CO_2 2.Low carbon

Scaling low-carbon construction materials

Philip Isaac and Jonny Hawkshaw review the potential for materials with lower embodied carbon to be used more widely in both small-scale domestic projects and larger-scale residential and commercial projects.

Introduction

Low-carbon construction is a vast topic encompassing procurement, transport, recyclability, operating carbon, end of life, refurbishment and, of course, the ultimate question of whether we should be building at all. While we can't hope to solve the construction industry's carbon footprint in one fell swoop, the aim of this article is to look at the diverse array of low-carbon materials available, with the hope of providing a reference point for scheming at early stages of a project where they may be appropriate. If it's true that the engineer's toolkit has only (relatively) recently expanded beyond steel and concrete to include timber, should it now also expand to include some of the materials discussed here?

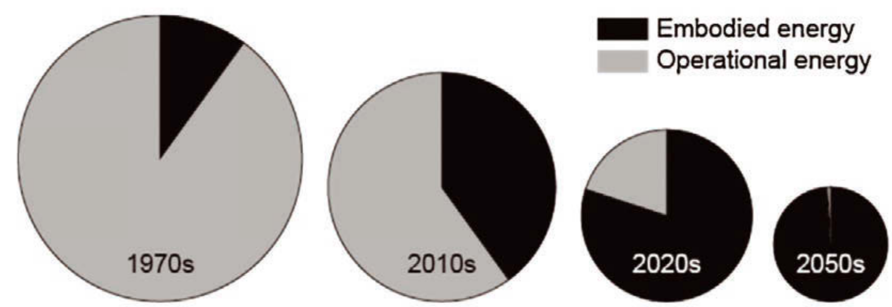


FIGURE 1: Share of embodied and operational energy in UK buildings, with size of pie representing total energy[2]

Background

Engineers stand today on the cusp of potentially the greatest challenge of their careers: embracing the concept of sustainable low-impact development which will define the future trajectory of our profession and, indeed, planet.

It is widely recognised that the construction industry is one of the largest contributors to greenhouse gases in the world, contributing an estimated 39% of emissions in 2017[1]. Operational energy has fallen as buildings have become more efficient and renewable energy usage has grown. However, embodied carbon – which structural engineers have the most impact on – has remained relatively constant **(Figure 1)**[2].

If the UK is to meet its 2050 legal obligation to be net-zero carbon[3], it is clear that the embodied carbon of buildings needs to be reduced. The Royal Institute of British Architects has set targets for the built environment of reducing embodied carbon by 50–70% by 2030[4].

Challenge with scale

To get to grips with this necessity, engineers must be willing and able to positively influence material choices on projects of all scales. Low-carbon materials have been widely, if not commonly, used on numerous small-scale projects, demonstrating great potential. However, to make a real impact, projects of all scales must embrace low-carbon materials.

To this end, this article focuses on low-carbon alternatives for two main categories of project, using the same typologies adopted in the London Energy Transformation Initiative (LETI) *Embodied Carbon Primer*[5]:

- small domestic
- medium/large residential and commercial.

If schools are included, these archetypes represent 75% of the new buildings likely to be built in the UK between now and 2050[5]. While it is recognised that the requirements of residential and commercial offices differ, the scale is considered similar in the context of this article.

Small domestic

Construction of small-scale projects is often typified by the use of mass concrete footings, brick and block walls, and timber joist floors, with the occasional steel beam or moment frame thrown in for good measure. A comparison of these traditional materials with alternatives is given in **Figure 2**, with descriptions for each of the alternatives provided in **Table 1** and discussed below.

Where measures of embodied carbon are provided, these are almost exclusively taken from version 3 of the ICE database[6], which covers stages A1–A3 unless noted otherwise.

Foundations

Although concrete is the most popular material for foundations on smaller-scale projects, due to its familiarity, cost, durability and ease of use, there are viable alternatives, including screw piles, stone trenches and timber sleepers. Even where concrete is specified, a significant volume can be saved by making an adequate assessment of the soil's shrinkability rather than defaulting to a 1m trench.

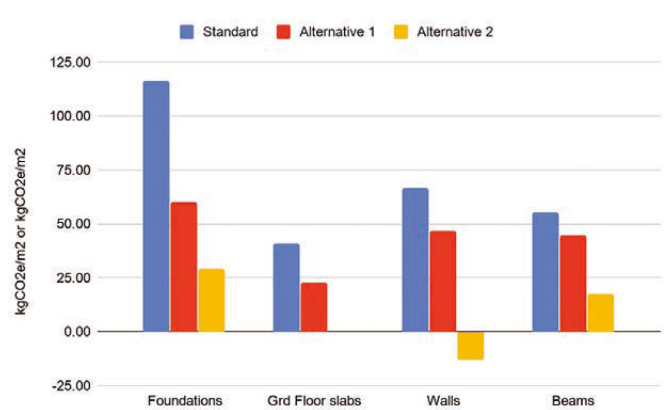


FIGURE 2: Embodied carbon calculations for options presented in Table 1

Screw piles

Screw piles **(Figure 3)** have the advantage of significantly reducing the amount of concrete required in high-shrinkability soil, reducing the excavation spoil created. They also have the potential for removal at the end of life. Screw piles can either be capped with a concrete ground beam from which the superstructure is built, or connected with timber joists to form a timber suspended floor, enabling concrete-free construction.

Screw piles are suitable in both coarse and fine-grained soils and can be particularly beneficial where the close proximity of trees would dictate trench footings of significant depth. They are not suitable in strata containing a high proportion of rock or large stones which can obstruct installation, or in ground underlain by weaker material which can lead to punching shear issues. Where screw piles are specified, a borehole should be ideally be sunk.

“SCREW PILES HAVE THE ADVANTAGE OF SIGNIFICANTLY REDUCING THE AMOUNT OF CONCRETE REQUIRED IN HIGH-SHRINKABILITY SOIL

↗FIGURE 3: Helical screw piles being installed

Stone trench foundations

Stone trench foundations are less widely used, although applications have been recorded, with the architect Frank Lloyd Wright known to have specified them on many projects. The dug trench is filled with angular stones or gravels, which are usually backfilled within a geotextile membrane with drainage provided at the bottom **(Figure 4)**. The stones or gravels act as concrete would in conventional foundations, spreading load from the superstructure into the ground over a required bearing area.

Limited technical guidance is currently available in the UK, but anecdotal reports suggest they may not be suitable in ground with a high water table, high plasticity or close to trees.

↙FIGURE 4: Typical stone trench foundation prior to casting of capping beam

Timber sleepers

Timber sleepers effectively act like padstones, spreading load from the superstructure into the ground over a required bearing area, with multiple layers used as required. This technique was used on the ‘Tree House’ project by Price and Myers. The sleepers are typically founded at ground level on a

TABLE 1: Embodied carbon for standard construction materials and lower-carbon alternatives (small scale)

	‘Standard’ construction material	Alternative 1	Alternative 2
Foundations	Concrete trench foundations *(0.45m wide × 1m deep trench)*	Screw piles with concrete ground beams *(4m long, 0.3m helix screw piles at 2m centres with 0.3m × 0.3m ground beam)*	Stone trench foundations *(0.45 m wide × 1m deep rubble trench with 0.2m × 0.45m ground beam)*
Ground-floor slabs	Ground-bearing slabs *(200mm compacted fill with 150mm concrete)*	Suspended timber floor not recycled at end of life *(150 × 47mm joists at 400mm centres, sleeper walls ignored for purpose of comparison, 15mm plywood decking and 50mm blinding to underside)*	
Walls	Cavity walls *(100mm aggregate blocks with standard bricks, rockwool insulation)*	Timber frame with standard insulation and timber cladding *(145 × 47mm studs at 400mm centres, 15mm OSB each side, 20mm brick slips, rockwool insulation)*	Timber frame with IsoHemp blocks and lime render *(assumed 300 × 47mm studs at 400mm centres with 300mm IsoHemp blocks)* *(NB Fig. 2 includes effects of sequestration)*
Beams	UC 203 × 203 × 52*	UB 254 × 146 × 37	350mm deep × 230mm wide* glulam beam not recycled at end of life

* Section chosen to have equivalent stiffness to UB section

FIGURE 5: Hemp-lime and timber frame construction

layer of impermeable material in order to control exposure to moisture for durability. As such, timber sleepers are susceptible to seasonal ground movements in soils with high volume change potential, so careful consideration of relative settlements is required. Where timber is exposed to regular wetting and drying, its durability tends to be low; therefore, drainage is a primary consideration.

Vertical structure

Bricks and blocks are synonymous with domestic construction in the UK; however, over time the embodied carbon of bricks has been reducing due to the increased use of renewable energy to fire the bricks, a trend that should continue[7]. Blockwork walls have similar carbon intensity to brick walls, although this comes primarily from the cement leaving limited scope for removal without a suitable alternative binder.

Timber frame

Based on the ICE data, timber framing can offer savings of approx. 30% of embodied CO_2 compared with traditional cavity wall construction, even when brick slips are used to clad the finished structure. There is widespread familiarity with this type of construction in the UK, meaning good availability of contractors and ease of building warranty. Timber-framed buildings of up to two storeys are common within the domestic market and taller is possible (within the limits of the Building Regulations). Care should be taken on site to ensure moisture barriers are effectively installed to ensure the longevity of the material can be guaranteed.

Timber frame with hemp-lime

A further development of traditional timber framing is the use of hemp-lime as an infill material **(Figure 5)**. While this type of construction may be best suited to one- or two-storey structures, it can also be applied at scale, e.g. The Triangle in Swindon, a 42-unit development by Curtins with Glenn Howells Architects. This type of application requires a suitable supply chain to be in place.

The figures presented in **Fig. 2** are based on IsoHemp hempcrete block environmental product declarations[8], which include sequestering, leading to negative values. The design of hemp-lime is covered in *The Hempcrete Book*[9] and its structural benefits have been researched by Gross and Walker[10]. The material is seen as durable and a design life of 50 years can be expected. However, further research is needed to unlock the full structural benefits of the material.

Timber frame with straw bales

Straw bales can also be used as infill to timber-frame construction. To improve consistency and reduce time on site, ModCell® has developed a panelised system of timber frames containing straw bales. A 427m thick ModCell® panel sequesters up to 145kg of CO_2/m^2 and can be used to achieve Passivhaus standards[11]. One example of their use is in The Nucleus at Hayesfield Girls' School, Bath[12] by White Design and Integral Engineering.

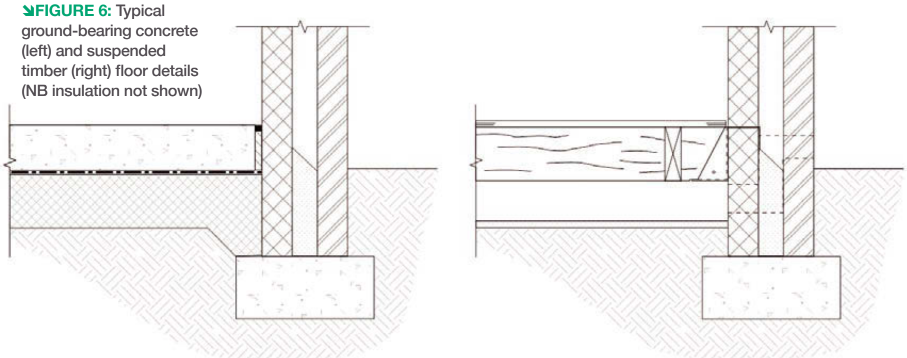
Durability against moisture and resistance to pest infestations are essential, along with practical considerations such as cable runs, plumbing and fire protection; therefore, detailing must be given proper consideration.

Floors

Timber floors are already widely used in small-scale and domestic construction, so the opportunities to reduce the embodied carbon of this particular part of the structure further are reasonably limited. However, ground-bearing concrete slabs can in some circumstances be replaced with suspended timber floors where levels permit (see **Figure 6** for typical details), reducing the embodied carbon by approx. 45% for this element (and greater if blinding can be omitted), even when end of life is not taken into account for timber.

A 150mm void, which must also be vented, is required to be maintained below the floor. Beam-and-block flooring, which is preferred by some contractors, has similar levels of embodied CO_2 to ground-bearing slabs.

FIGURE 6: Typical ground-bearing concrete (left) and suspended timber (right) floor details (NB insulation not shown)



Medium and large-scale residential and commercial

Projects of a greater scale encounter issues that differ from those on smaller-scale projects. The greater role that lateral stability plays is one such example, along with other factors such as procurement, speed of construction and robustness considerations. While many of the options presented in the *Small domestic* section are appropriate at a larger scale, there are numerous other alternatives that can be considered **(Table 2)**. A comparison of the embodied carbon of these is shown graphically in **Figure 7**.

Foundations

Vibro stone piles

Vibro stone piles have around 10–25% of the embodied carbon of normal concrete piles[13] and have been widely used, e.g. in the Oakgrove housing development in Milton Keynes, where Keller carried out the ground works. A BRE publication covers specifications for vibro stone columns[14]. In soft clays and silts (cu in the range of 20–40kN/m^2), stone column capacities in the range of 150–300kN are possible[15].

Timber piles

Timber piles **(Figure 8)** are common in many countries, including Canada, the USA and Australia. Untreated timber driven below the water table can last centuries without decay[16]. Where piles are not fully submerged, durability is greatly reduced, which tends to be an issue at ground level. To overcome this, the top of the pile can be finished in a material that is not susceptible to wetting and drying cycles, such as stone or concrete.

The specification of timber piles is covered in BRE Digest 479 and design loads of up to 700kN have been quoted[16]. Timber piles have also been widely

TABLE 2: Embodied carbon for standard construction materials and lower-carbon alternatives (medium scale)

	'Standard' construction material	Alternative 1	Alternative 2
Foundations	Concrete piles *(450mm diameter)*	Timber piles not recycled at end of life *(250mm square piles, top 2m concrete)*	Vibro stone columns *(700mm diameter columns)*
Columns	Concrete or steel columns *(300 mm square, 2% reinforcement or UC 203 × 203 × 46)*	Glulam columns not recycled at end of life *(350mm square, buckling length 3m)*	Limestone columns *(275mm square)*
Walls	Cavity walls *(100mm aggregate blocks with standard bricks, 140mm rockwool insulation)*	CLT *(100mm CLT panel, 140mm rockwool insulation, brick slips)*	SIP walls *(172mm panels, expanded polystyrene insulation and brick slips outside)*
Floors	Concrete slab *(200mm thick slab, 80kg/m³ reinforcement)*	CLT *(170mm thick CLT panel, 60mm wet screed)*	Steel beams with timber joists not recycled at end of life *(45 × 240mm LVL joists at 400mm centres spanning to UB 254 × 102 × 28 primaries, 15mm plywood decking)*

used on projects of considerable scale, e.g. the Red Bull Arena in New Jersey, constructed in 2008 used 3000 timber piles.

Screw piles

Screw piles are also appropriate for medium-sized projects. Due to the installation method, depths are usually limited to around 14m; however, 6–8m is more typical depending on the machinery available for installation. Maximum working loads on piles of this size can reach over 200kN[17] and the piles are able to carry load from the moment they are installed. The design life will depend on the ground conditions, but some manufacturers quote up to 60 years.

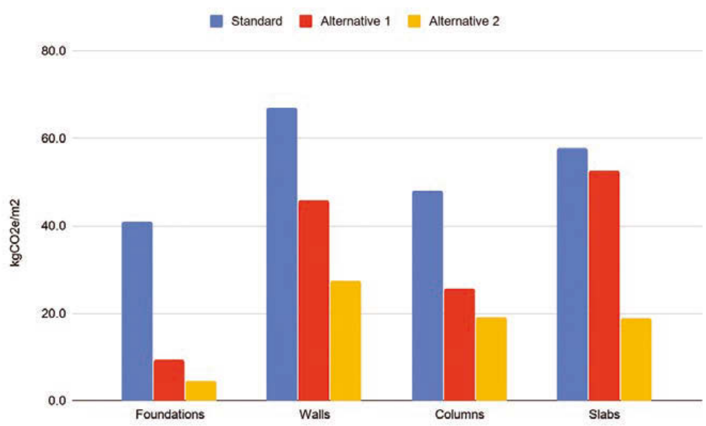


FIGURE 7: Embodied carbon calculations for options presented in Table 2

Vertical structure

CLT

While timber structures have been around for centuries, the development of engineered timber over the past few decades has expanded its use in longer spans and prefabricated elements, and opened up new uses as panelised elements. Cross-laminated timber (CLT) in particular has found a home in residential construction, from the 29-unit Murray Grove by Waugh Thistleton and Techniker (2009) to the 121-unit Dalston Works by Waugh Thistleton and Ramboll (2017) **(Figure 9)**. Both have CLT walls (internal and external), lift shafts and slabs.

According to Ramboll, the structure of Dalston Works has 50% less embodied carbon than an equivalent concrete frame[18], although this does not make clear whether end of life is taken into account.

The use of timber also brings a double-win in reducing the load on foundations and hence embodied carbon associated with their construction. In response to the growing demand for CLT, TRADA has produced a series of design guides.

Dowel-laminated timber, also known as dowellam or, originally, Brettstapel **(Figure 10)**, is another mass timber panel system which is formed from sawn timber sections mechanically fixed together with timber dowels by means of moisture movement. Its benefit over CLT is that the bonding process eliminates the need for glue or nails.

FIGURE 8: Installation of timber piles

SIPs

Structurally insulated panels (SIPs) are widely used in the USA, and a number of suppliers exist within the UK, making this a widely available option. SIPs offer advantages in terms of speed of construction, low U-values, good durability and high airtightness. They have been used as the primary loadbearing structure in buildings of up to five storeys, although one to three is more common.

One drawback of SIPs is the use of petrochemical-based insulation (expanded polystyrene or polyurethane) within the core. Panels have been produced with alternative

FIGURE 9: Dalston Works under construction, London

DANIEL SHEARING

cores made of compressed straw (e.g. Agriboard), which have lower embodied carbon. These products have yet to be used as widely as traditional SIPs; therefore, little data exists on their long-term performance. SIPs can also be difficult to recycle at the end of their life.

Despite these limitations, SIPs have around 70% of the embodied CO_2 of a traditional cavity wall (assuming the panel is clad with a brick slip).

Stone

Stone is another material gaining traction in recent years, led by the likes of Webb Yates Engineers and specialist contractors such as the Stonemasonry Company. This has included its use in staircases, columns and even slabs, with Clerkenwell Close by Webb Yates and Groupwork a recent example of the use of structural stone in the superstructure.

Stone offers a number of benefits over concrete, not just in terms of reduced embodied carbon, but also greater strength. Designing with stone has some conceptual similarities with precast concrete, as noted by Boote and Lynes[19]. The data available in the ICE database indicates that stone has around 65% of the embodied carbon of concrete per kg of material (although it should be noted limestone is around 12% heavier than concrete). The main contributor to the embodied carbon of stone is the quarrying and transport.

Designers should be aware of the need for additional material testing when using stone, along with overcoming the challenges with using a brittle material and designing for robustness.

Hybrid structures

Timber hybrids have been used across the world to achieve heights greater than is currently possible with timber on its own. The TallWood House by Fast and Epp[20] uses a hybrid of CLT floors, glulam columns and a concrete core for stability; the building stands at 53m (18 storeys). In this instance, timber was chosen partly due to the client's sustainability goals and partly due to the speed of construction owing to the lack of curing time required for floors and columns.

Fire safety of the structure was ensured by encasing primary loadbearing elements in a double layer of plasterboard[21], although this increased the embodied carbon of the project. The design of the CLT floor panels supported from columns was also novel and demonstrated that CLT panels could be made to work with concentrated supports.

Floors

CLT and dowel-laminated timber

CLT has become commonly used in floors owing to its fast construction and lower embodied carbon when compared directly to concrete. A 170mm thick CLT floor has 38% less $kgCO_2/m^2$ (assuming no end of life) compared with a 175mm thick concrete flat slab (assuming equal span and equivalent loads).

Issues with vibration and acoustics have been raised with CLT and designers should ensure at an early stage that both have been considered sufficiently. A thin screed has been used in the past to solve both issues, although doing so increases the embodied carbon: e.g. a typical 60mm wet screed topping contains approx. 17kgCO_2/m^2, assuming a cement-to-sand ratio of 1:4, giving an overall value of embodied carbon comparable to a concrete slab.

The addition of the screed also hinders the end-of-life de-constructability, reuse and recyclability of the system. Dry screeds could provide an alternative to this if they can be shown to meet the required acoustic and vibration requirements. Dowel-laminated timber is also appropriate as an alternative to CLT.

Engineered timber

Traditional timber joist floors can also be used independently or within a steel frame provided adequate fire protection can be applied for the building use and category. Where spans are larger, timber I-joists, laminated veneer lumber (LVL) joists and metal web joists can all be used. Span tables for these proprietary products are available from the manufacturers.

Concrete/steel

Where concrete or steel are specified for particular beneficial characteristics, efforts can be made to significantly reduce their embodied carbon. This includes using cement replacements in the case of concrete, or taking steps to aid the reuse of steel (as opposed to recycling it) at the end of its life. Until an adequate replacement for Portland cement can be found, concrete will continue to be one of the largest contributors to greenhouse gas emissions, and so its application on projects needs to be carefully considered.

Discussion

This article has chosen to focus on material types in relation to embodied carbon. However, the embodied carbon of a building can be reduced in many other ways. For a start, designers could do more to ensure greater utilisation of structural components. Research has found that utilisation ratios in steel buildings are typically around only 50%[22].

Another option is to avoid building from scratch. Refurbishment of existing structures is one of the simplest ways to significantly reduce the embodied carbon on a project. While this isn't always possible, it should be considered where an existing structure is present on the site.

An understanding of historic design methods, in relation to refurbishment, allows engineers to take advantage of inherent redundancy in old structures. For example, the designers of the De Karel Doorman building in Rotterdam **(Figure 11)** added 16 storeys to an existing three-storey building simply by changing the stability system of the building and making use of extremely high redundant capacity in the foundations. Where additional capacity is needed within existing structures, methods of strengthening are available which can also save overall material usage.

Of the materials discussed in this article, timber has the greatest proven track record of application in larger-scale developments. However, for timber to be considered a carbon-negative material and realise its sequestering capabilities, it must be reused at the end of its life. This is not accounted for within stages A1–A3 (cradle to gate) given that currently 100% of timber is downcycled, i.e. used for chipboard, biomass fuel or animal bedding and surface materials[23].

A major challenge is therefore how to reuse timber structurally to avoid downcycling. Challenges with regrading and the use of chemical and surface treatments, such as the adhesive bonding used within engineered wood products or treatments used for water resistance and fire, have all been cited as reasons for not reusing timber more widely. Careful detailing and fire strategies which look to minimise the use of surface treatments would help this[24].

A further proverbial thorn in the side of timber in the UK is the recent changes to the Building Regulations, which all but rule out its use in the external walls of buildings taller than 18m, although consultation over this is still ongoing at

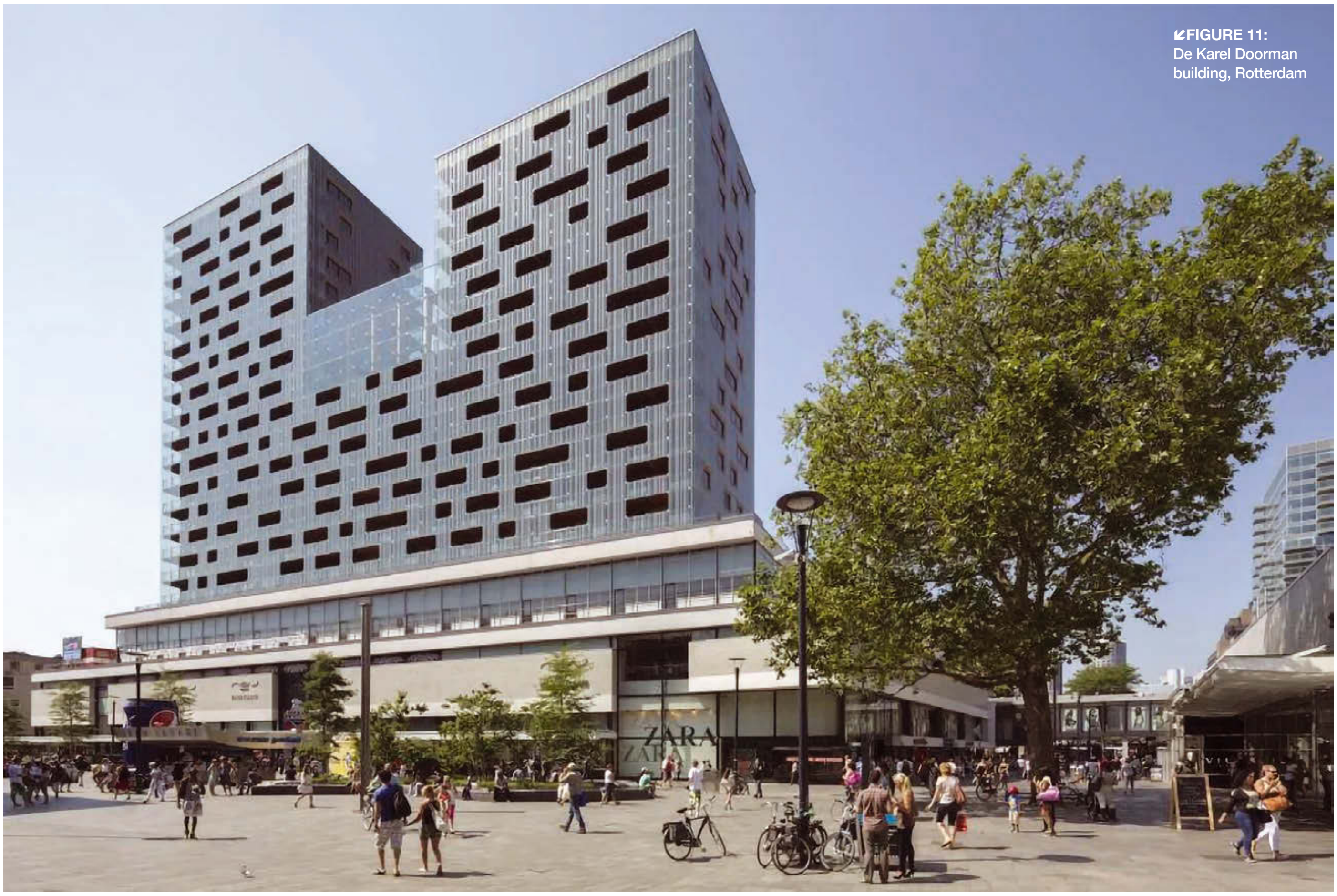


FIGURE 11: De Karel Doorman building, Rotterdam

the time of writing.

Similar concerns regarding end of life and recyclability exist for other materials and designers should give serious consideration to this when specifying materials, particularly when using composite materials or specifying proprietary products and systems.

Challenges

The wide-scale adoption of low-carbon materials depends on a myriad of factors, many of which are sadly outside of engineers' control. These include issues such as:

- appetite of the design team
- price uncertainty due to availability
- procurement routes and supply chains to meet demand
- contractor availability/expertise
- negative effect on design, e.g. limiting clear spans or wall thicknesses
- unfamiliarity with detailing requirements
- Building Regulations approval
- policing on-site works to ensure execution of design
- building insurance and warranties.

In essence, none of the issues pointed out above should be detrimental to the adoption of low-carbon building materials; however, an early awareness of these issues is important to ensure that they are adequately dealt with. Building Regulations approvals and insurance are one area in particular where early engagement with the relevant organisations can ensure issues aren't encountered down the line. It is hoped that, in time, the impact of these issues will lessen as more and more projects are completed.

Looking ahead

The examples outlined above clearly show that, starting today, it is possible to make reductions in embodied carbon with easy changes. There is also wide scope for further improvements and development of new materials, systems and typologies. Modular construction, for example, can offer significant savings in material wastage and forms a key component of the UK government's construction 2025 targets.

Continuing to do more with less will be one of the key aims if we are to make the dramatic reduction in embodied carbon required. This includes engineers becoming much more comfortable in the reuse of existing structures, as well as designing new structures for multiple uses.

Conclusion

The construction industry has a huge role to play in achieving a zero-carbon society. To achieve this, engineers must become much more familiar and confident in the use of low-carbon materials at all scales. This article has therefore chosen to focus on low-carbon materials that have already been successfully used on a range of projects, hopefully giving engineers more confidence to specify them in the knowledge that both technical expertise and precedents for reference exist.

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