Reducing Material Demand in Construction

A Prospectus for meeting the UK Government's "Construction 2025" ambitions for captial carbon emissions



UNIVERSITY OF CAMBRIDGE

Reducing Material Demand in Construction

UNIVERSITY OF CAMBRIDGE

Industrial Energy and Material Demand Reduction

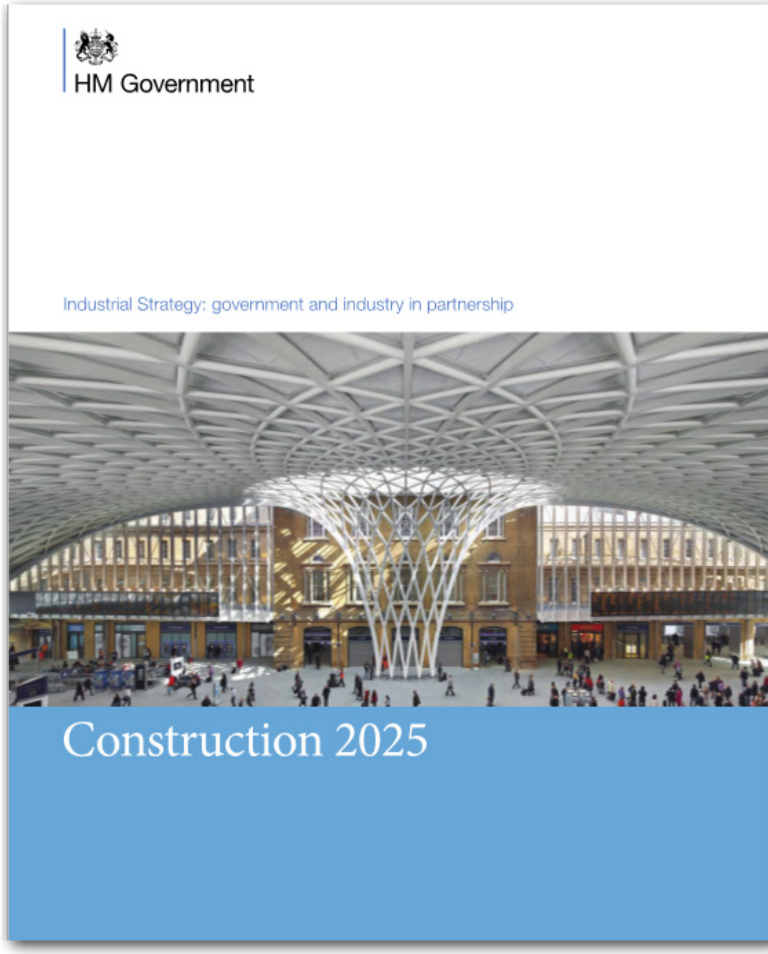
Most energy used in industry is required for the highly efficient production of bulk materials. The industries that produce these bulk materials, such as steel, cement, paper, plastic and aluminium, are already very efficient in their use of energy, and are unlikely to be powered in future by renewable energy sources. Therefore if we want to reduce industrial emissions, we have to reduce our demand for new material production.

This theme drives our large inter-disciplinary group of researchers in the University of Cambridge. Our recent book, "Sustainable Materials: with both eyes open", which can be read online at www.withbotheyesopen.com, sets out the technical case for using less material and explores six strategies to bring it about. Now our work is focused on making this happen in practice – in collaboration with industry and government partners along the whole supply chains of the bulk materials.

Our planned outputs include technical innovations to deliver material savings in production and design, demonstrations of the business case for material efficiency accounting for purchasing preferences, policy recommendations based on business, sector and trade analysis, and information tools to support well-informed decision making.

Our work in construction is led by Danielle Densley Tingley
Department of Engineering, University of Cambridge
Trumpington Street, Cambridge CB2 1PZ,
United Kingdom
Tel: 01223 332672
Email: dod21@cam.ac.uk
www.ukindemand.ac.uk

Executive Summary



Construction 2025, a partnership between industry and Government, has published four ambitions to transform the UK construction industry, one of which is a 50% reduction in emissions. Minimisation of operation carbon is already underway, driven by building regulations. But halving the emissions associated with the construction project itself –known as embodied or capital carbon emissions – requires a different approach.

One sixth of the world's CO_2 emissions, or equivalently half of all industrial emissions, arise from producing steel and cement. Half of this steel and all of the cement is used in construction, but the industries that make these two key materials are the most energy efficient in the world. It is unlikely that there will be any significant break-through technologies for producing these materials, and because we use them in such great volumes (currently 200kg of steel and 550kg of cement per person per year for everyone alive on the planet) currently we have no substitutes. This means that halving capital carbon emissions to meet one of the ambitions of Construction 2025 – means halving the amount of new material purchased by the sector.

Technically it's feasible to achieve this. For example, by avoiding over-design, we could halve the structural mass in new multi-storey steel buildings – it's currently cheaper to use excess material if it allows a saving in labour, so we use more than necessary. We're also using commercial buildings for a fraction of their potential lifetime. Even at the end of life, we could re-use modules, components and materials directly, rather than dumping or recycling them. Using half the material for twice as long is a realistic ambition for the construction sector, and would significantly reduce its capital carbon emissions.

This approach could also reduce delivery times – for example with offsite fabrication of components, or design for adaptability, upgrade and eventual deconstruction. And, with anticipated growth of construction worldwide in the next 10-30 years, the UK could become a global leader in the export of the systems, interfaces and design expertise to produce materially efficient construction. Capital carbon is significant, and the sector's Low Carbon Roadmap targets a 39% reduction by 2050, material efficiency will be required to meet this. With early action, the UK could develop as a leader in the area, maximizing export opportunities.

But the reality of using less (cheap) material in a country with high labour costs, is that initially, material efficiency may increase initial construction costs. As yet, we don't have enough evidence to know how costs will change, or to show the whole life cost benefit of longer service life, or reusable components. As we understand these costs better, we'll be able to identify where UK innovation could lead to lower cost, material efficient construction.

This document presents a summary of evidence about three core strategies for reducing material demand in construction, and concludes with suggestions about how UK leadership in the area could grow.

Lower costs 33%	Faster delivery 50%
Lower emissions 50%	Improvement in exports 50%

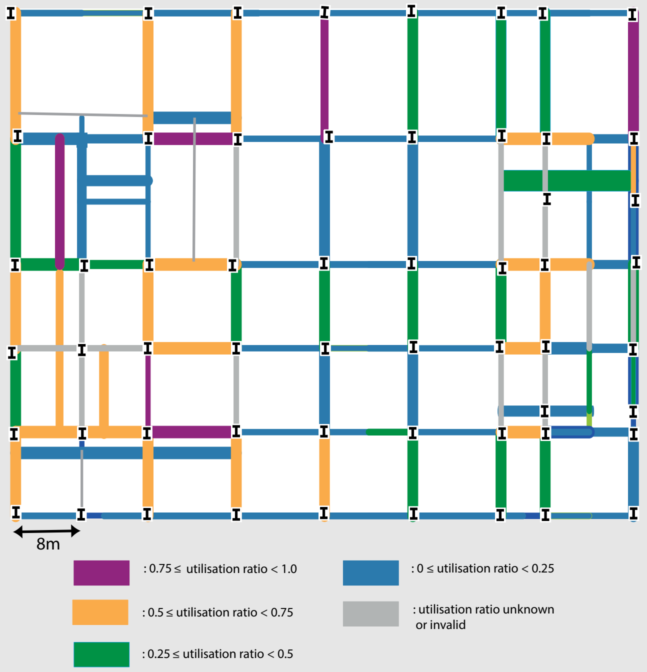
Designing For Purpose Not Surplus

When building designs use only the materials required, in the right place and without excess, then demand for materials and energy is reduced. However, in a detailed study of 23 commercial buildings, we found that multi-storey steel structures could, on average, be built with half the amount of steel and still meet the Eurocodes[1]. Ensuring each structural element is appropriately sized and working efficiently takes some additional design time but can result in a substantial material saving. Reducing the weight of a building through alternative, lighter-weight designs can minimise material usage, while construction waste reduction strategies also lead to a reduction in materials. In both cases the energy and carbon embodied in a building is reduced.

Cutting embodied emissions by 80%

BOX STORY 1

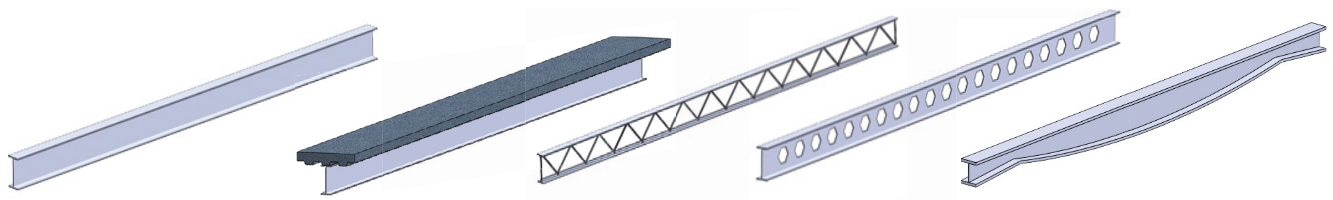
The minimum material requirements for commercial buildings in the UK are defined by the Eurocodes. We analysed 23 recent buildings in London, and found that on average only 50% of the steel in their beams was utilised in meeting the standards. This suggests that if we met the Eurocode requirements rather than exceeding them, and maintained buildings for their design life of 100 years rather than the current average of 40, we could cut the embodied emissions of commercial buildings in the UK by 80% - the target set by the 2008 Climate Change Act.



Efficient Structural Design

By designing to the Eurocodes, without overcapacity, significant reductions in material usage can be made. Most of the material mass in the superstructure is within the floor structure and our study found that perimeter beams in particular are often oversized and could be reduced with minimal additional design effort (Box story 1 image). The increasing use of offsite fabrication also creates a wider opportunity to optimise composite floor panels, and reducing the material in the superstructure decreases the loads to the foundations, creating further opportunities for material savings.

The least-effort approach to design is to focus on the worst loading case for a span and then to replicate the chosen beam size across the floor plate. This saves design time but results in increased material use. The high relative cost of labour versus materials is the greatest barrier to avoiding over-specification; as the cost of additional design time may not be matched by savings in material costs. Increased use of optimisation software and the move towards BIM may reduce this extra design cost (see Box Story 2) but nevertheless, when designers are paid a percentage of project costs, they have little incentive to reduce overall material costs. Instead, if clients specify material efficiency in the project brief (see Box Story 3), this drives the whole supply chain by providing a clear deliverable target. Regulation could also be used to mitigate against excessive material use.



Beam design options

Composite designs may reduce the weight of materials required, but can inhibit deconstruction and re-use at end of life, unless separable connections are used. Element optimisation can reduce material requirements by using more material where forces are greatest, producing variable profile depths. For example, optimised cantilevered beams would be deeper in the centre and taper towards the cantilevered end, rather than having a uniform depth along the beam. This approach can be applied to steel, concrete or glulam, and is particularly suited to off-site fabrication. Other examples of lighter-weight, more efficient structures include cellular beams, trusses and cable-stayed structures. Material choice can have a crucial role in producing lightweight structures; selecting high strength materials generally requires less material, as demonstrated in Box Story 3.

Waste Reduction

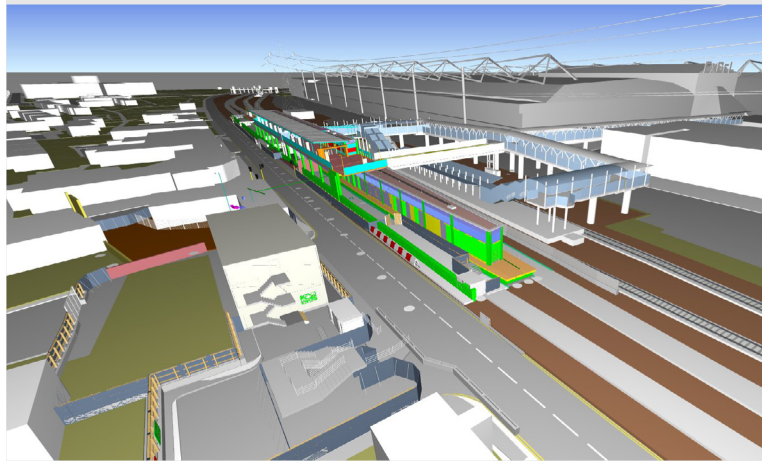
Projects such as Marks and Spencer's Cheshire Oaks store have demonstrated that zero waste to landfill can be achieved in construction projects by reusing and recycling waste produced[2]. However, despite targets set by European Directives, this is yet to become standard practice. Best practice in on-site handling and storage reduces the chances of material damage. Off-site construction, which occurs in a more controlled environment can also reduce waste. Designers can facilitate both on-site and off-site waste reduction, for example, by specifying that excavated material is used as fill elsewhere on the same site, and clients can support good practice through specification in the project brief.

BIM benefit

BOX STORY 2

Increasing use of Building Information Modelling (BIM) allows greater precision in specifying material requirements, which can reduce over-ordering and thus decrease site waste. The model can be developed with the contractor into a construction plan, to show for example how plasterboard can be cut and installed to minimise waste. If designs lead to improved element efficiency with more variation in structural elements, BIM can assist fabricators and contractors by providing a 3D model of element positions. BIM can also store building information to support maintenance of the building and eventual deconstruction and material reuse at end of life.

BIM Model Visualisation



Construction of the 2012 Olympic Velodrome

London 2012 Olympics Velodrome

BOX STORY 3

The design brief for the Velodrome asked for a lightweight construction leading to an integrated approach to design. A materially efficient double-curved cable net was chosen for the roof structure, providing the signature aesthetic structure with half the carbon footprint of the equivalent sized Aquatics centre. The cable-net design reduced the embodied carbon by 27% compared to a steel arch option. The seating supports were also integrated into the structural frame to avoid the need for a separate structure. The material strategies not only minimised embodied carbon but also worked in conjunction with other design features to produce the most energy efficient building in the Olympic Park, improving on 2006 energy efficiency building regulations by 31%, demonstrating the potential success of an integrated approach[3].

Building Life Extension

Buildings in the UK could last for at least 100 years but are generally replaced decades before that: if instead we facilitated adaptability, and maintained the value of buildings for over 80 years, we could save long-term costs and emissions by significantly reducing material use. Buildings are generally demolished because they no longer meet the users' aesthetic or practical needs, due to area regeneration or because changed planning regulations allow expansion. The opportunity for new construction is therefore to design buildings which are sufficiently flexible to be adapted in the future to meet as yet unknown requirements, whilst also having a timeless or adaptable aesthetic.

The Amphitheatre of Pompeii is the oldest surviving Roman amphitheatre and a protected part of Italian heritage

Why are buildings replaced?

Current buildings are maintained for only a fraction of their potential lifetimes, with a survey in Tokyo reporting that the average lifespan of a building is just seventeen years[1]. Our oldest buildings are treasured as key statements of our heritage and often demonstrate a timeless aesthetic. However many newer buildings, even when constructed as statement pieces, do not have this appeal and are often assessed by users solely on their function. Over time, users' requirements for the arrangement of internal space change – with different approaches and requirements for heating, ventilation and cooling, with new communications technologies and constraining ceiling heights. This combined with changing fashions in layouts and buildings designed to specific occupants' needs results in space that cannot be easily adapted and so buildings are replaced. Area regeneration, poor building maintenance and changed planning regulations (for example allowing increased building heights in a previously restricted area, or the potential to switch from commercial to residential use) can also influence decisions about building replacement[2]. Designs that allow for reconfiguration, that provide easy access for maintenance, and which facilitate replacement of shorter life span components, support the transition from first to second user and allow for changes in use.

55 Baker Street

BOX STORY 4

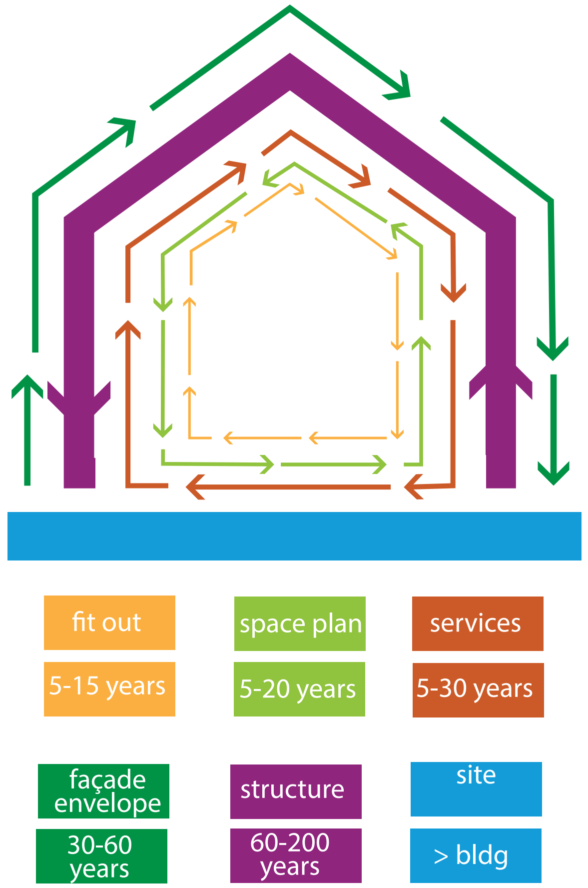
This project in central London is an excellent example of adaptive building reuse. The 1950's design was restrictive and no longer suited for use. The building was redeveloped, retaining the majority of the original concrete structure, but altering the layout to form large open plan spaces. The project highlights three key features that should be considered in new buildings: large open plan floors, increased floor to ceiling heights and provision of vacant external spaces around the building. These features give greater flexibility of use and allow for future extension and adaptation.

Design strategies

Evidence from Brand[3] suggests that a layered approach to building design is crucial in ensuring that different components can be upgraded, adapted or replaced. For example, it would allow upgrade or renewal of a building façade to ensure the building remains aesthetically appropriate to its area. Layered design also facilitates easy upgrade of services as technology develops or requirements change, embedding some flexibility into the building. If deconstruction is integrated into the strategy then it should be easy to remove elements without causing damage to the rest of the structure.

Building flexibility allows for future adaptation in building use, configuration or size. An established set of approaches can be applied to achieve flexibility:

- Designing in layers
- Modular construction
- Design for deconstruction – to enable components to be disassembled and replaced
- Access to services – for upgrade as technology develops
- Clear/long spans – the internal arrangement can either be open plan or separated using 'temporary' partitions
- Incorporate larger floor to ceiling heights than required to allow change of use and for provision of future services
- Access to key areas and elements with the shortest life spans so maintenance can be easily provided



Building layers and associated lifespans

There is a trade-off between material efficiency and providing additional capacity to support future expansion. For example, increasing floor to ceiling heights requires more material initially in the building structure, but allows increased flexibility for changes of use. Use change could also alter the imposed loading design criteria: if an open plan office space was converted to an exhibition space, the imposed loading would increase[4]. Design for adaptability therefore either requires a prediction of future requirements, or the option to replace sections of the structure to cope with different loading.

Design for adaptability might incur additional costs at initial construction, but these should be recouped during the life of the building as the building can be adapted to suit different users, making it quicker to change lease. Evidence from adapting existing buildings (as shown in box story 4) demonstrate that retrofit and adaptation can be quicker than new construction; time and cost savings should be further accelerated if the building has been designed to facilitate this adaptation. Further evidence shows that well-designed retrofit projects can also lead to in-use energy savings similar to those that would result from building replacement[5]. At eventual end-of life, component salvage and reuse is easier in buildings designed for upgrade, as discussed on the next page.

Material Options

Most construction depends on four key structural materials: steel, reinforced concrete, timber and masonry. Material re-use allows the embodied carbon already expended to be valued over a longer time and avoids the need for new material production; however at present such re-use is rarely practised in the UK due to search and certification costs. Strategies for design for deconstruction are well developed, but rarely implemented due to slight increases in initial costs, and because deconstruction is often prevented by time pressures driving demolition. The use of natural materials such as wood may lead to reduced embodied emissions, but this depends on how they are processed.

Examples of the four main structural materials: concrete, steel, timber and masonry

Material Re-use

Material reuse can occur either on an individual element level, i.e. a steel beam, as in the BedZED project[1], or on a component level, e.g. a steel truss, as demonstrated in the construction of the Ottawa Convention Centre, which reused nine 160ft long trusses from the old building on the site[2]. Steel is particularly suited for reuse due to its durability and robustness during deconstruction. However, three major barriers inhibit steel re-use today: firstly, although new steel is certified based on a process audit, re-used steel generally must be re-certified by mechanical testing to confirm its grade and this is costly. Secondly, although deconstruction rather than demolition can be profitable due to the value of reclaimed materials and components, it takes longer, and under current contracting practice delays to a project programme are undesirable. Thirdly, because re-use today is rare, there is a supply problem: finding the appropriate section sizes and lengths can be difficult and expensive. These barriers can all be overcome, but this will require learning from project experiences.

Timber and masonry can also be re-used, although the recovery process for bricks is labour intensive and relies on the use of lime mortar. Currently, projects tend to utilise cement based mortars which are often stronger than the bricks, making it difficult to separate bricks without damage. Reinforced concrete is inherently difficult to salvage and re-use due to the difficulty in separating individual elements. Non-structural materials can also be salvaged and re-used, and this is more common than structural reuse as re-certification is not required.

Design for Deconstruction

New buildings could be designed for deconstruction to reduce future salvage times. There is a substantial overlap between deconstruction strategies and those required to facilitate adaptability. Deconstruction tactics focus particularly on the reversibility of connections and the separation of building layers and individual components. Provision of a deconstruction plan and storing building information are also key elements for this strategy.

Reducing embodied carbon requires that a balance is struck between material usage strategies. A building designed for a longer life may not be fully optimised in its material use as it holds additional capacity in the columns and foundations to allow for future vertical extension. Similarly, when reusing components at present, there is a risk, that due to limited availability, elements larger than necessary will be used, and this could outweigh the benefits of reuse. The understanding of these trade-offs would be improved through the accumulation of experience in practice.

Vulcan House

BOX STORY 6

This is an excellent example of a project where design for deconstruction was integrated into the design as part of a whole building sustainability approach. A BREEAM Excellent building, the steel frame was designed using bolted, reversible connections so that at the end of its service life it could be deconstructed and the individual elements reused. The project demonstrates the ease of incorporating this strategy into an office building, enabling an increase in the supply of reusable material in the future.

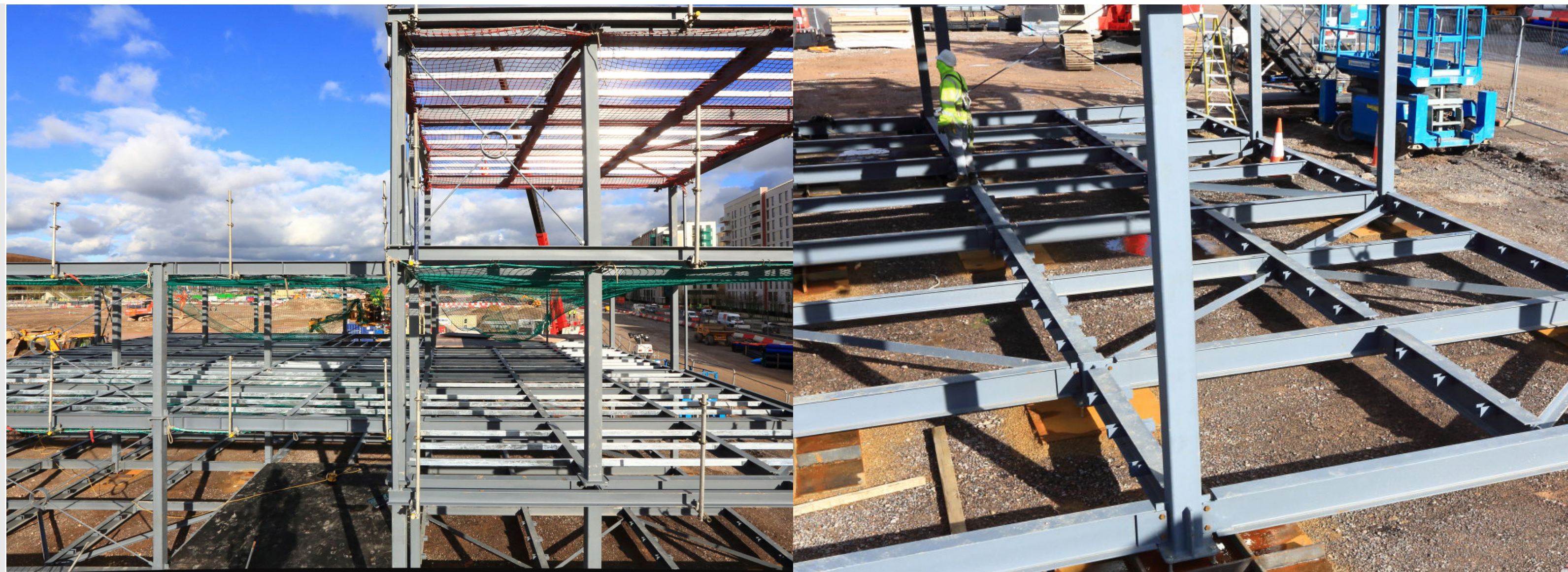
A range of natural construction materials: rammed earth, straw bales and timber.

Natural Alternative Materials

BOX STORY 5

Could we replace energy intensive materials like steel and concrete with lower carbon materials? Natural materials, ranging from straw bales to timber to rammed earth, are valid alternatives, but understanding their net effect on the environment requires care. Plant derived materials absorb carbon dioxide during their growth but some energy must be expended to prepare them for use, and there is considerable variability in the impact of the end of life stage, depending on whether the product is reused, recycled, incinerated or landfilled. For example, to be economically viable in the UK, wood is dried in kilns to shorten the time from harvest to sale, at the end of life it releases methane if left to rot, or carbon dioxide if incinerated, although re-use and recycling are low impact options.

Natural materials can be used, both structurally and non-structurally, as an alternative to more energy intensive materials. For example, rammed earth construction is load bearing, suited to low rise construction, has good thermal mass and a unique aesthetic appeal, it therefore presents a viable alternative for low rise concrete construction. Although concrete will generally still be required for the foundations, and a low cement content will be required in the earth mix to stabilise the soil, the replacement of the concrete wall can reduce the embodied carbon of the building.



This entirely deconstructable steel frame by ES Global forms a temporary marketing suit, Chobham Manor in London. The majority of the structure could be re-used elsewhere providing significant environmental savings, this combined with faster construction times provides clear benefits that could be extended beyond the temporary structures market.

Towards UK leadership

We could construct buildings and infrastructure with less material and maintain its value for longer, this would save emissions, could speed up delivery and is a major opportunity to build up UK export strength. But although this document has demonstrated early examples of a different approach to construction, we haven't yet grasped the opportunity for leadership in this area. What can we do to accelerate our activity?

- We want to stimulate the development of demonstrator projects beyond best practice. The Velodrome at the London Olympics was a great demonstrator, driven by a well written project brief, and we could be using this and other leading examples to inspire and inform the client sector about the opportunity for leadership in specification.

- Eurocodes recommend minimum structural material requirements, but do not restrain excess material use, and as yet regulation of capital carbon emissions has had little prominence. A review of standards and certification could seek to increase the prominence of decisions that lead to excess or short-term material use.

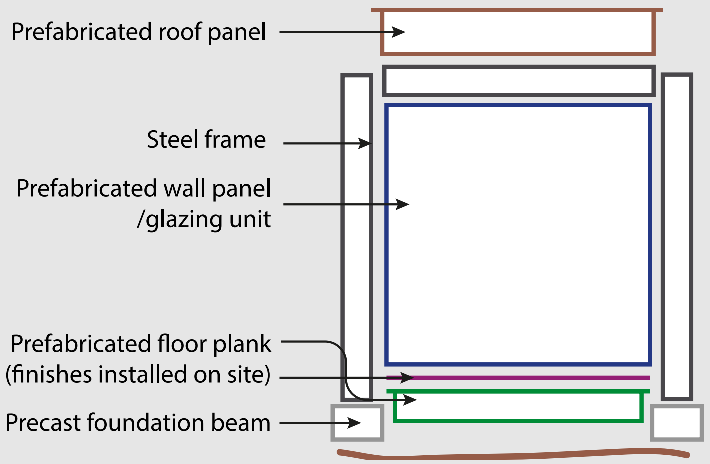
- Planners at local and national level have significant influence on total material requirements for construction. Better informed planning decisions might support increased adaptability to support longer life buildings for example through providing sufficient vertical capacity for later additional floors, or by ensuring that new build designed for one purpose can subsequently be adapted to other purposes. Planners can also influence the chance that new buildings will become part of local heritage, and therefore be maintained by natural preferences for longer times.

Our research team is engaging throughout the supply chain of construction and materials, to develop evidence about changes towards material efficiency and stimulate action. We are documenting case studies of best practice, examining costs and how they are influenced by policy decisions, collaborating with groups seeing to nurture new supply chains for material re-use and working to understand the impact of policy decisions on material demand. We have also initiated a professional network with representatives from throughout the construction sector in the UK, to share best practice, and identify opportunities for stimulating material demand reduction.

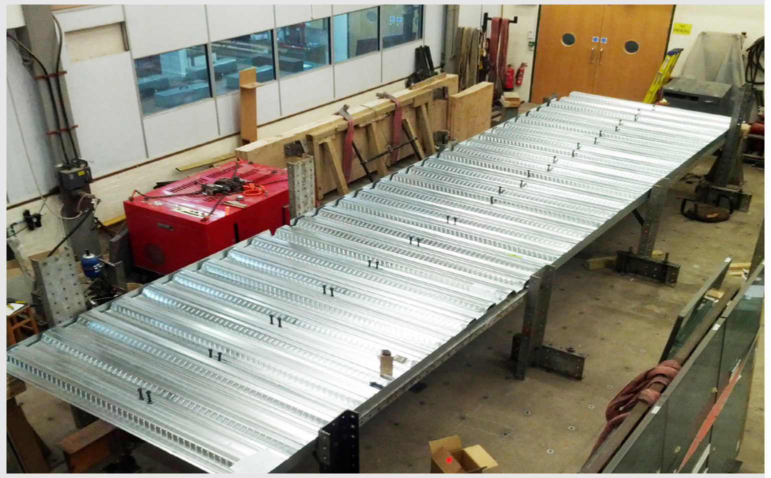
Re-usable Supermarkets

BOX STORY 7

Supermarkets in the UK are typically refurbished after 10 years, and replaced after 20. The replacement store is generally opened on a different site to allow a change of size, and the old store is demolished. Could we instead build supermarkets from a pre-fabricated kit that could be erected rapidly, with only mechanical joints, and dismantled and re-used after 20 years? We spent a year working with one of the UK's major retail chains on this question, finding that the major challenge was to develop a re-useable floor slab that remained perfectly flat. Whilst the board decided not to pursue the proposal due to a 16% cost increase compared to a conventional store, the faster construction time and improved flexibility in-use where seen as important commercial benefits.



Supermarket design



We conducted experiments that showed bolted connectors between a composite beam and floor slab perform similarly to welded shear studs. Bolted connectors allow the beam to be deconstructed at end of life and reused, unlike welded studs.

Notes

Purpose Not Surplus

1. This comprehensive study by Moynihan and Allwood (2014) used utilisation ratios to assess the efficiency of individual structural elements, ascertaining that utilisation was on average 52%, demonstrating that we could almost halve the quantify of structural steel in our buildings. The paper, entitled 'Utilization of structural steel in buildings' can be found in the Proceeding of the Royal Society A.
2. Waste minimisation was just one feature of Marks and Spencer's Cheshire Oaks store, more information on the sustainability strategies can be found here: https://plana.marksandspencer.com/we-are-doing/climate-change/cheshire-oaks
3. A series of learning legacy documents outline the strategies utilised to reduce embodied (Cullen et al. 2011) and operational (Carris, 2011) carbon in the London 2012 Velodrome, these can both be found on the Learning Legacy website: http://learninglegacy.independent.gov.uk/

Images:

4. BIM image courtesy of Lang O'Rourke
5. Velodrome image by Bromiskelly, licensed under Creative Commons, available here: http://goo.gl/drCL49

Longlife Buildings

1. This study by Russell & Moffatt (2001) explores building life extension through improved building adaptability. The report can be found at: http://www.eastdunbarton.gov.uk
2. Work by The Athena Institute (2004) documents the reasons for building demolishment across 227 buildings in St. Paul, Minnesota. For the full report see: http://briscoman.com/sites/default/files/Athena_Demolition_Survey.pdf
3. Widely studied work from Steward Brand's book How building's learn: what happens after they're built (1995) outlines the different, changing layers of a building, separating components considering their potential life spans can facilitate maintenance and repair.
4. Imposed loading tables 6.1 & 6.2 in BS EN 1991-1-1:2002
5. The Buildings chapter in the recent report from the IPCC (2014) discusses the need to retrofit the current building stock, commenting that up to 90% energy savings have been achieved from deep retrofit (p.4).

Images

6. Old and new Baker Street images, courtesy of Make Architects
7. Diagram adapted from Stewart Brand's Shearing Layers in How Buildings Learn (1995)

Material Options

1. A case study of the pioneering BedZED project by Sergio and Gorgolewski can be found here: http://www.reuse-steel.org/files/projects/
2. A press release that summaries the features of the LEED Gold Ottawa Convention Centre can be found here: http://ottawaconventioncentre.com/en/media-centre/media-releases/2013-01-30

Images

3. Concrete by Ivan Cronyn (http://goo.gl/wPr5jl)
4. Steel by After Corbu (http://goo.gl/GJJHO3)
5. Timber by Steve Silverman (http://goo.gl/zOmDpS)
6. Bricks by AuntieP (http://goo.gl/d29eD3)
7. Rammed Earth by Fort Girl (http://goo.gl/sm8jkA)
8. Straw Bales by ercwhtmn (http://goo.gl/ivtR5P)
9. Timber beams by Phil Shirley (http://goo.gl/6DJLSQ)all licensed under Creative Commons
10. Chobham House images courtesy of Rob Brown Photography

Other images:

Front cover Eden Project image by Fenners1984, licensed under Creative Commons, available here: http://goo.gl/sPjjqN
Introduction steel by Jake Trussel, licensed under Creative Commons, available here: http://goo.gl/LlkQLj
Introduction velodrome image by DCMS, licensed under Creative Commons, available here: http://goo.gl/zoX0dJ

The Eden Project

The Eden Project domes are an excellent example of material efficient, lightweight structures. The insulating hexagonal ETFE cushions that rest on the steel structure result in an iconic structure with minimised environmental impacts.

The Chrysler Building

This timeless piece of art deco architecture forms a key part of the unique Manhattan skyline. This elegant structure demonstrates that with the right design approach, our commercial buildings can become part of our heritage, motivating us to preserve them and extend their life.

Portal Power

This stack of steel beams are the components of a portal frame structure that is waiting to be re-used. Re-use of portal frame structures forms a core component of the business model of Portal Power – a specialist in designing and constructing portal frame buildings.