3.Lean design

Rationalisation versus optimisation – getting the balance right in changing times

Ian Poole explores ways to improve the utilisation ratio of designs, and encourages engineers to challenge assumptions that favour rationalisation over optimisation.

Introduction

UK structural engineers declared a climate emergency in 2019, with over 170 signatories committing to radical changes to tackle the climate crisis (www.structuralengineersdeclare.com). This article focuses on one of the key commitments that the signatories agreed to address:

- Minimise wasteful use of resources in our structural engineering designs, both in quantum and in detail.

This commitment infers that we are currently producing wasteful designs. Indeed, most practising structural engineers come to realise that wastefulness is inherent in how we design, and that it is mostly intentional.

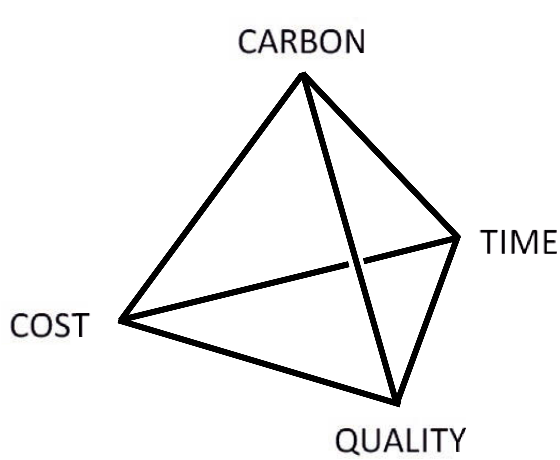
Wastefulness is a by-product of ingrained behaviours in the industry involving designers, clients and contractors, whereby using additional material has allowed us to improve quality, save time, and reduce overall cost – the three key requirements from any client. However, there is now a fourth variable, *carbon*, which designers must consider **(Figure 1)**.

What is the problem?

The study presented by Gholam[1] in this issue found that structural engineers typically design to a maximum utilisation ratio of 0.8, with average utilisations of approx. 0.6. A white paper produced by the Structural Engineering Institute in the USA reported an even lower average utilisation of 50% in steel buildings[2].

Assuming a linear relationship between utilisation and material use, these papers suggest that structural designers are using somewhere between 20–50% more material than necessary. Given this, optimising our designs appears to offer a significant and achievable opportunity to realise the commitment above.

FIGURE 1: Amended project management triangle for climate emergency



Reasons for low utilisation

Risk mitigation

The reasons structural engineers often cite for not designing to 1.0 utilisation are the assumption of error (on site or in the design), and the need to cover design uncertainties or unknowns, which means using material as risk mitigation.

While this approach is reasonable, it doesn't consider the bigger picture, in that using additional material increases carbon emissions, which accelerates climate change and increases the risk to the livelihoods of the global population.

The approach is also circular, in that if contractors know designs have spare capacity, there is little pressure to get things right.

Finally, risk and uncertainty are mitigated in design codes using partial factors of safety, applied to both the loads and the materials that we use. These codes exist to definitively justify that a design is safe, without the engineer making any extra allowance.

It is a tough leap for engineers to make, but we are now unwittingly in a position where, when designing a building, we are not only responsible for the health and safety of those who construct and use the building, but also for the health and safety of the global population due to the consequences of construction on carbon emissions and climate change.

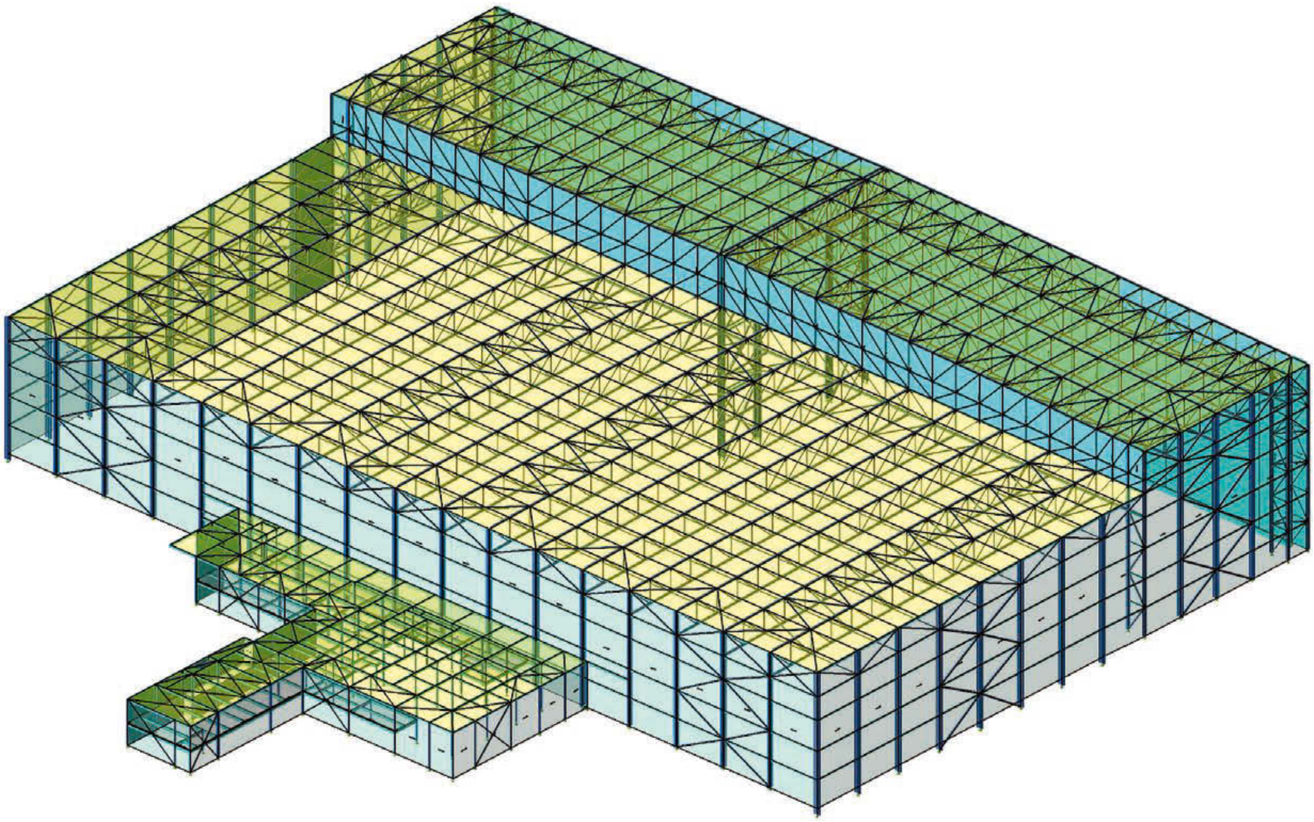
Rationalisation

While risk mitigation may explain why designers waste up to 20% of material (by generally designing to a maximum utilisation of 0.8), it doesn't explain why a further 20% is wasted (by generally designing with an average utilisation of 0.6). This can be explained by rationalisation, which will be the focus of this article.

Rationalisation is the process whereby members with similar geometries and load actions are grouped together. This is seen to have various advantages, principally:

- simplifying the design process: reducing the number of calculations, simplifying co-ordination, minimising effects of change, and hence saving time and cost
- simplifying the construction process: reducing the number of unique sections and connections, reducing the risk of error, increasing repeatability, and hence saving time and cost.

It is important to note that the increased material cost due to rationalisation is generally small compared to labour cost savings and revenues associated with reduced programme times. On a recent project that the author worked on, the total material cost was approximately equal to just one month's revenue from the operational building. This presents a challenge that sets the construction industry apart from other similar industries (e.g. aviation): to reduce material without the financial incentive to do so.



↖**FIGURE 2:** Design model used for case study

Rationalisation interrogated

If rationalisation requires an additional 20% of material (and carbon), we should be certain it is providing the benefits we assume. After all, knowledge is generally passed on, and as discussed by Rosling[3], our understanding of the world often lags behind the times, defined by outdated knowledge and assumptions.

Rosling asserts that we must challenge the idea that today's culture must also have been yesterday's and will also be tomorrow's. To this end, in the climate emergency, previous reasons and arguments must be discounted, today's reasons and arguments must be informed rather than assumed, and we must endeavour to shape and predict future trends (due to the time lag between design and construction).

The following points summarise the key changes to our working culture that reduce the need for rationalisation in our design:

- Designers have the tools available to eliminate long calculations and efficiently design members using powerful computer-aided design (CAD) software.
- Changes can be quickly incorporated and calculations re-run with the aid of analysis software, and do not require changes to large quantities of paperwork as in the past.
- Coordination using building information models (BIM) has removed the need to simplify details, provide flat soffits, ensure equal beam depths, etc.
- The use of BIM allows us to link design models and CAD software more efficiently, reducing the consequence of structural designs on production and checking of drawings.

Altogether, the benefits of rationalisation to the designer are minimal given the tools available, providing there is reasonable allowance of time in the programme. The rationalisation benefits therefore must be realised in the construction stage. This is the assumption that most young engineers are taught when they begin undertaking design work, based on historical truths. However, are these reasons still valid in a rapidly changing industry?

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Case study

The case study presented is a long-span, single-storey, steel structure constructed in 2019. The final design **(Figure 2)** comprised 2500t of primary steelwork (roof steel ~125kg/m^2 with ~70m spans), and was highly rationalised to focus on minimising construction time on site (achieved in 10 weeks). Structural optimisation was therefore compromised due to the following design decisions:

- A small number of unique sections were used to increase repetition and minimise unique connections. It was assumed that this would minimise site works and the risk of error leading to programme delays.
- Truss depths were limited to avoid vertical splices – this was estimated to make the design four times faster to erect due to off-site preassembly minimising site works. However, it compromised a greater structural depth which would have improved the efficiency of the structure (in some areas, vertical clearances within strict building height requirements also restricted structural depth).
- Load combinations had to consider gravity loads, uplift due to wind through dominant openings, and large point loads acting at various locations. As complexity in loading increases, form-finding solutions become more complex and incur added time to design and construct.

This wasn't to say that the engineers did not try to create an efficient structure. In fact, through challenging the brief, which specified no internal columns (as would be typical for this type of building), the design team realised an opportunity to introduce an internal column without compromising the functionality of the building.

The driver of this change was a saving in cost (estimated £1.5M) and programme (estimated six weeks). Although not quoted as a reason at the time, the 600t of steelwork saved also equated to a saving of over 1000t of CO_2e.

Ultimately, despite achieving the brief and offering additional value, the design conformed to the wastefulness reported in research studies referenced earlier, with an average utilisation of 0.56, owing to the large amount of rationalisation.

This case study, completed following construction, looks at the opportunities that might have allowed for improved utilisation and the possible effects on construction (cost, programme, quality) as provided by the steelwork contractor.

Opportunities

A total of 19 opportunities were identified in the case study. These could be generalised into three categories:

Challenging the codes

Options to 'design for performance' rather than to codes were considered, such as reducing the partial factor of safety applied to the self-weight of steel and relaxing deflection criteria. However, it was decided that the design should conform to codes for the optimisation study.

Optimising form

Optimised form is known to offer vast benefits, as outlined in the ongoing Build-Opt[4] research project and in the article by Gholam[1], so many opportunities related to optimised form, such as modifying truss types, geometries, grid spacings and restraint systems, were considered.

However, these were not investigated, due to time limitations and the difficulty of quantifying other impacts. For example, increasing truss depths would increase cladding, internal volume (heating and lighting), and affect compliance with cranage requirements.

Optimising utilisations

The form of the structure was therefore unchanged, and the aim was simply to optimise the chosen form through the removal of rationalisation, while

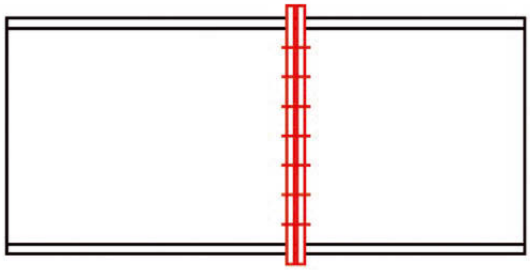

FIGURE 3: Compression splice – connection would not be compromised due to differing incoming sections

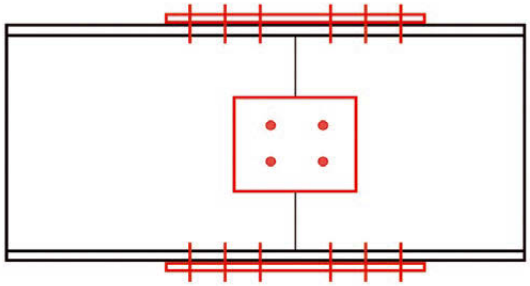

FIGURE 4: Tension splice – additional packing and jigging will be required if incoming sections differ, increasing time and cost

minimising the impact on programme, as assessed by the steelwork contractor. This was achieved through the following approaches:

Designing spliced sub-assemblies independently

As splice locations were specified in the truss design, it would take minimal time to design each spliced section independently. This allows reductions in sections as forces reduce along the truss length. When adopting this method, a sensible approach is required where the engineer must consider the connection types **(Figures 3 and 4)**.

Increasing unique sections forming truss internals, bracing and tie members

Increasing the number of unique sections in our designs to reduce material is encouraged due to much higher levels of quality control and availability of steelwork than in the past, when worse quality control (leading to error) and more common lack of supply (causing delays) would require increased rationalisation.

There is also a huge range of section capacities within similar section geometries, which allow for similar connections to be used even if members differ.

Finally, the ease of connection design, especially if design models are shared directly with the contractor, minimises additional time spent designing unique connections that may have previously been assumed to be an issue.

Assessment

The final part of the study would require an assessment of the structure's as-built 'rationalised member utilisation' and the attempted 'optimised member utilisation' solution, using a few iterations of the design model to approximate the latter.

The material reduction was estimated to be 34%, which closely aligns with the increase in average utilisation ratio (0.30) **(Figures 5 and 6)**. Critically, the contractor feedback was that the optimised solution would have minimal impact on programme time.

Ultimately, the material saving from optimisation would equate to approx. 900t of steel, and more pertinently to a CO_2e saving of almost 1500t*. For context, this is equivalent to the annual carbon footprint of approx. 180 people in the UK[5], or 900 people taking a return flight from London to New York[6].

More scarily, taking a semi-quantitative prediction of the effect of current carbon emissions on future populations and the '1000t rule', this level of saving is likely to prevent a premature death relating to climate change in the future[7].

Reflection

This study found that many arguments made in the past for rationalisation do not align with current best practice, both in design and construction. Further, assumptions made on the benefits of rationalisation in the design stage were in many cases unfounded.

Given the findings reported in the publications referenced earlier relating to average utilisations, it is likely that many other designers are making similar decisions based on outdated knowledge and assumptions. This unnecessary rationalisation is wasting material, which in turn is needlessly pumping carbon into the atmosphere.

It should be noted that this study takes a relatively soft approach to 'optimisation', in that the opportunities were only considered if they had minimal effect on design time and construction programme, such that they would reasonably meet client requirements on the project.

Indeed, many may argue that this doesn't go far enough, and that projects today should prioritise reducing carbon over cost and programme considerations, in which case there would be further opportunities (touched

* This figure considers only carbon associated with Scope A1–A3 steelwork, assuming a value of 1.64kgCO_2e/kg steel, which is adopted from the Inventory of Carbon and Energy database using average recycled content of 59%, as reported for European steel. Further carbon savings would be expected due to reduced transport (A4), reduced site works (A5), and reduced concrete in the substructure and foundations.

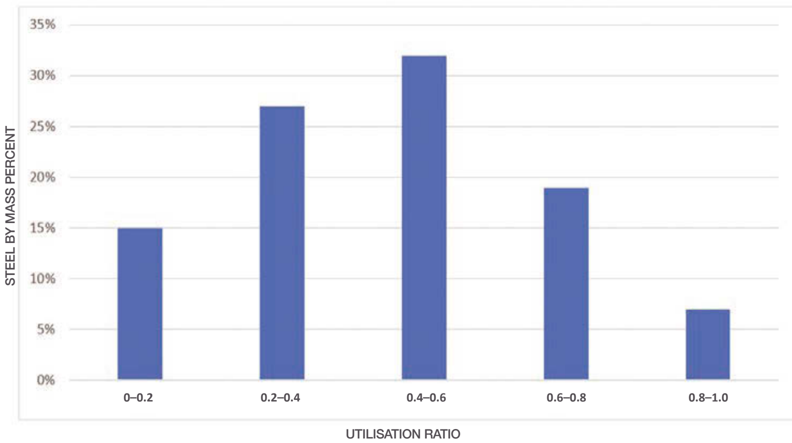

FIGURE 5: Rationalised member utilisation

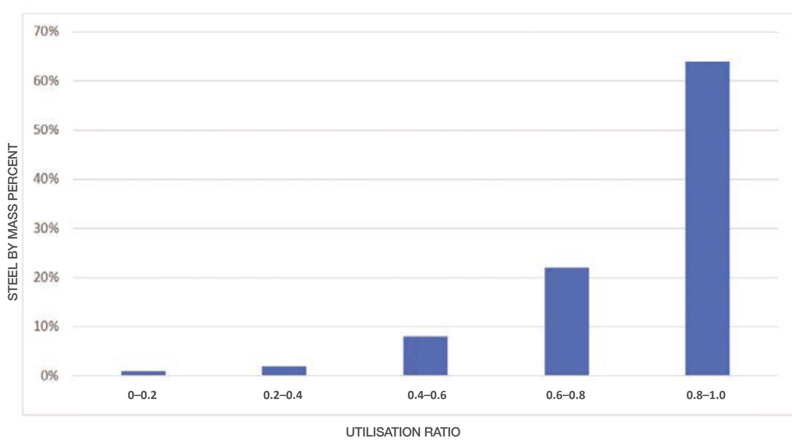

FIGURE 6: Optimised member utilisation

on above) which would lead to material reduction.

Finally, this study has been possible due to the collaboration between designer and contractor. Collaboration allowed carbon savings to be made on the project (e.g. through sharing design models to aid connection design), and the valuable lessons that form the basis of this article to be learned.

Revisiting the design after construction to learn lessons was hugely beneficial, and is something we should do more often to improve the industry and address the climate emergency.

Conclusions

The conclusion from this study is that we must challenge any assumption made in the design stage where rationalisation is adopted over optimisation, to ensure any assumed benefits are correct and to justify additional use of material and carbon.

In most cases, given the tools available to us in the present and the future, and the urgent need to reduce carbon consumption, the balance must shift dramatically from rationalisation towards optimisation.

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Ian Poole MEng

Ian is a structural engineer at Mott MacDonald. He sits on the Institution's Sustainability Panel and is active in LETI, contributing to and reviewing its Embodied Carbon Primer.

"WE MUST CHALLENGE ANY ASSUMPTION MADE IN THE DESIGN STAGE WHERE RATIONALISATION IS ADOPTED OVER OPTIMISATION

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FURTHER READING

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tse@istructe.org

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