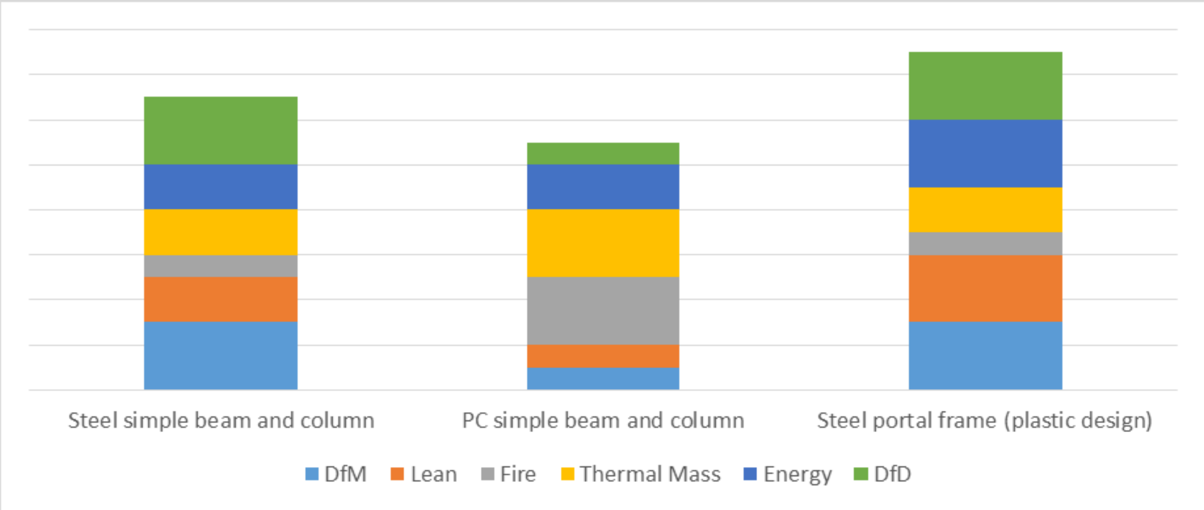
Three types of frame have been reviewed, a primary consideration in choosing the framing options to review has been the requirement to consider design for manufacture and design for de-construction. In this respect steel frame and precast concrete frame are considered.

| | **weight** | **weight** | **embodied energy $E_E$** | **materials transport energy $E_{MT}$** | **reclaimable energy $E_R$** | **$E_E$+$E_{MT}$+$E_R$** |
|---|---|---|---|---|---|---|
| | **(kg/m)** | **(kg/m$^2$)** | **(kWh/m$^2$)** | **(kWh/m$^2$)** | **(kWh/m$^2$)** | **(kWh/m$^2$)** |
| **Steel simple beam and column** | | | | | | |
| *beam (686x254x170UB)* | *170* | *24* | *132* | *7* | *33* | *106* |
| *column (254x254x73UC)* | *73* | *8* | *45* | *2* | *11* | *37* |
| *tie beams* | *34* | *3* | *17* | *1* | *4* | *14* |
| *Total* | | *35* | *194* | *10* | *49* | *156* |
| **PC simple beam and column** | | | | | | |
| *beam (850x450mm)* | *956* | *133* | *63* | *40* | *6* | *97* |
| *column (450x450mm)* | *506* | *57* | *27* | *17* | *3* | *41* |
| *tie beams* | *225* | *20* | *10* | *6* | *1* | *15* |
| *Total* | | *209* | *100* | *63* | *10* | *153* |
| **Steel portal frame (plastic design)** | | | | | | |
| *beam (533x210x109UB)* | *109* | *15* | *85* | *5* | *21* | *68* |
| *column (533x210x109UB)* | *109* | *12* | *68* | *4* | *17* | *55* |
| *tie beams* | *34* | *3* | *17* | *1* | *4* | *14* |
| *Total* | | *30* | *169* | *9* | *42* | *136* |

The energy figures presented above do not take in to account the floor and foundation requirements for each floor system. These will need to be considered if a decision based on energy is to be made. For the three storey building system being considered previous studies have indicated that the floor system (not the frame) is likely to form the dominant element of energy figures.

It is evident from the results below that there is advantage in adopting a portal frame approach as it reduces steel frame quantities. The inherent lateral stiffness of a portal frame also offers opportunity to stabilise the building, potentially omitting the requirement for braced cores.

In deciding which frame system to use there are a number of assessment criteria that can be used from the client brief. These have been used in a simple scoring matrix presented below to give an un-weighted assessment.




| | DfM | Lean | Fire | Thermal Mass | Energy | DfD | Total |
|---|---|---|---|---|---|---|---|
| *Steel simple beam and column* | *3* | *2* | *1* | *2* | *2* | *3* | *13* |
| *PC simple beam and column* | *1* | *1* | *3* | *3* | *2* | *1* | *11* |
| *Steel portal frame (plastic design)* | *3* | *3* | *1* | *2* | *3* | *3* | *15* |

The assessment highlights that a steel portal frame would achieve most of the client brief requirements. With the extent of repetition of the structure at West Cambridge, developing a highly engineered and potentially bespoke steel beam and column section may prove economic. However, this approach would need to be reviewed against the requirement to competitively tender future phases of construction.

There are a number of issues that will need to be addressed as part of the development of the frame system:

- Cost
- Vibration and dynamic response characteristics (in combination with main frame)
- Fire protection including connections
- Services routing through beams

Initial analysis of the portal frame have highlighted a potential benefit in adopting a plastic design approach for sizing the steel frame elements.

## References

P Tzokova, S Smith - Energy and Structural Engineering Materials (issued as part of CUED Move West)

C H Goodchild - Economic Concrete Frame Elements

Appendix A8

# Energy and Structural Engineering Materials

prepared by Petia Tzokova and Simon Smith, Smith & Wallwork Engineers

smithandwallwork
engineers

# Energy and Structural Engineering Materials

*Discussion Paper*

The paper is written as part of the feasibility stage of the reintegration of the Department of Engineering to the West Cambridge Site. The Engineering Department at Cambridge University aims to be a 100,000m$^2$ department by 2025. This will require 60,000m$^2$ of new building on West Cambridge. Buildings will be delivered in a phased manner, the first being the new UKCRIC centre.

This document uses the low-energy metric in "Energy Brief of new Engineering Department Buildings in West Cambridge" by David MacKay to obtain values for the total whole-life energy of structural materials. This paper presents energy values of structural materials and relates them to structural performance as well as typical building values.

| | | | |
|---|---|---|---|
| Author: | *Petia Tzokova* | | |
| Review: | *Simon Smith* | | |
| Revision history: | *Rev 0* | *Draft issue* | *29.09.2015* |
| | *Rev 1* | *KS Edit* | *29.09.2015* |
| | *Rev 2* | *KS Edit* | *16.1.2016* |


## Summary

Based on current industry data and benchmark structural data, this report indicates that a steel frame and pre-stressed concrete plank structural scheme delivers the lowest energy option (for a 4 storey building with a 7.5m column grid on shallow foundations).

A steel frame and cross laminated timber rib slab solution delivers a 16% increase in the energy figures compared to the steel and pre-stressed concrete solution.

A concrete frame options delivers a 51% increase in the energy figures compared to the steel and pre-stressed concrete solution.

Further to the development of the design of the UKCRIC/Phase 1 building, an option which is based on the early structural scheme design for this building has been included. The main development from the previous 3 schemes is the inclusion of a basement and 'strong floor' facility, which has increased embodied energy impacts by virtue of the increased material quantities for these features.

It has become apparent in carrying out this study that the data available is limited in a number of areas and as such information given here should be treated with caution.

Areas where data and assumptions require further research are:

- Transport energy intensity,
- Interpretation of reclaimable energy ($E_R$),

- Future approaches to use of structural materials that may affect energy consumption,
- Benchmarking of material quantities in buildings of different types,

Further consideration should also be given to the following issues prior to making a decision on how this energy study could influence the choice of structural frame:

- Relationship with the operational energy of the building,
- Impact of the Engineering Department's requirement for design for deconstruction,
- Impact of the Engineering Department's requirement for design for manufacture,
- Impact of the Engineering Department's requirement for future flexibility.

As the design and procurement of future buildings moves forward, thought should be given to how predicted and measured energy data will be calculated, recorded and compared.

## Method

The energies considered were embodied energy ($E_E$), material transport energy ($E_{MT}$) and reclaimable energy ($E_R$). Whole-life energy (E) is defined in this document as:

$$E = E_E + E_{MT} - E_R$$

This definition differs from the Engineering Department Energy Metric as it excludes in-use energy ($E_{IU}$) and occupants' energy for transport ($E_T$). These are not considered to be significantly affected by the choice of structural engineering materials.

Three separate comparative analyses were performed:

1. **Material-based (/t)**, where the energy is presented in kWh/t of material. The materials considered are in-situ reinforced concrete, precast concrete, structural steel and glulam.
2. **Beam-based (/m)**, where the energy is presented in kWh/m length of beam. The beams considered all have similar structural performance and are in-situ reinforced concrete, structural steel and glulam.
3. **Building-based (/m²)**, where the energy is presented in kWh/m² of floor area of a building. A four storey frame and associated shallow foundations is considered for an in situ concrete frame, steel frame (with pre-stressed concrete floor planks) and steel frame (with CLT floor planks).

The following values have been used in calculating the **materials based energy (/t)** magnitudes:

Embodied Energy:

| | Density (kg/m³) | Rebar (kg/m³) | $E_E$ (GJ/t) | $E_E$ (kWh/t) |
|---|---|---|---|---|
| Concrete (insitu) | 2500 | 150 | 2.6 | 714 |
| Concrete (prestressed) | 2500 | 50 | 1.7 | 478 |
| Steel | 7850 | - | 20.1 | 5583 |
| Glulam Timber | 480 | - | 12.0 | 3333 |

*These are typical cradle-to-gate figures for structural materials used in the UK.*

Transport Energy:

| | Transport (MJ/t-km) | Transport (km) | $E_{MT}$ (GJ/t) | $E_{MT}$ (kWh/t) |
|---|---|---|---|---|
| Concrete (insitu) | 3.6 | 100 | 0.4 | 100 |
| Concrete (prestressed) | 3.6 | 300 | 1.1 | 300 |
| Steel | 3.6 | 300 | 1.1 | 300 |
| Glulam Timber | 3.6 | 2000 | 7.2 | 2000 |

*These figures assume transportation to site on diesel heavy goods vehicles, over distances typical for UK construction sites.*

Reclaimable Energy:

| | Reclaimable (factor) | $E_R$ (GJ/t) | $E_R$ (kWh/t) |
|---|---|---|---|
| Concrete (insitu) | 0.00 | 2.6 | 0.0 |
| Concrete (prestressed) | 0.10 | 1.7 | 0.2 |
| Steel | 0.25 | 20.1 | 5.0 |
| Glulam Timber | 0.25 | 12.0 | 3.0 |

*These figures assume a certain percentage of the material can be reused at the end of its service life, and re-used (rather than recycled) in a new building, with the credit taken by the original building. The factor is the fraction of the structural frame that could reasonable be assumed to be reused, and consequently the ER is the material embodied energy saved by substituting new materials for reused. (NB ER is subtracted rather than added in the Whole Life Energy definition).*

Total Energy:

| | E (GJ/t) | E (kWh/t) |
|---|---|---|
| Concrete (insitu) | 2.9 | 814 |
| Concrete (prestressed) | 2.6 | 730 |
| Steel | 16.2 | 4488 |
| Glulam Timber | 16.2 | 4500 |

The following values have been used in calculating the **beam based energy (/m)** magnitudes:

A 7.5m span beam taking a floor dead loading of 2.6t/m and a floor live loading of 3.0t/m was calculated using industry codes of practice and the following beams of similar structural performance were used to calculate energy data.

| | Weight (kg/m) | $E_E$ (kWh/m) | $E_{MT}$ (kWh/m) | $E_R$ (kWh/m) | Total (kWh/m) |
|---|---|---|---|---|---|
| Concrete (insitu) 700mm x 350mm | 615 | 437 | 61 | 0 | 498 |
| Steel 533x210x82UB | 82 | 458 | 25 | 114 | 369 |
| Glulam Timber 1000mm x 215mm | 105 | 323 | 194 | 81 | 436 |

The following values have been used in calculating the **building based energy (/m²)** magnitudes:

For the first three options, a four storey building is assumed with a 7.5m x 7.5m grid, supported on shallow foundations onto ground with an allowable bearing pressure of 150kN/$m^2$ and a 150mm thick rc ground bearing slab.

The fourth option is based on the outline structural design specification for the proposed UKCRIC building, the first phase of the Engineering Department's new campus on the West Cambridge site, issued by Smith and Wallwork on December 2015, attached to this briefing note. The major difference between this option and the other 3 is the inclusion of a single storey basement and strong floor, which increases the material quantities per m2 significantly.

The input data and results for each of these four buildings are shown below:

| | Material Quantities (kg/$m^2$) | $E_E$ (kWh/$m^2$) | $E_{MT}$ (kWh/$m^2$) | $E_R$ (kWh/$m^2$) | Whole Life Energy (kWh/$m^2$) |
|---|---|---|---|---|---|
| RC frame | 875 frame<br>378 substructure | 874 | 125 | 0 | 999 |
| Steel frame (hollow core planks) | 50 steel frame<br>345 planks<br>244 substructure | 607 | 143 | 86 | 664 |
| Steel frame (CLT planks) | 50 steel frame<br>90 planks<br>185 substructure | 705 | 214 | 145 | 774 |
| UKCRIC building (sheet piled basement, strong floor, bespoke pc planks, see p6) | 79 steel (frame plus sheet piles)<br>573 (bespoke pc plants)<br>691 (concrete strong floor and raft foundation) | 1207 | 265 | 137 | 1334 |

Results for all four comparative analyses are presented in graphical format overleaf.

## Further Work

The next steps to be completed in this analysis is to include the embodied energy of other major components of the building, specifically the cladding. The 3 components of the lifecycle energy metric as calculated here ($E_E$, $E_{MT}$, $E_R$) will then represent a more accurate representation of the buildings they calculated for, and can be used to inform design decisions on the effect on the energy cost metric, U.

## References

MacKay, D. - Energy Brief for Design of new Engineering Department Buildings in West Cambridge, 2015

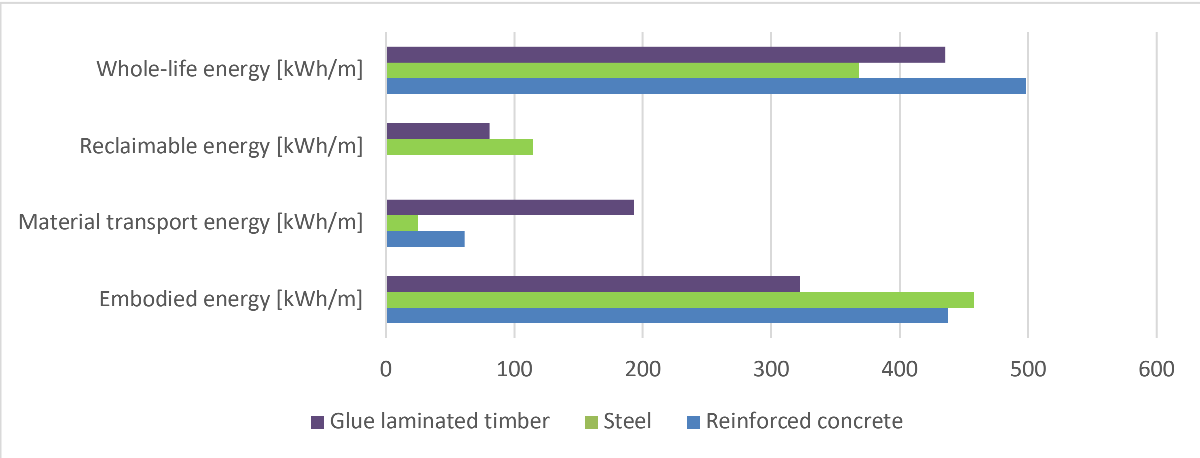
Hammond, G. P. and Jones, C. I. - The Inventory of Carbon and Energy (ICE), 2011

MacKay, D. - Sustainable Energy Without the Hot Air, 2009

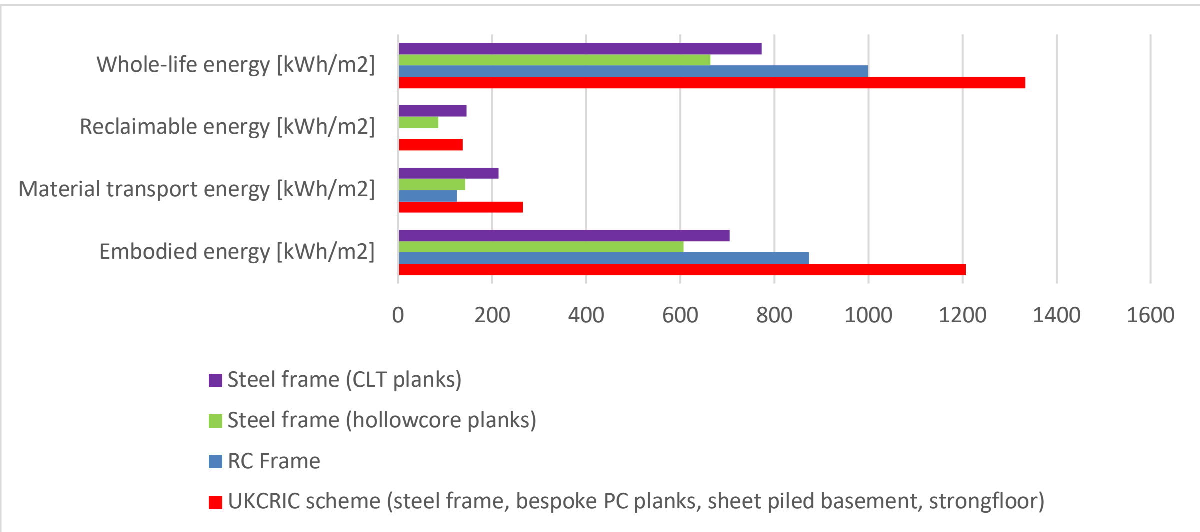
Allwood, J. - Sustainable Materials with Both Eyes Open, 2012

## Material Based Results (kWh/t)

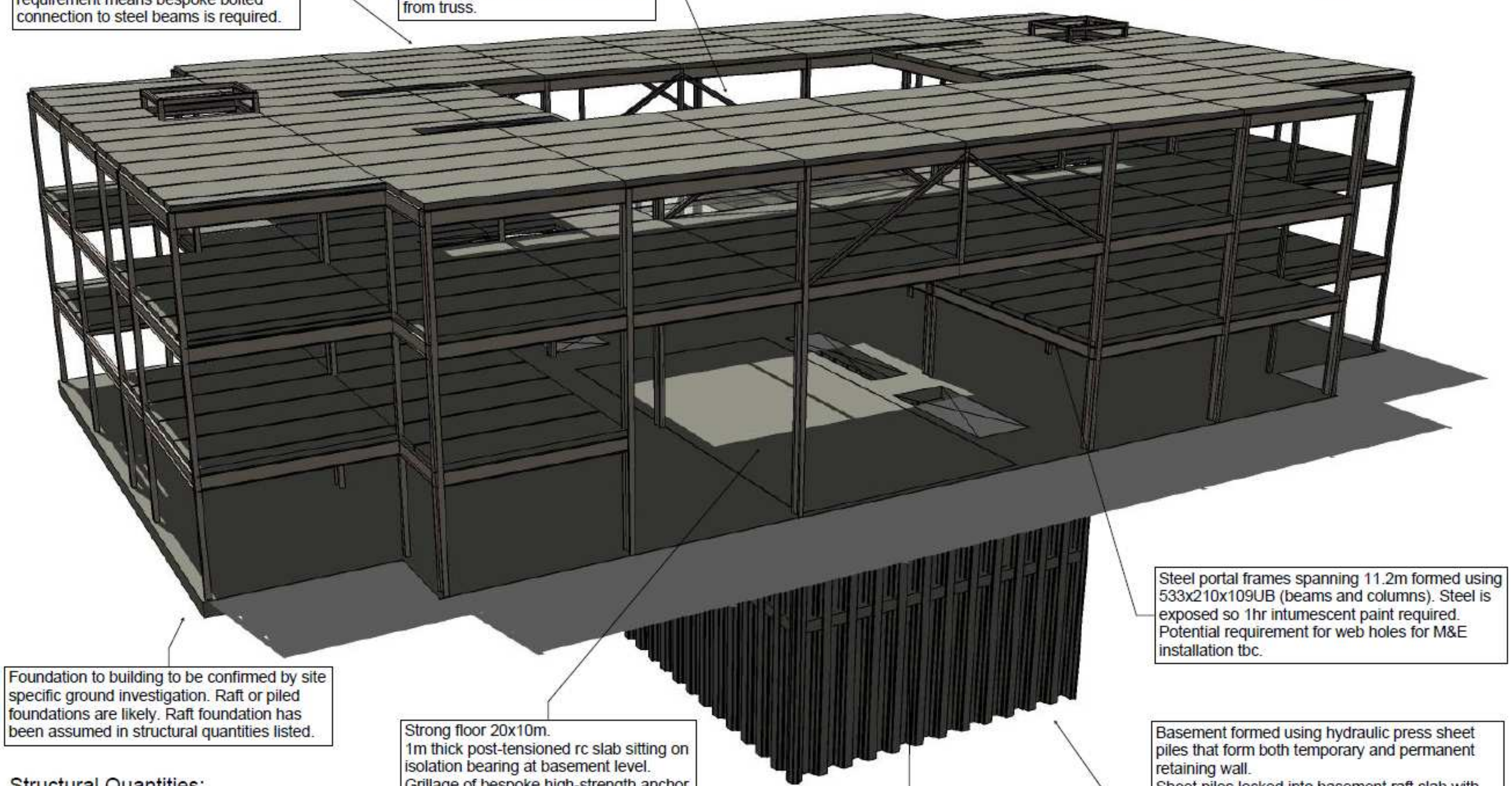

## Beam Based Results (kWh/m)




## Building Based Results (kWh/m²)



Cambridge University Engineering Department
Move West - Phase 1 Building 11.2m x 7.2m grid
Structural Concept
December 2015 - 000193/SK/009




## Structural Quantities:

Sheet piling 80m on plan
Insitu concrete 1175m3
Steel frame 225t
PS concrete floor planks 4425m2
Notes:
- Insitu concrete assumes raft slab
- Insitu concrete includes strong floor, grd and basement
- Steel frame excludes connections and secondary steelwork
- Gross area of model 4250m2 (excludes floor voids)

Appendix A9

# Design for Deconstruction

prepared by Katie Symons and Simon Smith, Smith & Wallwork Engineers

# CUED New Civil Engineering Building

Design for Deconstruction

000193

3rd January 2017

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**Contents**



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**Report Revision History**

| Author | Description | Date | Ref |
|---|---|---|---|
| SSmith | First Issue | 21st December 2016 | 0 |
| SSmith | Section 6.2 units to kWh, page 22 charts updated | 3rd January 2017 | 1 |

## 1. Introduction

This paper is written at completion of RIBA Stage 3 and relates to the new Civil Engineering Building, the first building in the Cambridge University Engineering Department (CUED) move to the West Cambridge Campus. It addresses the following aspects associated with Design for Deconstruction (DfD):

- A brief background to DfD is given.
- DfD measures adopted in the design in particular the pre-cast concrete floor planks.
- DfD stage 1 tender performance specification.
- Review of the DfD proposals using the Energy Cost Metric.

## 2. Summary

The new Civil Engineering Building comprises a steel frame supporting pre-cast concrete floor planks with a concrete raft foundation. The floor system is a bespoke pre-cast concrete plank. Planks bearings are bolted to steel beams and adjacent planks are bolted together.

The CUED brief for the for the new building includes issues such as low whole life energy, design for manufacture, adaptability, embedded sensors and design for deconstruction as well as visible engineering to be considered.

In addition to these brief requirements the design of the building must accommodate future extension, it forms the first element of a long linear building in the masterplan.

All this means that the new Civil Engineering Building will not be business as usual. The design team, main contractor and sub-contractors will need to invest extra time to design, manufacture and install certain elements of the building that are bespoke. In this respect cost plan is enhanced to reflect the brief requirements.

DfD in construction is not often considered (albeit indirectly it is through a health and safety requirement to consider safe demolition). In manufacturing industries (electrical goods and automotive) end of life (ie recycling and re-use) is starting to become the norm.

At the new Civil Engineering Building the adoption of DfD will allow both the steel frame and pre-cast concrete planks to be re-used. It has other potential benefits including the elimination of wet trades on site, it allows easier adaption of the building in the future and it gives more control over the quality of exposed concrete soffits (when compared to standard pc hollow core units). In developing a DfD pre-cast concrete floor system there is potential for an academic research paper, such a system does not yet exist, it would be a first.

DfD also generates some cost and risk issues. Bespoke pre-cast concrete is not widely available in the UK and as such tendering opportunities will be limited. In addition to this the slightly unusual nature of the bolted connections means that significant time and effort is required in order to get a reliable price for the fabrication and installation, something that many sub-contractors are not willing to do (especially in a competitive situation). This has already been the case with Smith and Wallwork market testing indicating a wide range of costs and interest (despite detailed 'tender' information being provided).

An energy cost metric study has been carried out on the current stage 3 design (DfD compliant steel frame and precast floor planks) and compared to an industry standard design (DfD non-compliant steel frame and pc hollow core planks). Overall the DfD design is likely to save in the region of 750,000kWh of energy. However, the DFD design is likely to attract in the region of £300,000 additional construction cost when compared to an industry standard pc hollow core solution. Using the energy cost metric it can be seen that an energy cost of 50p/kWh is required to 'justify' the DfD investment.

Alternatively, if an energy cost of 25p/kWh is taken, then the maximum premium for DfD measures would be in the order of £33/$m^2$ or £125,000 construction cost to establish the lowest value of F.

It should be noted that the energy cost metric may not be the only consideration in the selection of the concrete floor plank solution. Other issues such as adaptability and soffit quality should also be considered.

## 3. Background to Design for Deconstruction

The UK construction industry has a long history of government review, each recommending opportunity for improvement.

- 1934 - 'Reaching for the Skies'
- 1944 - the Simon Report
- 1967 - the Barnwell Report
- 1994 - the Latham Report 'Constructing the Team'
- 1998 - the Egan Report 'Rethinking Construction'

Whilst none of these reviews directly addressed design for deconstruction, both the Latham and the Egan reports highlighted opportunities for the industry to move away from crafting bespoke buildings on site to manufacturing and installing buildings. Design for manufacture (as it is known) by default starts to introduce opportunities for design for deconstruction.

The website www.designingbuildings.co.uk highlights a number of common principles in the design for deconstruction process:

- Design for prefabrication, preassembly and modular construction: Prefabricated units are easily deconstructed and can be transported in large units.
- Simplify and standardise connection details: This allows for efficient construction and deconstruction and reduces the need for multiple tools.

- Consideration of worker safety: The design should aim to reduce potential hazards and the use of potentially hazardous materials.
- Minimise building parts and materials: The design should aim to minimise the amount of building materials and equipment required.
- Select fittings, fasteners, adhesives, sealants etc that allow for disassembly.
- Reduce building complexity: This will reduce costs and improve buildability as well as simplifying the deconstruction process.
- Design with reusable materials: Consideration of materials that are adaptable and will be useful in the future.
- Design for flexibility and adaptability: The design should consider any future renovations or adaptations that may be required to extend the life of the building

Professor of Engineering and the Environment at Cambridge University, Julian Allwood is focusing on the area of material efficiency. One of his research areas is ‘to enable material re-use prior to destructive re-cycling’. The principles of his work have been used to inform the structural frame and floor design for the New Civil Engineering Building.

## 4. Stage 3 Building Design

The new Civil Engineering Building is a three-storey structure providing 4,375m$^2$ of specialist lab and workshop, seminar and office space. It will be located on the east boundary of the West Cambridge campus and forms the central section of what will become a large linear building. It is designed to be extended to the north and south elevations.

### 4.1. Proposed Structure

The proposed structure is a three-storey steel frame supporting bespoke pre-cast concrete planks. The structure will be exposed as part of the internal finish of the building. The primary structural grid is 7.2m by 10.8m with requirement for localised column transfers over the main structures lab and entrance foyer. This primary structural grid of 7.2m by 10.8m covers 75% of the building footprint, maximising the opportunity for repetition in the structural frame.

The steel frame has been designed to accommodate future extension, future provision for services distribution and to accommodate different cladding solutions. The connections of the steel frame are designed as bolted with no site welding.

The concrete floor and roof planks have been designed with bolted connections to adjacent planks and to the top flanges of the steel beams.

The proposed sub-structure is a concrete raft with a localised steel intensive basement below the structures lab strong floor. Silent piling methods are employed to form the basement in order to minimise ground vibrations which will affect nearby vibration sensitive research work.

The structure has been developed with clear benchmark targets (materials quantities and cost) to focus the design on achieving an economic design. The design currently lies below the 75kg/m$^2$ steel benchmark established and a structure target cost of £325/m$^2$ has been set and tested to reflect the exposed nature of the design.

Elements of structure that represent off-site manufacture and/or pre-fabrication are precast floor planks, steel frame and sheet piling. These elements represent 50% of the total cost of the sub- and super-structure package.

### 4.2. Options Considered

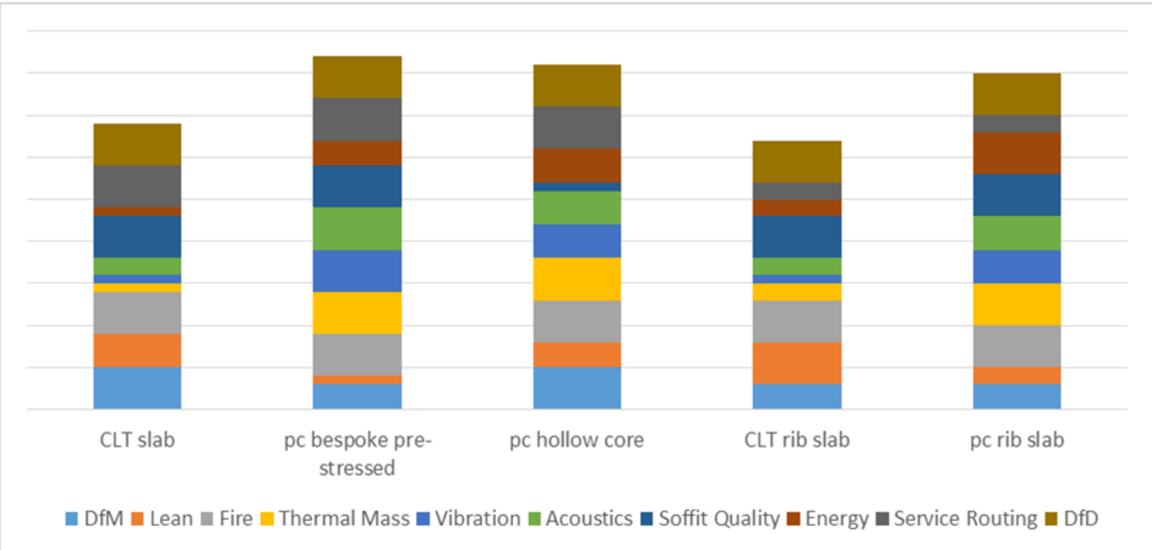
The brief for the CUED Move West project calls for the design to consider a number of distinct strategies when developing the proposals for the Phase 1 building, namely:

- Low life energy
- Design for manufacture
- Adaptability and Upgradability
- Embedded intelligence monitoring
- Design for deconstruction

In addition to these requirements fire, thermal mass, vibration, acoustics and services routing were also considered in the appraisal of insitu concrete, precast concrete, steel and timber frame options.

An initial parametric study focussing on the CUED energy metric reviewed insitu flat slab, steel frame and precast floor planks and steel frame and CLT floor planks. This study (which incorporated sub-structure) highlighted that a steel frame with precast floor planks delivered the lowest energy solution.

A second study using the Civil Engineering Building structural grid introduced the ten assessment criteria established and precast floor planks and steel frame scored highest.



Significant market testing was carried out in order to develop options for the precast floor planks. Fifteen precast companies were asked to review and provide costs for a bespoke precast plank solution. The current cost plan allowance of £180/m$^2$ for this element of the build has determined the adoption of bespoke precast bolted plank system.

## 5. Design for Deconstruction Contract Specification Requirements

A project specific specification that encompasses design for manufacture and design for deconstruction has been produced by Smith and Wallwork and included in the stage 1 tender documentation. The relevant clauses from the specification relevant to DfD are reproduced below.

*4.1 Design for Deconstruction general overview*

*Design for Deconstruction (DfD) is an emerging concept which looks to promote consideration of the whole life cycle of buildings in their design. Rather than think of a building as a 'finished product' upon completion of construction, the constituent components are designed and assembled in such a way as to maximise their potential for future adaptation, easy maintenance, disassembly and further reuse at the end of the building's life. The main design principles include prefabrication and modularization of building components, and the simplification of connections and building systems. By making components easier to remove it is possible to extend or change the building to meet the evolving functions over its lifetime, one of the key requirements of the new Department of Engineering campus development.*

*4.2 Design for Deconstruction applications to the Civil Engineering Building*

*It is expected that parts of the building will need to be modified within the design life of the building to meet the changing requirements of the research to be carried out within the building. Therefore, DfD features of the building should be considered on the basis that components of the building shall be required to be deconstructed much earlier than the design life for the building structure.*

*Elements of the stage 3 design that embody the DfD principles include:*

- *A steel frame that uses bolted, not welded, connections,*
- *Solid precast concrete planks to form the upper floors, connected using bolted connections and steel brackets between planks and to the steel frame, rather than in situ concrete stitching.*

*Furthermore, as the first phase of the new Department of Engineering campus, it is anticipated that buildings of a similar construction will be built adjacent to the Civil Engineering building, connecting into the North and South facades. The structural design makes the following allowances for this:*

- *Cast in fixings to the raft foundation for connection to the raft foundations of future adjacent buildings,*

- *The design of structural elements (beams and columns) on the North and South perimeter to include loads from floors of the future adjoining buildings,*
- *The provision of steel work connecting plates to accommodate easy installation future extension at the North and South gables,*
- *The connections for the façade on the North and South perimeter to the structure to be easily demountable when the future adjacent buildings come on line.*

*4.3 Design for Deconstruction project requirements*

*The contractor will be required to report and justify any changes to the design during Stage 4 that move away from DfD principles that are included in the stage 3 design. The contractor shall be expected to look for ways to introduce elements of DfD wherever possible during the stage 4 design.*

*The contractor shall be required to seek approval from the Client team for the removal of the precast concrete plank bolted connection system, or a change from bolted to welded connections in the steel frame.*

## 6. Energy Cost Metric and Design for Deconstruction

Applying the Energy Cost Metric to the structural frame and floor system enables a detailed energy review of the proposed structure and in particular allows an energy comparison of the proposed bespoke DfD planks with industry standard pc hollow core planks.

### 6.1. Input Data

The energies considered are embodied energy ($E_E$), material transport energy ($E_{MT}$) and reclaimable energy ($E_R$). Whole-life energy (E) is defined in this document as:

$$E = E_E + E_{MT} - E_R$$

This definition differs from the Engineering Department Energy Metric as it excludes in-use energy ($E_{IU}$) and occupants' energy for transport ($E_T$). These are not considered to be significantly affected by the choice of structural engineering materials as in both cases concrete planks are being used (ie thermal mass of the building remains similar).

The following values have been used in calculating the *materials based energy (/t)* magnitudes:

Embodied Energy:

| | Density (kg/m$^3$) | Rebar (kg/m$^3$) | $E_E$ (GJ/t) | $E_E$ (kWh/t) |
|---|---|---|---|---|
| Concrete (precast) | 2500 | 100 | 2.5 | 695 |
| Concrete (prestressed) | 2500 | 35 | 2.0 | 556 |
| Steel | 7850 | - | 20.1 | 5588 |

*These are typical cradle-to-gate figures for structural materials used in the UK.*

Transport Energy:

| | Transport (MJ/t-km) | Transport (km) | $E_{MT}$ (GJ/t) | $E_{MT}$ (kWh/t) |
|---|---|---|---|---|
| Concrete (precast) | 3.6 | 300 | 1.1 | 300 |
| Concrete (prestressed) | 3.6 | 300 | 1.1 | 300 |
| Steel | 3.6 | 300 | 1.1 | 300 |

*These figures assume transportation to site on diesel heavy goods vehicles, over distances typical for UK construction sites.*

Reclaimable Energy:

| | Reclaimable (factor) | $E_R$ (GJ/t) | $E_R$ (kWh/t) |
|---|---|---|---|
| Concrete (precast) | 0.0 | 0.0 | 0.0 |
| | 1.0 | 2.5 | 695 |
| Concrete (prestressed) | 0.0 | 0.0 | 0.0 |
| | 1.0 | 2.0 | 556 |
| Steel | 0.0 | 0.0 | 0.0 |
| | 1.0 | 20.1 | 5588 |

*These figures assume a certain percentage of the material can be reused at the end of its service life, and re-used (rather than recycled) in a new building, with the credit taken by the original building. The factor is the fraction of the structural frame that could reasonable be assumed to be reused, and consequently the ER is the material embodied energy saved by substituting new materials for reused. (note: ER is subtracted rather than added in the Whole Life Energy definition).*

Total Energy:

| | | E (GJ/t) | E (kWh/t) |
|---|---|---|---|
| Concrete (precast) | 0% re-use | 2.9 | 995 |
| | 100% re-use | 1.1 | 300 |
| Concrete (prestressed) | 0% re-use | 2.6 | 856 |
| | 100% re-use | 1.1 | 300 |
| Steel | 0% re-use | 16.2 | 5888 |
| | 100% re-use | 1.1 | 300 |

### 6.2. Scenarios Considered (Energy Only)

The stage 3 design of the new Civil Engineering Building uses approximately 270t of steel and 3800m$^2$ of 250mm thick bespoke precast planks. The embodied energy and transport energy of the stage 3 structure frame and floor system is 3.2x10$^6$kWh and 0.8x10$^6$kWh respectively.

When comparing this design to an industry standard pc hollow core plank system and steel frame (assuming a 10% in steel tonnage due to lighter weight planks), the embodied energy and transport energy of the stage 3 structure frame and floor system is 2.1 x10$^6$kWh and 0.5 x10$^6$kWh respectively. This represents a saving of 1.4 x10$^6$kWh prior to any re-use scenario.

A range of re-use scenarios has been considered and is presented below.

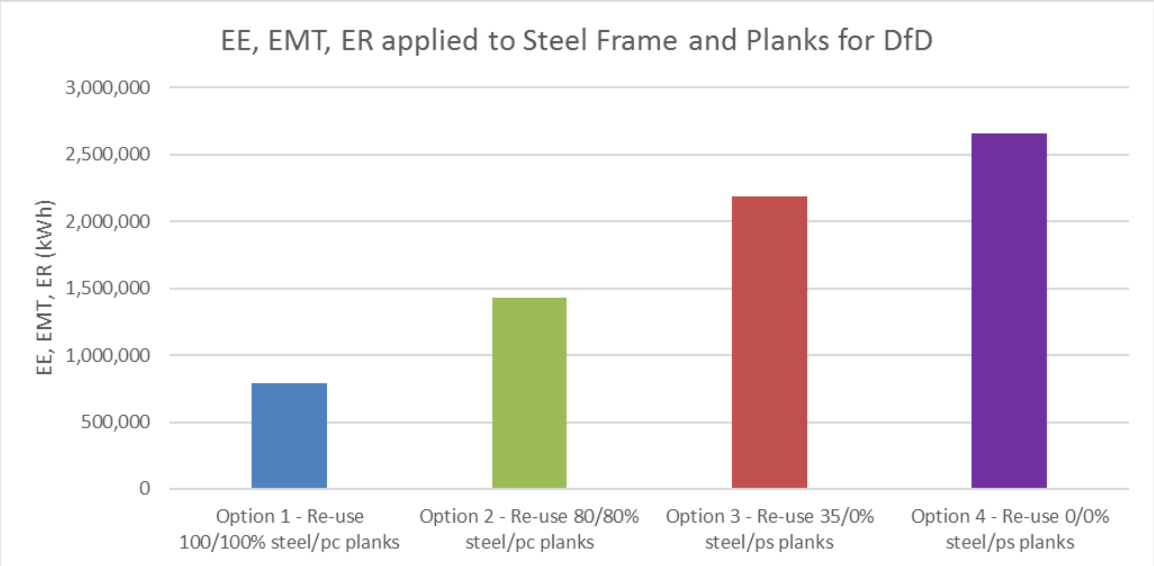
- Option 1: Bespoke bolted pc planks & steel frame 100%/100% re-use of steel and concrete
- Option 2: Bespoke bolted pc planks & steel frame 80%/80% re-use of steel and concrete
- Option 3: PC hollow core planks & steel frame 35%/0% re-use of steel and concrete

- Option 4: PC hollow core planks & steel frame 0%/0% re-use of steel and concrete

The re-use potential for the current stage 3 design with bespoke bolted planks ranges from option 1 full re-use (ie 3.2 x$10^6$kWh) to option 2 80% steel frame and pc plank re-use (ie 2.5 x$10^6$kWh).

The re-use potential for the pc hollow core plank and steel frame ranges from option 3 partial re-use of the steel frame (ie 0.5x$10^6$kWh) to option 4 0% re-use of the steel frame and planks (ie 0kWh). The pc hollow core plank option involves grouted and shear stud connected planks to beams and as such de-construction without damage is limited.

It is estimated therefore that the total energy saving in adopting a DfD approached is likely to be in the region of 0.75x$10^6$kWh (ie option 2 vs option 3).




### 6.3. Scenarios Considered (Energy and Cost)

Within the energy brief, an Energy Cost Metric was defined with the intention that design decisions are to be made on the basis of resulting in a minimum value of the objective function, F, where:

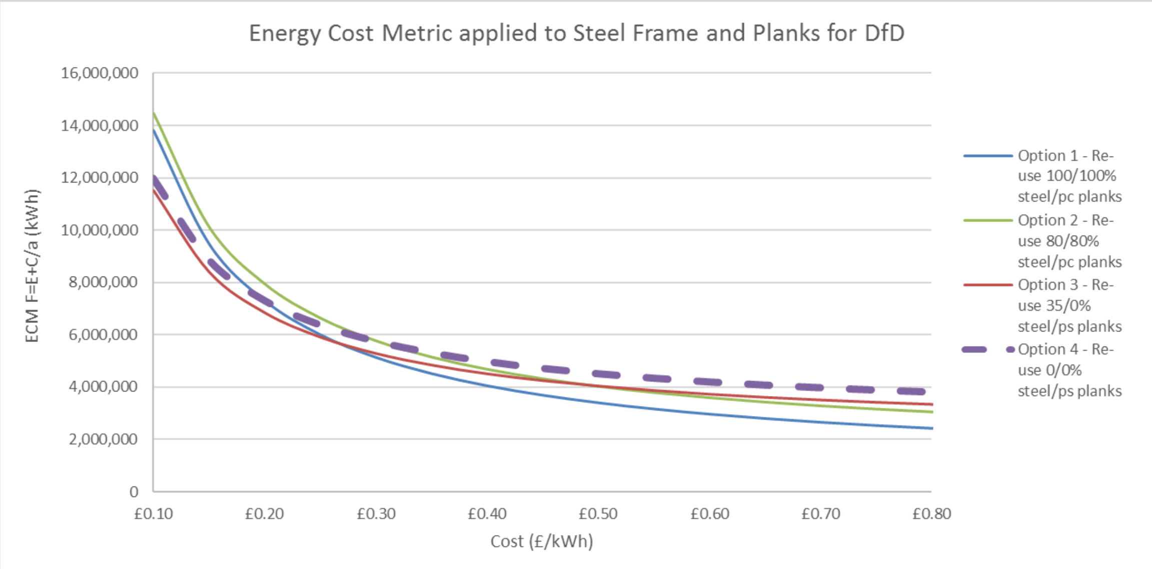
- $F = E + C/\alpha$
- E is the approximate total whole-life energy (in kWh or MJ), defined below,
- C is the cost,
- $\alpha$ is a weight such as 25 p/kWh, to be determined by the University.

The following cost data has been taken from AECOM stage 3 revision 3 cost plan:

- Steel £2000/t
- Bespoke pc planks £180/$m^2$

A cost of £100/$m^2$ has been taken for pc hollow core planks which includes grouting, shear stud connection to beams and an enhancement for visual soffits and detailing around columns.

An analysis of all for options has been undertaken for varying α values (10p/kWh to 80p/kWh) and these are represented on the graph below.




The results of the energy cost metric review when applied to DfD can be summarised as follows:

- At 25p/kWh the minimum value of F is achieved by option 3, steel frame 35% re-use and pc hollow core planks with 0% re-use.
- At 30p/kWh the minimum value of F is achieved by option 1, steel frame 100% re-use and bespoke precast planks with 100% re-use.
- At 50p/kWh option 2 (steel frame 80% re-use and bespoke precast planks with 80% re-use) has a lower value of F than option 3 (steel frame 35% re-use and pc hollow core planks with 0% re-use).
- If a 25p/kWh unit of α is to be used as a basis of choosing whether DfD measures are justified from an energy cost metric, then the spreadsheet shows that a premium of £33/m$^2$ or

The full data set can be seen in appendix C.

## 7. References

The following reports and documents were referred to in the production of this report.

Documents provided as part of the stage 1 tender:

- Drawing EM00025-SAW-CE-ZZ-DR-S-0300
- Design for Manufacture and Deconstruction Performance Specification
- Energy Cost Metric Performance Specification
- Concrete Specification
- Structural Steelwork Specification

Documents completed as part of the RIBA stage 2 and 3 work:

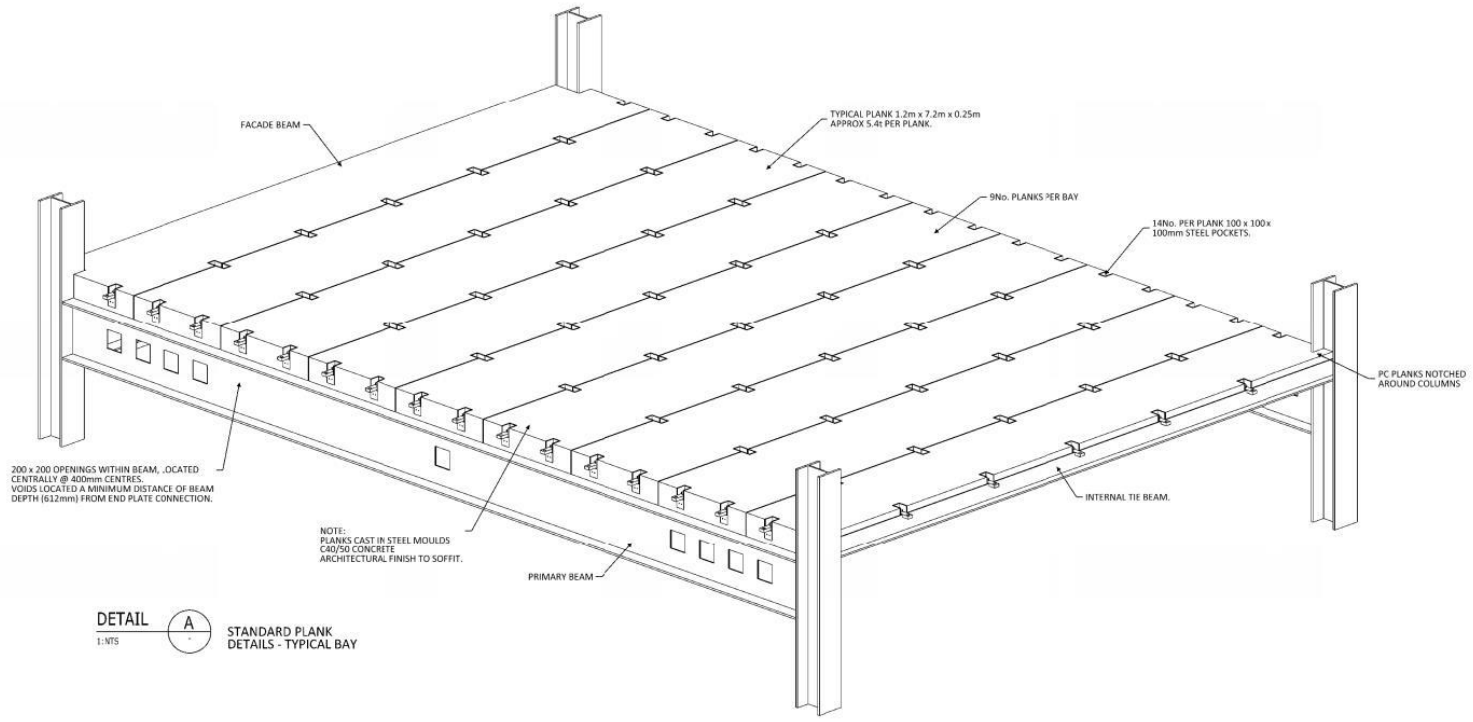
- Discussion Paper: Energy and Structural Engineering Materials
- CUED, Technical Report: Design for Deconstruction
- Discussion Paper: Frame Study 7.2m x 11.2m
- Precast Concrete Flooring Market Testing Summary
- SK023 Engineering Sketch Precast Concrete Bolted Planks

The documents have been referenced in the production of this report:

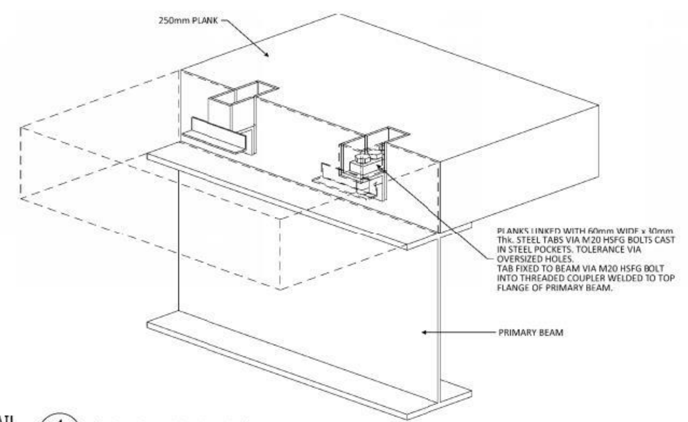

- MacKay, D. - Energy Brief for Design of new Engineering Department Buildings in West Cambridge, 2015
- Hammond, G. P. and Jones, C. I. - The Inventory of Carbon and Energy (ICE), 2011
- MacKay, D. - Sustainable Energy Without the Hot Air, 2009
- Allwood, J. - Sustainable Materials with Both Eyes Open, 2012

Appendix A

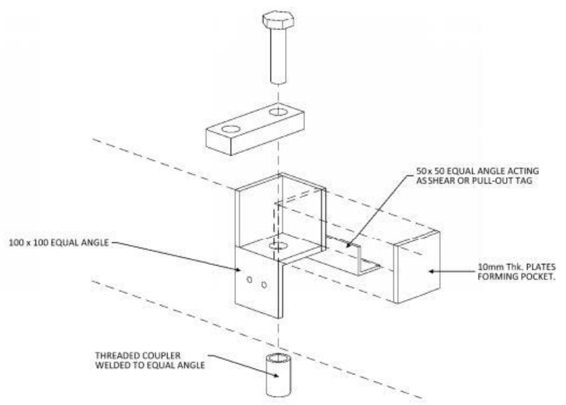
Stage 3 drawings




DETAIL A
1:NTS
STANDARD PLANK DETAILS - TYPICAL BAY




DETAIL 1
1:NTS
STANDARD PLANK DETAILS - PRIMARY BEAM CONNECTION




DETAIL 2
1:NTS
STANDARD PLANK DETAILS - POCKET DETAIL

**smithandwallworkengineers**

50 St Andrews Street, Cambridge, CB2 3AH
T: 01223 750249
E: contact@smithandwallwork.com

NOTE
1. Do not scale from this drawing.
2. All dimensions are in millimetres u.n.o.
3. All levels are in metres above ordnance datum u.n.o.
4. This drawing is to be read in conjunction with all relevant architects and engineers drawings and specifications.

| Rev | Date | Description | By | Chk'd |
|---|---|---|---|---|
| P04 | 31.08.16 | ISSUED FOR TENDER | AP | SSm |
| P03 | 05.08.16 | ISSUED FOR STAGE 3 | AP | SSm |
| P02 | 15.07.16 | ISSUED FOR COSTING | AP | SSm |
| P01 | 18.03.16 | ISSUED FOR STAGE 2 | AP | SSm |

Drawing Title:
GENERAL ARRANGEMENT
TYPICAL DETAILS
SHEET 1

SaW Project Ref: 000193
Scales: NTS
Original Size: A1

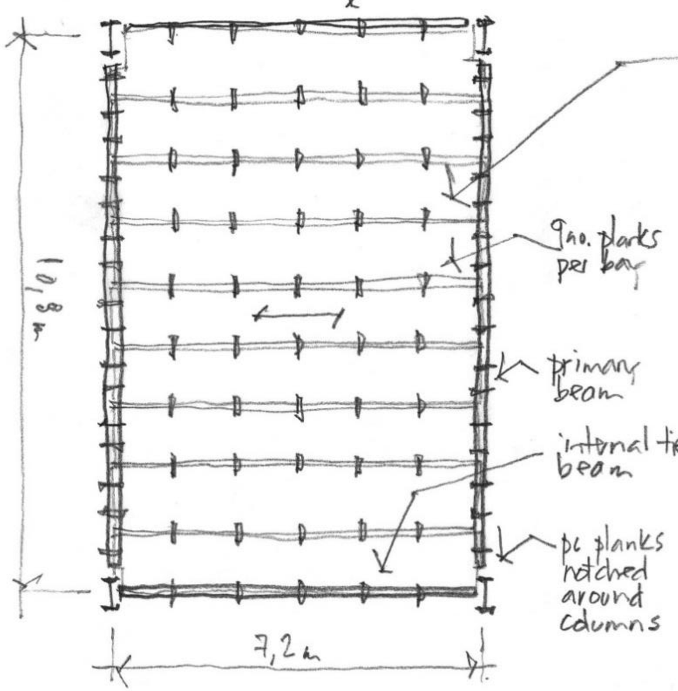
Project Details:
THE CIVIL ENGINEERING BUILDING
WEST CAMBRIDGE SITE
CAMBRIDGE

Client:
UNIVERSITY OF CAMBRIDGE

| Project | Originator | Volume | Level | Type | Role | Number |
|---|---|---|---|---|---|---|
| EM00025- | SaW - | CE - | ZZ - | DR - | S - | 300 |

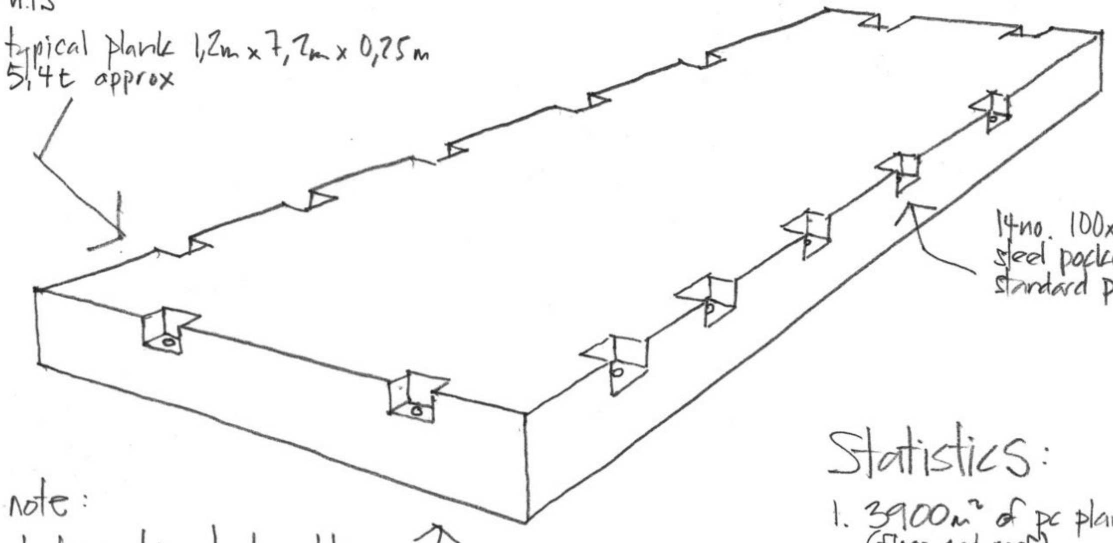
Status: D2
Suitability Description: FIT FOR TENDER
Revision: P04
Revision Description: TENDER

## Typical Bay:
1:100 @ A3




## Standard Plank Iso:
n.t.s

typical plank 1,2m x 7,2m x 0,25m
5,4t approx

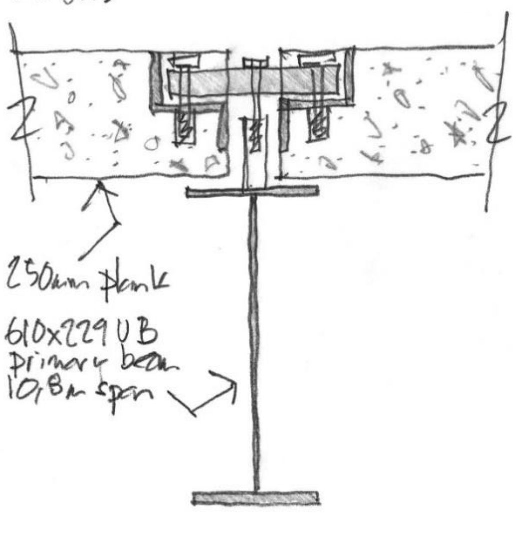



note:
planks cast in steel moulds
C40/50 concrete?
architectural finish soffit

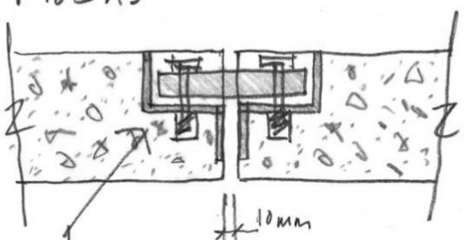
## Statistics:

1. 3900m² of pc planks (floor and roof)
2. approx. 290no. standard planks ie 2500m²
3. approx. 31no. facade planks ie 280m²
4. remainder are bespoke

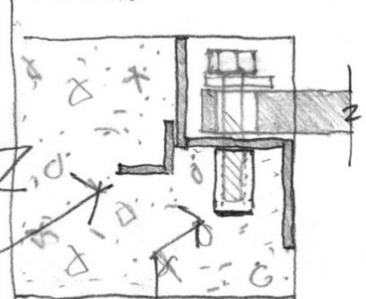
## Detail: primary beam
1:10 @ A3



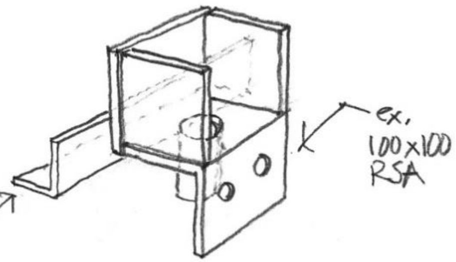

## Detail: plank long edge
1:10 @ A3




## Steel Pocket:
1:5 @ A3




Iso of steel pocket:




Smith and Wallwork Mar16
000193/SK/023

Appendix B

Market testing

# University of Cambridge Department of Engineering

## Civil Engineering Building

*Precast Concrete Flooring Market Testing Summary*

This is an updated record of the Market Testing exercise undertaken by Smith and Wallwork during the Stage 3 of the design of the CUED Phase 1 building on the option of a bespoke precast concrete flooring system that meets the aspirational brief requirements for Design for Deconstruction.

| | | | |
|---|---|---|---|
| Author: | *Katie Symons* | | |
| Revision history: | *Rev 0* | *Stage 2* | *18/03/2016* |
| | *Rev 1* | *Interim Stage 3* | *10/6/2016* |
| | *Rev 2* | *Stage 3* | *8/7/16* |

The table below summarises the responses from precast concrete manufacturers and organisations regarding the practical and economic feasibility of using a bespoke precast concrete floor plank system for the Civil Engineering building. Avoiding the use of in situ concrete, replacing connections to the steel frame with fully demountable cast in fixings allows the system to be modified and removed without destroying the panels in future, adhering to Design for Deconstruction principles.

The total area of planks required has been taken off the 3D model for the building as 3900m2. A sketch (SK023) showing further development on the connection details for the precast planks was sent to precast manufacturers in May/June 2016, as an update to the concept design drawings S200 and S201 sent during stage 2. Comments were requested on the practicalities of this type of system, any previous experience, and a typical cost, and are recorded below:

| Company | Contact | Date | Quote | Comments |
|---|---|---|---|---|
| Bison | John Sterland, Structural Precast Estimator | 6/6/16 | **250mm thick units with 100kg/m3 reinforcement £165-170/m2.** | Supply only, design and installation of slab by others. |
| Milbank | Terry Senior, Estimating Manager – Specialist Precast | 31/05/16 | **£228/m2 including all cast in sockets etc for a 260mm thk reinforced slab.** | Allowance of £20/bracket. |
| Spanwright | Bill Gray, Sales Director | 10/6/16 | **Bespoke 275mm thk reinforced slab, including provision for cast-in sockets, £140-150/m2.** | Allow for £25/bracket, suspect the number of brackets can be reduced, allowing for further reduction price. |
| Acheson & Glover | Steven Bunting, Technical Estimating Director | 10/03/16 | **£110/m2 production,**<br>**£170/m2 delivered,**<br>**£185/m2 installed.** | Assumed articulated lorry deliveries, use of 80t cranes for installation. Allowed £25/bracket, 14 no. per plank, suggested use of off-the-shelf products in lieu of these to reduce costs. |
| Forterra | Martin Bolton, National Sales Manager | 10/6/16 | **£152/m2** | Supply only, based on 150kg/m3 rebar and no allowance for brackets. |
| Coltman | Karl Timmins, Design Engineer | 7/6/16 | **£252/m2 for 250mm thk reinforced units** | No other details on quote, returned with queries due to large increase on previous quote. |
| Flood Precast | Martin Darby, precast design engineer | 7/6/16 | **£122/m2 for supply only, including allowance of £20/bracket.**<br>**£162/m2 including installation.** | Best estimate for installation is assuming an 80t mobile crane (£40/m2). |
| Macrete | Nigel Hogg | 10/6/16 | **Previous price: option 2 – 300mm thk reinforced slab £160/m2**<br>**Awaiting updated price.** | Options allowing for 1.5kN/m2 finishes and 1kN/m2 partitions load.<br>Awaiting updated response with lower design loads. |
| ABM | Mike Sanderson, Business | 10/06/16 | **£137/m2 excluding brackets.** | Allowing for 100kg/m3 rebar. |

| | | | | |
|---|---|---|---|---|
| | Development manager | | | |
| FPMcCann | Daniel Westgate, Bespoke Precast department | 10/6/16 | **£226/m2** | Including allowance of £40/steel bracket. |
| Creagh | Bernard Graham, Special Precast department | 10/6/16 | **£225/m2** | Including steel brackets. |

Appendix C

Energy Cost Metric and Design for Deconstruction

The energy cost metric study carried out in this report analyses four different structural frame options which are presented below along with the data sets used.

- *Option 1: Bespoke bolted pc planks and steel frame 100%/100% re-use of steel and concrete*
- *Option 2: Bespoke bolted pc planks and steel frame 80%/80% re-use of steel and concrete*
- *Option 3: PC hollow core planks and steel frame 35%/0% re-use of steel and concrete*
- *Option 4: PC hollow core planks and steel frame 0%/0% re-use of steel and concrete*

## Materials data set:

| | Density ($kg/m^3$) | Rebar ($kg/m^3$) | $E_E$ (GJ/t) | $E_E$ (kWh/t) |
|---|---|---|---|---|
| Concrete (precast) | 2500 | 100 | 2.5 | 706 |
| Concrete (prestressed) | 2500 | 35 | 1.9 | 518 |
| Steel | 7850 | - | 20.1 | 5588 |

| | Transport (MJ/t-km) | Transport (km) | $E_{MT}$ (GJ/t) | $E_{MT}$ (kWh/t) |
|---|---|---|---|---|
| Concrete (precast) | 3.6 | 300 | 1.1 | 300 |
| Concrete (prestressed) | 3.6 | 300 | 1.1 | 300 |
| Steel | 3.6 | 300 | 1.1 | 300 |

## Option 1 data set:

| Option 1 - Re-use 100/100% steel/pc planks | | | | | | | | CEB | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | weight | transport | re-use | | total | | | weight | | | | transport | re-use | total |
| | kg/m2 | | % steel | % planks | kWh/m2 | | | beams (t) | columns (t) | bracing (t) | planks (m2) | | | |
| steel | 81 | | 100% | | | | | 170 | 91 | 8 | 3800 | | | |
| (kWh/m2) | 455 | 24 | 455 | | 24 | | kWh | 949,228 | 509,188 | 44,004 | | 80,727 | 1,502,420 | 80,727 |
| precast | 625 | | | 100% | | | | | | | | | | |
| (kWh/m2) | 441 | 188 | | 441 | 188 | | kWh | | | | 1,677,035 | 713,070 | 1,677,035 | 713,070 |
| | | | | | 212 | | | | | | | | | 793,797 |

## Option 2 data set:

| Option 2 - Re-use 80/80% steel/pc planks | | | | | | | | CEB | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | weight | transport | re-use | | total | | | weight | | | | transport | re-use | total |
| | kg/m2 | | % steel | % planks | kWh/m2 | | | beams (t) | columns (t) | bracing (t) | planks (m2) | | | |
| steel | 81 | | 80% | | | | | 169.875 | 91.125 | 7.875 | 3800 | | | |
| (kWh/m2) | 455 | 24 | 364 | | 115 | | kWh | 949,228 | 509,188 | 44,004 | | 80,727 | 1,201,936 | 381,211 |
| precast | 625 | | | 80% | | | | | | | | | | |
| (kWh/m2) | 441 | 188 | | 353 | 276 | | kWh | | | | 1,677,035 | 713,070 | 1,341,628 | 1,048,477 |
| | | | | | 391 | | | | | | | | | 1,429,688 |

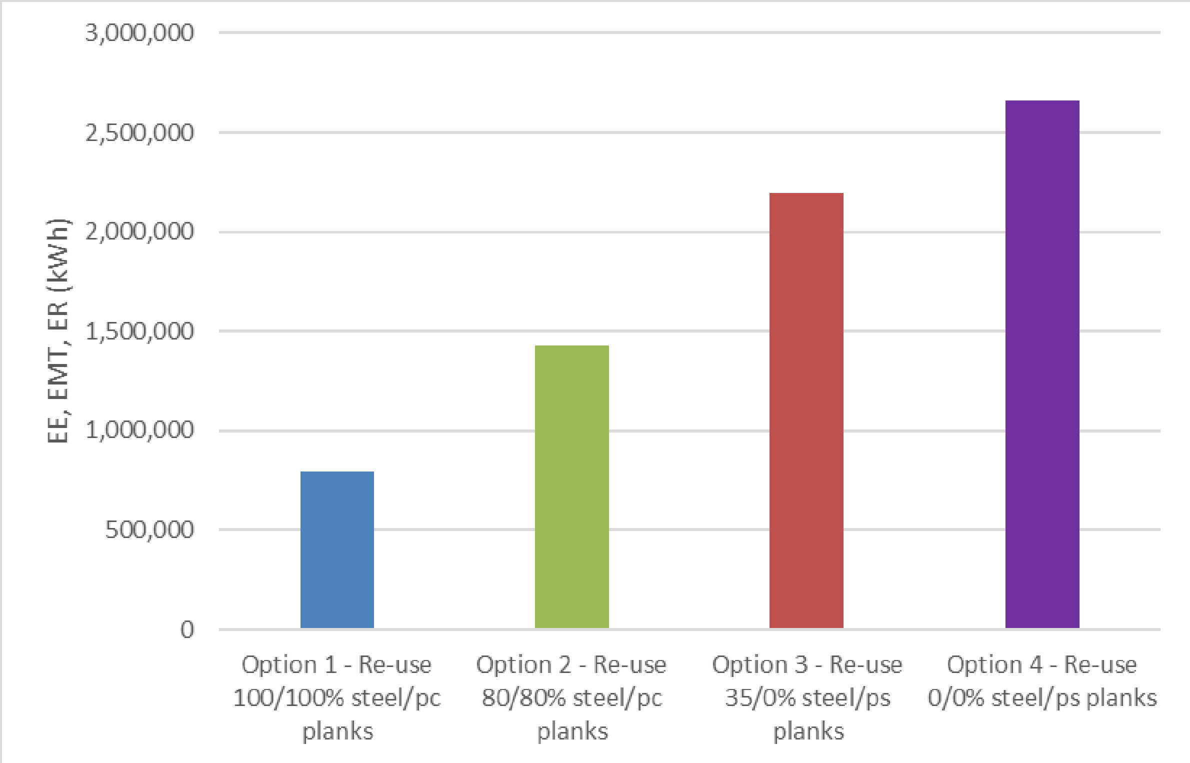
## Option 3 data set:

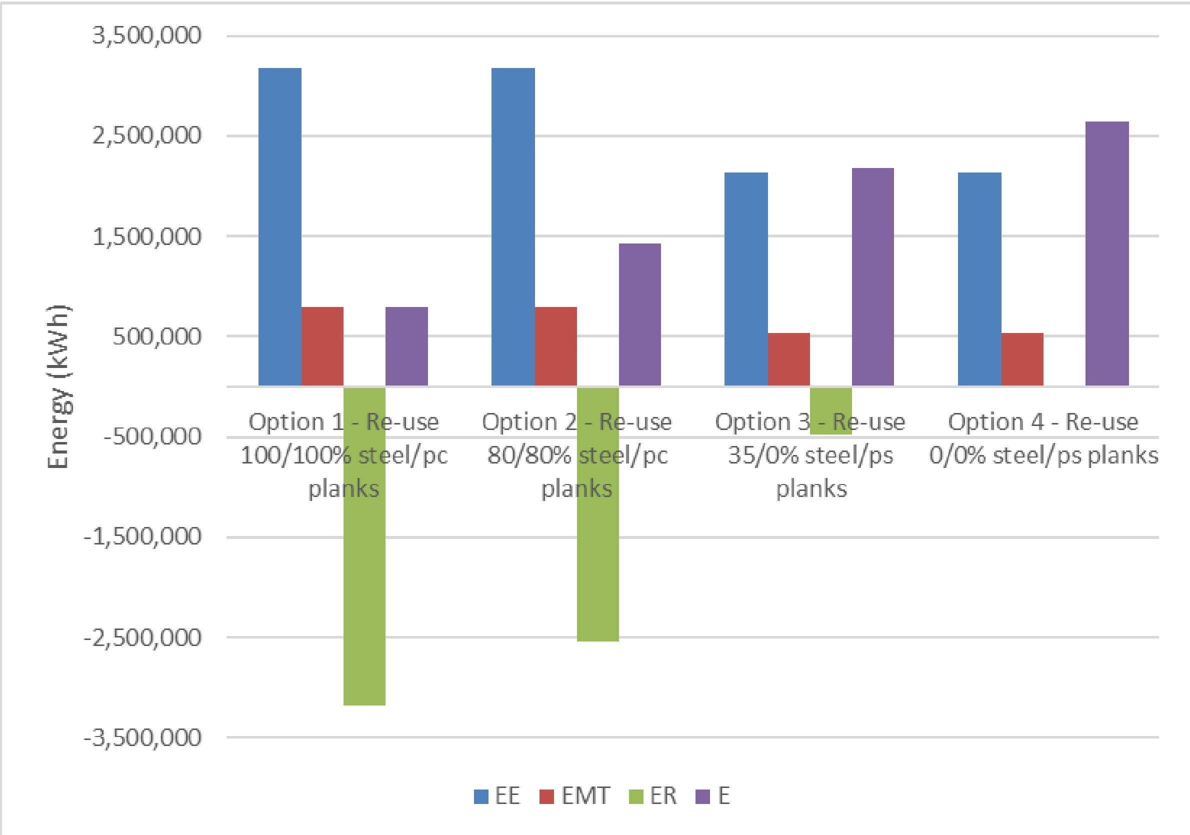
| Option 3 - Re-use 35/0% steel/ps planks | | | | | | | | CEB | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | weight | transport | re-use | | total | | | weight | | | | transport | re-use | total |
| | kg/m2 | | % steel | % planks | kWh/m2 | | | beams (t) | columns (t) | bracing (t) | planks (m2) | | | |
| steel | 73 | | 35% | | | | | 152 | 82 | 7 | 3800 | | | |
| (kWh/m2) | 407 | 22 | 143 | | 287 | | kWh | 850,350 | 456,148 | 39,420 | | 72,318 | 471,071 | 947,164 |
| pc hollow | 400 | | | 0% | | | | | | | | | | |
| (kWh/m2) | 207 | 120 | | 0 | 327 | | kWh | | | | 787,652 | 456,365 | 0 | 1,244,017 |
| | | | | | 614 | | | | | | | | | 2,191,181 |

## Option 4 data set:

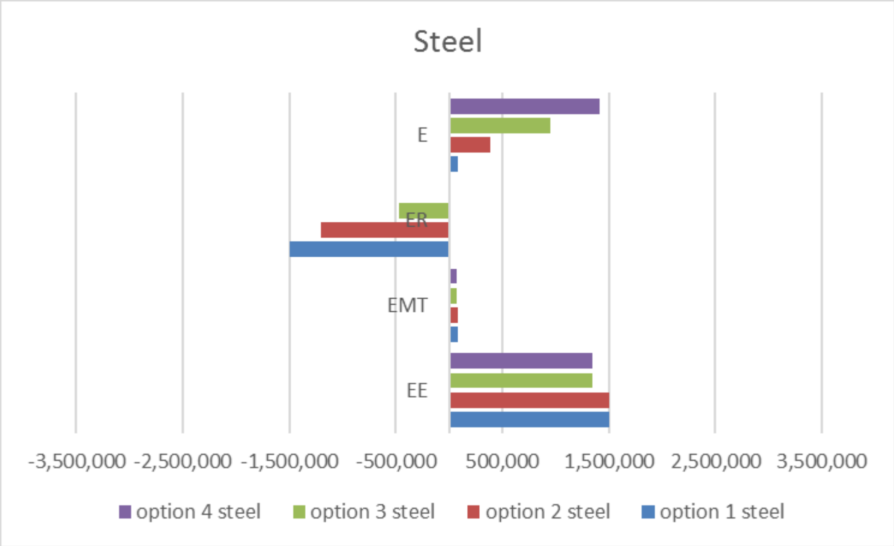
| Option 4 - Re-use 0/0% steel/ps planks | | | | | | | | CEB | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | weight | transport | re-use | | total | | | weight | | | | transport | re-use | total |
| | kg/m2 | | % steel | % planks | kWh/m2 | | | beams (t) | columns (t) | bracing (t) | planks (m2) | | | |
| steel | 73 | | 0% | | | | | 152.179688 | 81.6328125 | 7.0546875 | 3800 | | | |
| (kWh/m2) | 407 | 22 | 0 | | 429 | | kWh | 850,350 | 456,148 | 39,420 | | 72,318 | 0 | 1,418,236 |
| pc hollow | 400 | | | 0% | | | | | | | | | | |
| (kWh/m2) | 207 | 120 | | 0 | 327 | | kWh | | | | 787,652 | 456,365 | 0 | 1,244,017 |
| | | | | | 757 | | | | | | | | | 2,662,252 |

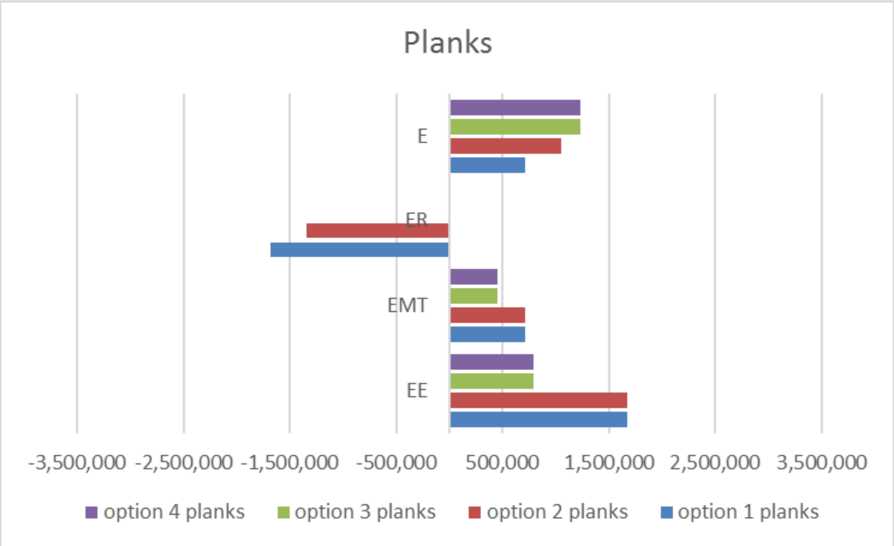
Total energy (kWh) prediction for each option $E = E_E + E_{MT} - E_R$:

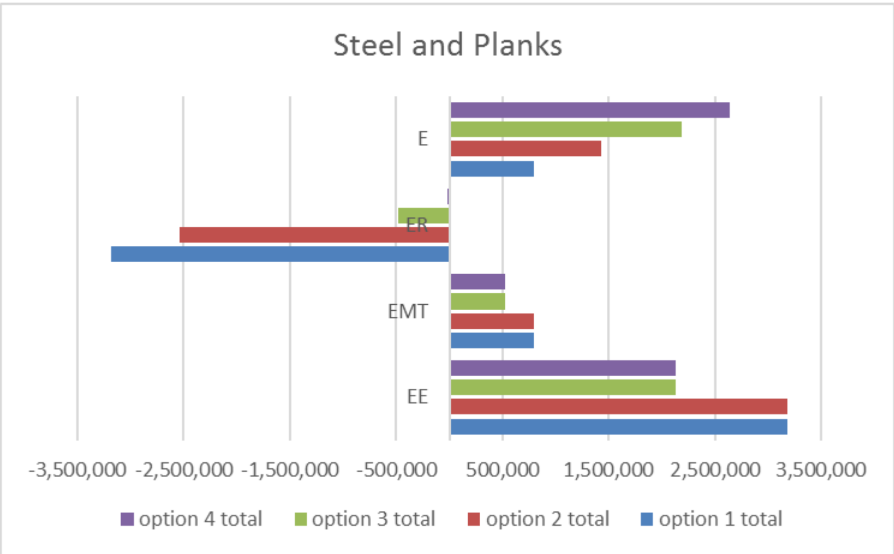


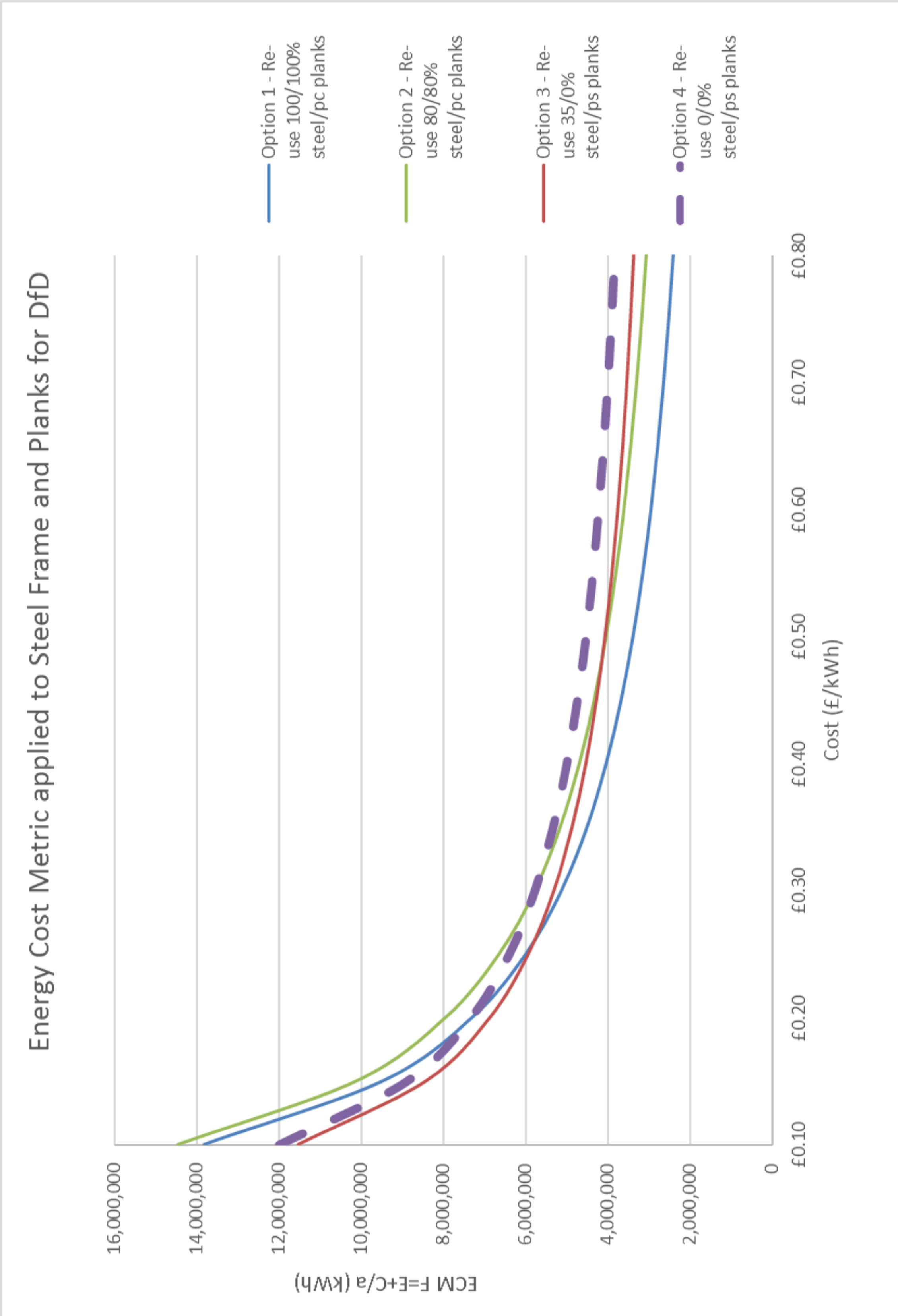
Energy (kWh) for each option by element:



Energy cost metric with varying value of α:
(steel cost £2000/t, DfD precast planks £180/m$^2$, PC hollow core planks £100/m$^2$)



resource efficiency collective

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