The Institution of Structural Engineers

Design for zero

IStructE Guide

The Institution of StructuralEngineers

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Foreword

'The Bogey Monster is coming, dear children. Unless you behave…' Wherever and however you live, this book is part of the Darwinian tale of our time. The climate emergency is our monster, bogeying away everywhere to its heart's content. It is a properly existential mash-up affecting us all; the unintended consequence of humanity's myriad inventions over millennia… most well-intentioned, some not. 'Everything that wasn't invented by God is invented by an engineer', said RAEng Senior Fellow Prince Philip[†]. Here, in the beneficial potential of inventive engineers, lies a route map for the disproportionate impact that engineers, a small group of properly motivated people, could and should have in generating positive change.

'Do no harm', says the engineers' Hippocratic Oath, but we should reframe that more optimistically to oblige engineers to 'do good'. The breadth of this book implies the need for practitioners with a tsunami of new skill and knowledge, with as much strategic competence as technical, with as much ethical, social, and economic learning as scientific. They will need good data to judge their performance, not a blind adoption of codes based on 150 years of tradition and the one-way ratchet of catch-all rules. Responsible engineering requires imagination as well as technique, and there is as much for the thoughtful reader on and between the lines of this book. Try reading between the lines with Hans Zimmer's theme for TV's *Blue Planet* thundering in your ears.

The climate emergency is the price we have paid for the transformation of our lives brought about by the Age of Enlightenment and the Industrial Revolution. Whether our account with history can be settled depends on global action. Carrots and sticks will both be needed. Honourable exceptions notwithstanding, if you have an economic infrastructure rooted in the imperative to maximise sales of 'stuff', with tiny margins, it is a recipe for over-consumption. Change is washing over us from the bottom up through Greta Thunberg and Instagram. There is a quiet revolution in corporate culture exemplified by the BCorp movement[1], which rewires the core purpose of businesses so that social and environmental benefit is as important as the return to shareholders. Ex-climber and billionaire entrepreneur, Yvon Chouinard, and Patagonia show that business success and social benefit can be mutually supportive. Our corporations and economic structures are, after all, only inventions of humans that humans also have the capability to adapt. No business, no profession, no gladiator ever had the intrinsic right to exist in perpetuity. At this point, it is customary to call upon Charles Darwin to scare us with his famous maxim.

Events happen, and how we respond to them has defined our success as an inventive, adaptive species. One day soon, we may liken our emergence from the COVID pandemic and the climate emergency to the immediate aftermath of World War II, when countries emerged from their darkest hours with a renewed sense of purpose coupled with an optimism about what was possible. Margaret MacMillan, Oxford's former Professor of International History writes: 'At the end of the First World War it had been possible to contemplate going back to business as usual. However, 1945 was different, so different that it has been called Year Zero'[2].

It is a familiar tenet that technology advances fastest during a crisis. We could argue that, in terms of the combined impacts of a global pandemic, a global climate emergency, scarce planetary resources, and a growing population with a justifiably increasing equality of expectation, we are in the mother and father of all global crises. If 1945 was Year Zero, 2020 was Year Carbon Zero/Pandemic Zero/Equality Zero/Resource Zero. How we respond to this watershed is our generation's opportunity to 'behave'. We can't let the Bogey Monster get us. None of us know what the next chapter of the story will be, and how it will all end. But here, in its practical wisdom, is a book of hope that signals a small part of the way forward.

In its scale and complexity, the climate emergency leaves even those at the coalface casting about for a touchstone: What can we actually do? And perhaps with that question, comes a reckoning. This is where engineers have true value to society. Innocent peace-loving townspeople overwhelmed by demons from afar who decimate their fields, carry off their children and cause the once blue sky to grow dark. *Lord of the Rings*, Voldemort, religious texts the world over…*Design for zero*…it's nothing, and yet it's everything.

† Speaking on BBC Radio 4's *Today* programme.

There are parallels here to the beginning of the Welfare State after the *William Beveridge Report*[3]. By all accounts, Beveridge was that rare combination of an analytical mind with the ability to synthesise, coupled with a clinching skill as a consummate communicator. In the thick of war, he chose to articulate what he identified as 'five giants on the road of reconstruction': 'Want… Disease, Ignorance, Squalor and Idleness'.

Beveridge saw that good intentions were simply not enough. His 'cradle to the grave' social programme alienated some politicians but it struck a chord with the public and the rest is history.

Nearly three centuries before that, John Bunyan wrote a best-selling book with a sense of moral purpose, *The Pilgrim's Progress from This World to That Which is to Come*[4]. It was a dream sequence with an omniscient narrator, with a catchy title that echoes down the ages until it smacks us right between the eyes today in today's moment of need.

What has any of this to do with this book? Like Bunyan, the authors combine analytical wit with propositional common sense. They tackle the state of our world in the spirit of moral imperatives: Build Nothing; Build Less; Build Clever; Build Efficiently.

So, I take his book as a manifesto for change. Its strength comes through its evidence-based proposals. That it is published by our own Institution of Structural Engineers is telling…this is a thoughtful and purposeful call from inside the walls.

Among the seemingly endless climate conferences, climate declarations, calls to arms, and meetings on what to do, I found myself drawn in, and read the whole thing at a single sitting. It is good to see the propositions well-founded, and laid out in a holistic way. The findings of the Minimising Energy in Construction (MEICON) research project[5] are given their transformational place, and much is new, given relevance by being placed in context. By the end I felt, this is our generation calling…as engineers our response will be our 1945 moment. One of the consequences of that war was that the ruling classes lost their moral authority, as they were recognised to be part of the problem who had played a leading part in the circumstances leading to the conflict. Empires disintegrated, their organisational structures overstretched, their financial resources spent. I find myself asking if those gears are grinding out another such change…in what we read here, could we have part of the skeleton of a new designerly world order.

When faced with a great uncertainty, precedent and analogy can help by showing how the intellectual and physical process of design and making leads to a quintessential long-lasting solution. Experiment (trial and error) and careful interpretation and iteration show how others have done wonders before. If they could, so could we. It's a matter of 'tuning' their example to our own circumstances. I've used two 'instruments' in my life as key examples of sustainable design that respond to their purpose and perform their function beautifully:

One is Salisbury Cathedral, the subject of my university thesis and more or less the only good thing I did there. Cathedral-making was captured by the lasting testament of Jacob Bronowski in *The Ascent of Man*[6]: 'They took a dead heap of stones which is not a cathedral, and… turned it into a cathedral by exploiting the natural forces of gravity—the way the stone was laid, the brilliant invention of flying buttresses and the arch, and so on. And they created a structure out of the analysis of nature into this superb synthesis.'

The other is a Stradivarius violin… the craft, the deep understanding of materials, the longevity of fragile objects if they are properly cared for, the emotion generated when it is played and heard. In the forest where Stradivarius found the spruce for his violin tops, the trees are still growing. These have come to be called *Il Bosco Che Suona* — The Sounding Forest[7]. Marcello Mazzucchi is a retired forest ranger who can judge whether timber is ideal for instruments. He is so tuned in to his world that he can look at a tree, tap it, and say 'there's a violin trapped inside'. Spruce, willow, maple, growing in a forest — out of those quiet trees Stradivarius learned to conjure instruments that, as close as can be judged, are simply wonderful. In designing a wonderfully balanced piece of engineering that performs beautifully, he too created a structure out of the analysis of nature into a superb synthesis.

I love both of these, the cathedral, and the violin, for many reasons… but their essence is pure engineering… pared back, using their materials harmoniously and following the laws of physics: designed and made by humans so that anything added would diminish them, and anything taken away would bring failure. If we could just do that every time, we'd be laughing. In advocating performance-based design over code-slavery I compare a Strad to Usain Bolt: if he was designed by a modern engineer with all our code-based, conditioned, risk-averse lack of performance knowledge, he would run the hundred metres in 40 seconds, bringing a different sort of emotion, and a Strad following the same principles would sound like a plank. It's all about performance, drive, passion, empathy, tuning. This book shows how we could turn those skills towards the biggest instrument of all… our planet.

At its heart, engineering is a political act 'for the use and benefit of humanity'. While global politics can be top-down or bottom-up, change needs a critical mass of actively engaged and committed people. In terms of the climate emergency, millions are now engaged. Unlike the crafting of a Stradivarius, the act of creation needed to move us forward is beyond the capability of any single individual. With an engineer's disproportionate influence on 'zero' comes an enhanced responsibility to join with others to use it wisely. As engineers we should kill some sacred cows; adopt Lean Start; Long Life: Loose Fit; educate ourselves and our clients and end users, and 'behave'.

'You got us into this mess, now get us out of it'. We wonder who is going to do all of this? Engineers need to build a critical mass who learn the professional underpinnings of the *Design for zero* story and take active steps as a collective to improve. The range of skill and knowledge described in these pages leads me to believe that engineers as we have known and loved them are only a partial answer: the new engineer is going to be a combination of human and artificial intelligence working in harmony with a transformative and integrated range of skills that are born out of the past but firmly glued in the future. The engineer is 'dead' …so, with our thanks for all they achieved, and with help from books like this one, long live the 'engineer'.

Chris Wise RDI, FREng, FICE, HonFRIBA, FIStructE
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Chair of the Useful Simple Trust

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Five positive actions to take today

1. Make carbon as important as safety in your calculations

- Take ownership for carbon, just as you take ownership for safety.
- Calculate and communicate how much positive impact your work has.
- Establish design methods that improve the environment we occupy.

2. Interrogate and challenge every brief

- Engage your team to find ways to reduce the need for new construction.
- Show your clients the value of investing in carbon calculations.
- Examine your natural environment and learn from it.
- Reduce, then eliminate, specification of carbon-intensive virgin materials.

3. Extend the life of assets and resist demolition

- Use structural measurement to enable changes in use.
- Resist cosmetic demolitions: find new ways to love old buildings.
- Upcycle deconstructed components into objects of higher societal value.

4. Make reuse the starting point for new design

- Upcycle, and make ‘form follows availability’ your design mantra.
- Educate yourself on how to assess structural capacity and reliability of an old component (about which you may know very little).
- Embrace the Golden Thread of information; store accurate drawings, data, and specifications for your successors to use.

5. Choose the lowest-carbon materials, technologies, and products

- There are no negative emissions technologies.
- Do not rely on carbon offsetting.
- Aim for your projects to leave positive impacts beyond zero carbon.

Summary

Our present climate emergency requires us all to take immediate action on the release of carbon dioxide into the atmosphere. Reaching zero-carbon emissions by the middle of this century will give us a good chance of limiting global temperature rise to 1.5°C. Buildings and construction currently account for around 40% of energy-related CO_2 emissions. Business as usual is incompatible with the climate emergency and deep changes across the design, construction, use, and reuse of buildings and infrastructure are required if we are to have any chance of providing a sustainable environment for the 9.7bn people, including 6.5bn city dwellers, who will share our planet in 2050.

Recent successes in reducing operational carbon emissions of built assets must now be matched by similarly deep reductions in their embodied carbon emissions. This means thinking differently about how we use all materials. Herein lies the great opportunity for structural engineers as material specification lies clearly within our professional domain. To achieve this change, we must make carbon as important as safety in our calculations. To make this change a positive one, we can adopt the approach of *The Upcycle*[8] — and use our design work to be more good, rather than just less bad.

In 2018, the research project Minimising Energy in Construction (MEICON)[5] reported on a survey into the culture and practice of structural engineering design as it relates to embodied energy and carbon. They found understandable conflicts between individual desires to do the right thing, and the unremitting pressures of commercial life.

The survey results revealed wide variations and uncertainty in both regulated and cultural behaviours, contributing to habitual overdesign. Yet they also demonstrated that material efficiency is a fertile environment for new and creative designs. Embracing this will allow structural engineering to demonstrate the great value we can bring to clients and society. It represents a renaissance for our sector that we must all celebrate to drive a virtuous circle of design improvement and carbon reduction.

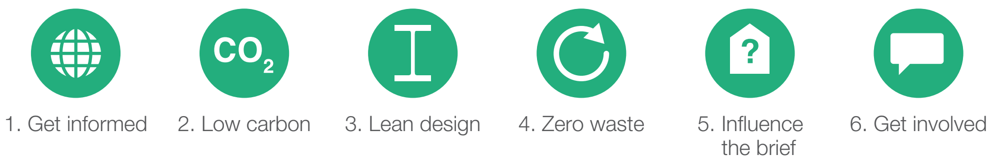
This book builds on the findings of MEICON. In Part 1 we examine the origins of some of our design practices and sources of carbon emissions. In Part 2, we present a vision for the future, supported by case studies of real projects that have successfully reduced carbon. In this book, we talk mainly about reducing carbon but recognise carbon as just one part of considering the sustainability impact of our work on the planet. Each project we work on should aim to leave the planet in a better condition than we found it.

Our case studies are deliberately chosen at the core of practice; we focus here on the low-hanging fruit rather than the glamourous extremes. This is because every project you are involved in must change. In Part 3, we show how you can advocate for improved design and how you can get involved.

The book is part of our collective efforts to transform our approach to carbon emissions and we don't yet have all the answers. We therefore call upon you to join us in this effort and tell us how your practice is changing as a result of the climate emergency.

Visit **www.istructe.org/climate-emergency** for more related guidance, and to find out how you can help the work of the Climate Emergency Task Group (CETG) within the six themes shown in Figure 0.

Figure 0: Six themes of the Climate Emergency Task Group (CETG)



Definitions

The following definitions used in this book are adopted from *Improving consistency in whole life carbon assessment and reporting*[9]:

Whole Life Carbon: the sum total of all asset related GHG emissions, both operational and embodied over the lifecycle of an asset including its disposal (Modules A1–A5, B1–B7, C1–C4). Overall, whole life carbon asset performance includes separately reporting the potential benefit from future energy recovery, reuse, and recycling (Module D).

Operational Energy Carbon: those GHG emissions (B6) arising from all energy consumed by an asset in use, as projected or measured, over its lifecycle.

Embodied Carbon: the GHG emissions associated with materials and construction processes throughout the whole lifecycle of an asset. Embodied emissions therefore include: material extraction (Module A1), transport to manufacturer (A2), manufacturing (A3), transport to site (A4), construction (A5), use phase (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), deconstruction (C1), transport to end-of-life facilities (C2), processing (C3), and disposal (C4).

Upfront Carbon[†]: those GHG emissions associated with materials and construction processes up to practical completion. Upfront emissions therefore include; material sourcing (Module A1) transport to manufacturer (A2), manufacturing (A3), transport to site (A4), and construction (A5).

Operational Water Use Carbon: those GHG emissions (B7) arising from water supply and wastewater treatment for an asset, as projected or measured, over its lifecycle.

A Net Zero Carbon Asset: where the sum total of all asset related GHG emissions, both operational and embodied, over its lifecycle including disposal (Modules A1–A5, B1–B7, C1–C4) plus offsets equals zero. Minimising emissions should always be prioritised over offsetting.

Net Zero Operational Energy Use Carbon Asset: achieved when those GHG emissions arising from all energy and water consumed by an asset in use (B6, B7), as projected or measured over its lifecycle, plus offsets, equals zero.

Net Zero Embodied Carbon Asset: where the sum total of Modules A1–A5 plus B1–B5 plus C1–C4 over its lifecycle plus offsets equals zero.

Net Zero Upfront Carbon Asset: where the sum total of GHG emissions from material sourcing, transport, manufacture and construction (Modules A1–A5) plus offsets equals zero.

Net Zero Whole Life Carbon Asset: where the sum total of all asset related GHG emissions, both operational and embodied, over its lifecycle including disposal (Modules A1–A5, B1–B7, C1–C4) plus offsets equals zero.

Net Zero Operational Water Use Carbon Asset: where those GHG emissions arising from water used by an asset, as projected or measured over its lifecycle, plus offsets equals zero.

Net Zero in Use Asset: where the operational carbon from energy and water use, and embodied carbon, as projected or measured over its use stage (Modules B1–B7), plus offsets equals zero.

Net Zero — Carbon Neutral: for simplicity and consistency, ‘net zero’ and ‘carbon neutral’ are considered to be interchangeable.

† Often referred to as ‘Capital Carbon’ in civil engineering.

The following definitions are also used in this book:

Carbon sequestration: removal and long-term storage of CO_2 from the atmosphere in biomaterials such as timber. The carbon stored in these materials is known as 'biogenic carbon'.

Carbon storage: any means of preventing or delaying the release of sequestered carbon.

CO_2e: carbon dioxide equivalent emissions, or 'carbon' for short. This can also be referred to as global warming potential (GWP).

Life-cycle stages or **lifecycle modules** from BS EN 15978[10].

LCA: lifecycle assessment.

EPD: (Environmental Product Declaration) an independently verified and registered document that communicates transparent and comparable information about the lifecycle environmental impact of products[11].

Circular economy: system where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised by slowing, closing and narrowing energy and material loops[12,13].

Deconstructability: ability for a building or structure to be taken apart at any stage during its lifecycle.

Design rationalisation: sizing of multiple similar structural elements based on worst-case load levels in one member[14].

Design working life: period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary[15].

Lightweighting: process of minimising material consumption in design such that an appropriate level of performance against relevant limit state design criteria is achieved, and no more.

Overdesign: overly conservative design of structural elements.

Reliability: ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed. Reliability is usually expressed in probabilistic terms[15].

Reuse: taking a component from a structure and using it again in the same way as originally intended.

Repurpose: taking a component from a structure and using it again, but to fulfil a different function or purpose from that originally intended.

Serviceability limit states (SLS): states that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met[15].

Ultimate limit state (ULS): states associated with collapse or other similar forms of structural failure[15].

Utilisation Ratio (UR): ratio between an actual performance value and the maximum allowable performance value that is deemed limiting for a structural member[14].

We and Us: the community of people who, at any stage of a building's lifecycle, have the ability or potential to impact on its total embodied energy.