A toolkit for designing lower-carbon domestic structures

Mike Davies, **Harry Furnival-Doran** and **Gemma Sheterline** of SD Engineers present the findings of the practice's research into lower-carbon options for the sub- and superstructure of domestic projects, indicating how UK Net Zero Carbon Buildings Standard targets can be met.

Introduction

The climate emergency is a key consideration for the built environment. For domestic projects, the embodied carbon per square metre is often high – the RIBA 2030 Climate Challenge[1] identifies the current baseline for domestic buildings at around 1,000kgCO_2e/m^2, compared with a target of below 300kgCO_2e/m^2 by 2030. The substructure and superstructure choices impact embodied carbon greatly, but often domestic projects come with smaller budgets and so rarely have the resource to consider more environmentally friendly options. SD Engineers has invested in research into lower-embodied-carbon options and compiled the findings into a useful guide called the Carbon Toolkit.

Most of the firm's domestic work has been London based, and so this study focuses on the addition of a rear extension to typical Victorian/Georgian properties with 215mm solid historic brick walls supported on shallow foundations in London clay **(Figure 1)**. While the study uses this specific building typology as its basis, the principles and methodology are applicable to domestic extension projects more broadly, regardless of location or structural framing type.

The research proves that modest changes to the structural strategy can lead to substantial reductions in embodied carbon. The aim of this article is to provide other designers and clients with the tools and research they need to make informed and better choices.

Domestic extensions often benchmark poorly due to the minimum dimensions for foundations and masonry not aligning with the applied loads, and the weight of steel needed to control deflections of the existing masonry. This reinforces the importance of addressing embodied carbon early in the design process before solutions become fixed.

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FIGURE 1: Walled Garden: a rear extension in southwest London

Hierarchy of net-zero design

As engineers, we should all be familiar with the Hierarchy of net-zero design **(Figure 2)**. We refer to this before implementing any potential design changes, considering the following questions:

- Can the client ambition be provided without any new construction?
- How can we reuse the existing structure as far as possible? Consider foundations, beams, minimising wall openings, etc.
- How do we make best use of the existing load paths and avoid transfers which lead to heavier material use? Challenge conservative legislation with regards to foundation depth and imposed load. Site test on soil properties.
- Is it essential to hide the structure? Shallow, heavier sections are not as efficient as a lighter, deeper alternative. Consider pier foundations instead of strips.

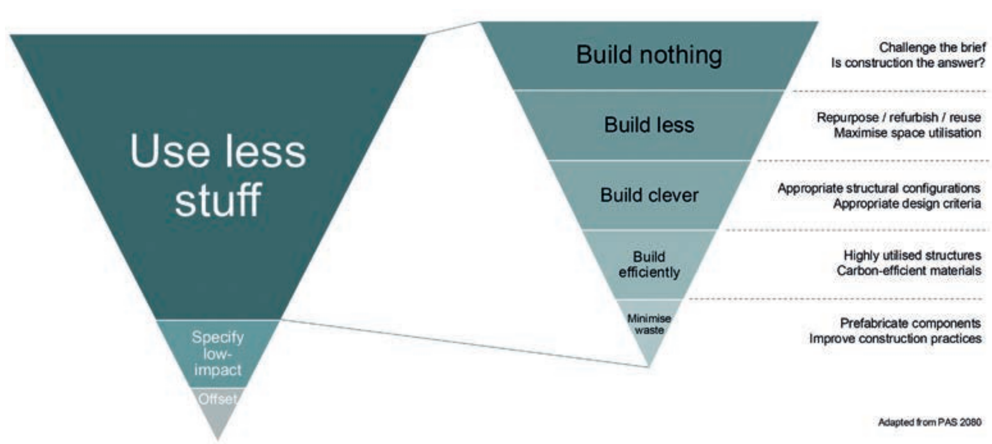

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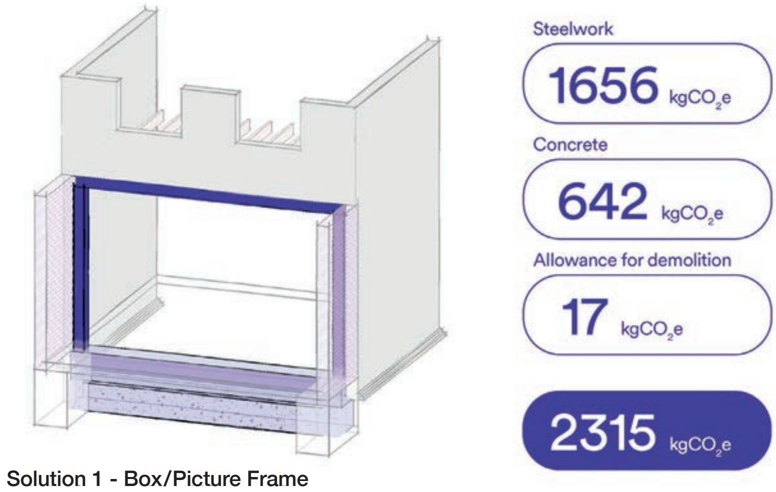
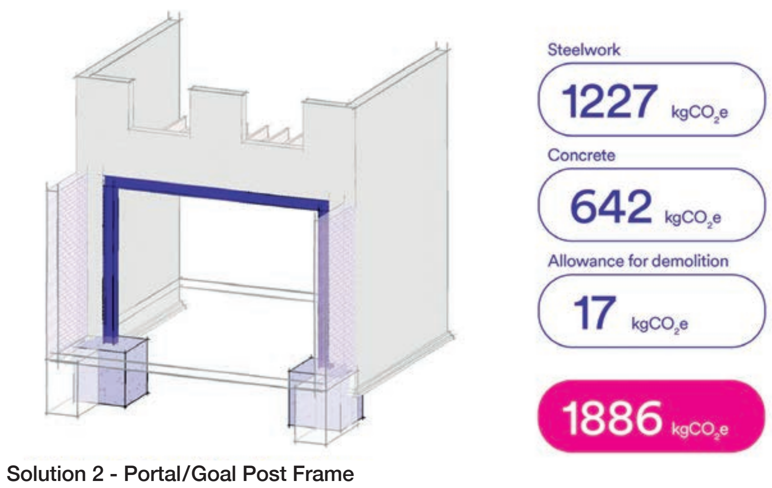
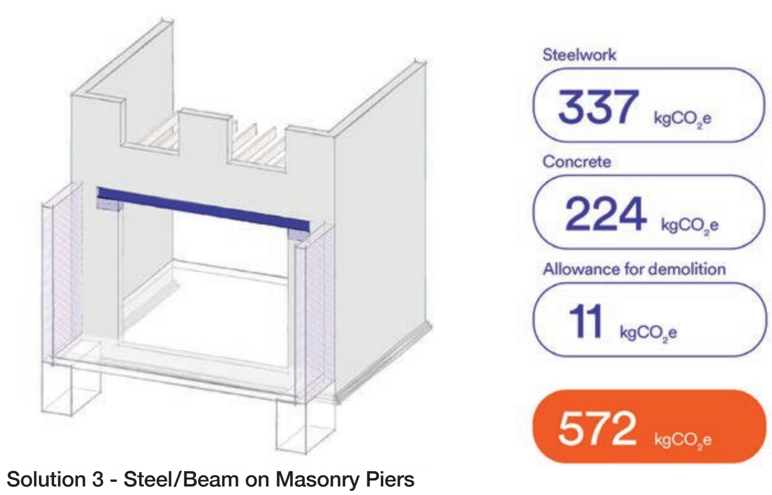
FIGURE 2: IStructE Hierarchy of net-zero design



←FIGURE 3: Typical box frame and associated embodied carbon



←FIGURE 4: Typical portal/goalpost frame and associated embodied carbon



←FIGURE 5: Typical steel beam on masonry piers and associated embodied carbon

Superstructure study

Case study – base case

A typical design proposal for a domestic project is the addition of a rear extension which requires the removal of a 4.5m wide, 3m high and 215mm thick brick wall at ground level. The replacement structure is required to provide lateral stability to the rear of the house, as well as support the remaining wall above, a portion of the first floor and loft conversion, and the roof of the new extension.

The architectural requirements of the opening wall may vary, but the structure will typically stay within the wall thickness, approximately 215–330mm wide. Minimising the depth of the structure is preferable to produce a flat soffit between the two spaces. For a given load scenario and performance criteria, the proportion of the wall being removed correlates to the intensity of the proposed structural intervention, often dictating the density of embodied carbon.

Our study compares three typical approaches to achieving this scenario, comparing structural requirements against architectural intent, associated embodied carbon, and costs courtesy of Multiproject (SE) Ltd. Further refinements to the three typical approaches are also explored.

The carbon figures presented are for life-cycle modules A1–A5, representing the emissions associated with the specified structural materials from raw material extraction up to practical completion of a given construction project. This is often referred to as upfront carbon, and it is where designers can have the greatest impact to reduce the whole-life carbon of a given construction project. Version 3 of the IStructE's Structural Carbon Tool was used to approximate the figures for each design iteration, utilising the inbuilt material factors database. For consistency, material strengths/grades remain the same between the studied options.

Typical structural solutions

1) Box frame

A typical solution for a rear wall removal includes the installation of four steel members to recreate and replace the removed wall **(Figure 3)**. The top steel supports the loads above while the vertical members and stiff connections reinstate the lateral stability the old wall provided. This base case assumes the bottom steel sits on a new concrete foundation. The inherently stiff frame reduces steel sizes for large opening widths or high loading. The stiff connections required for this frame can be more complex, which can add cost. A box frame offers the most open-plan solution.

2) Portal frame

Omitting the bottom beam concentrates the loads into the base of the vertical members and so the foundations need to be designed accordingly **(Figure 4)**. The steels will need to be stiffer than those used for a box frame to achieve the same lateral stiffness; this can reduce head height. The columns generally need to sit inboard from the party wall to make the foundation work and so offer a slightly smaller opening than a box frame. The stiff connections required can be more complex, which can add cost.

3) Steel beam on masonry piers

Retaining masonry piers (generally 750mm each side of the opening) and installing a single top steel beam provides lateral stability but a smaller opening **(Figure 5)**. The remaining masonry walls and foundation need to be checked against the applied load from the end of the beam. The limiting factor on pier width can be the net load to the foundations, typically assumed to be 100kN/m² in the absence of site-specific investigations. Trial pits are beneficial to confirm corbel width. If needed, the piers can be underpinned.

Summary of solutions 1–3

A steel beam on masonry piers (solution 3) offers substantial carbon and cost savings, only comprising 25% of the carbon and 20% of the cost compared with a box frame (solution 1) **(Figure 6)**. However, the compromise is the reduced clear opening.

A portal frame (solution 2) offers both carbon and cost advantages, being approximately 70% of the box-frame option.

The implication on head height and opening width should be assessed early on and the savings considered within the overall carbon and costs of the scheme.

Refinements and optimisation

Further structural refinements to reduce the carbon can be achieved. Each option is presented in isolation, but a combination of these options could be applied.

Reusing steel is an effective way to reduce embodied carbon when steel framing is a significant part of the structure, offering a carbon-intensity reduction of up to 97% (according to Cleveland Steel). One of the main challenges is ensuring the right stock is available at the right time, so planning in procurement or designing with some flexibility in member sizes will help facilitate the actualisation of reuse in practice. Domestic projects are likely to have a smaller order volume than commercial projects, and so the stock-matching process is more streamlined, making domestic projects stronger candidates for more ambitious reuse percentages. To learn more about the practicalities of steel reuse in domestic projects, refer to Cleveland Steel's website **(www.cleveland-steel.com/)**.

Reusing the existing foundations should only be pursued where there are no signs of defects to the existing structure that could be connected to its foundations. It is presented as a refinement in this study, primarily to emphasise the scope for optimisation and to acknowledge project-specific variables.

Low-carbon masonry alternatives can contribute to carbon reduction when used in volume. These products are

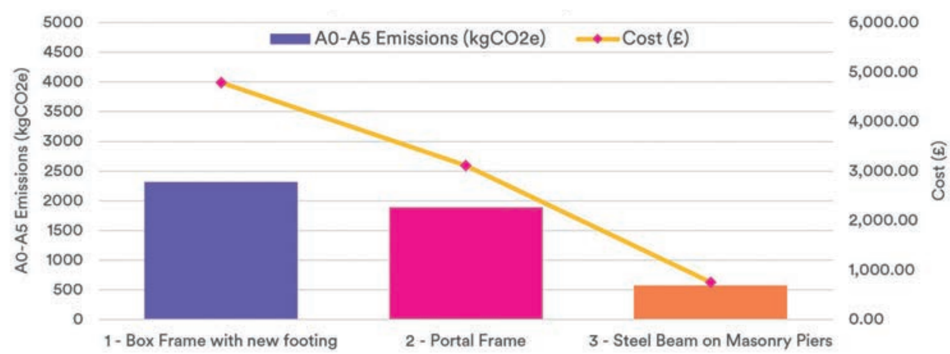
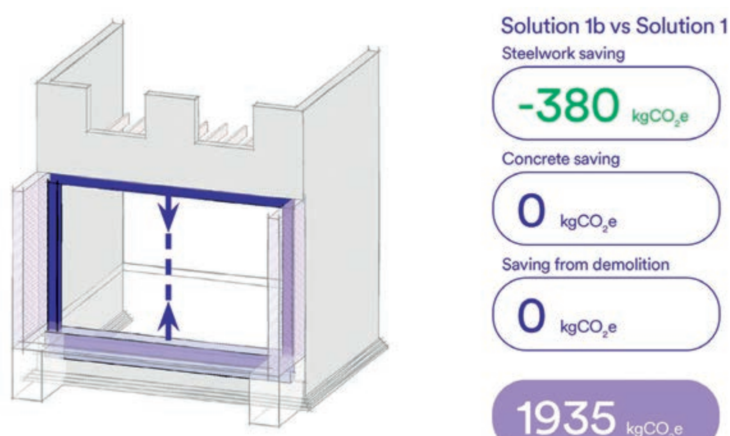


FIGURE 6: Comparison of cost and carbon for typical superstructure options

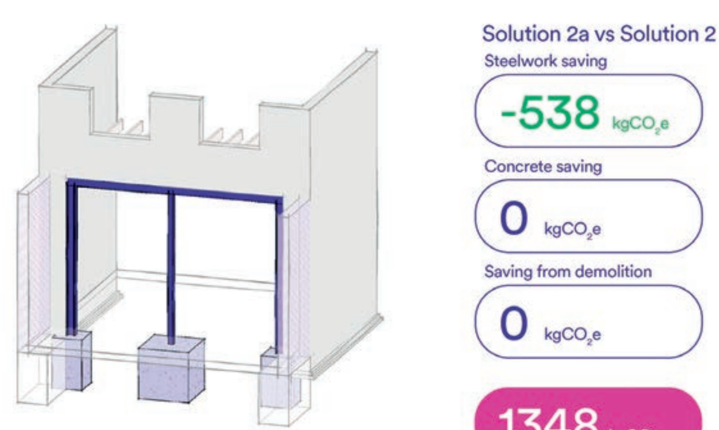
Solution 1a - Box Frame with Reused Foundations

FIGURE 7: Box frame with reused foundations



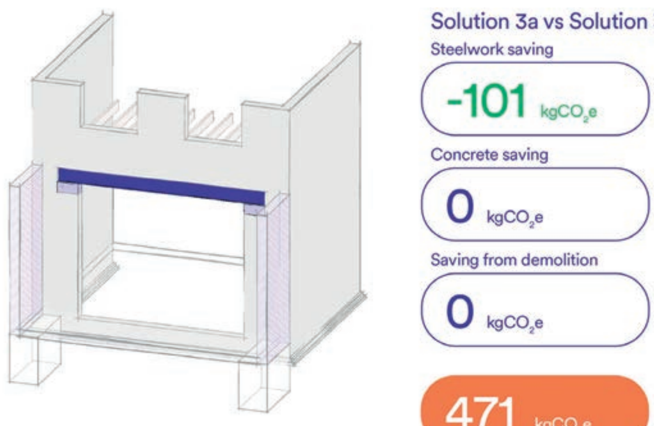
Solution 1b - Box Frame with Predeflection

FIGURE 8: Box frame with pre-deflection



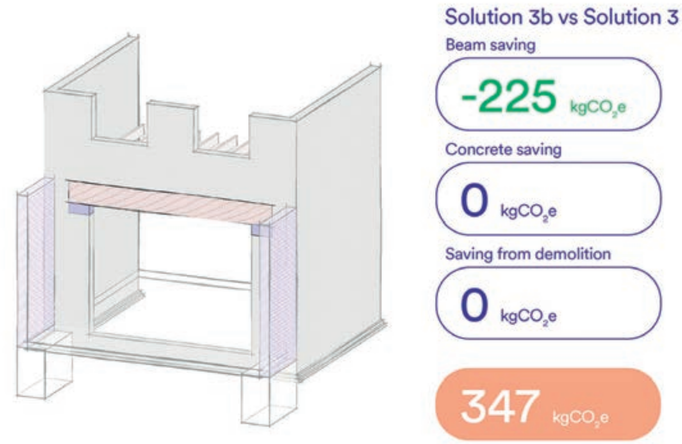
Solution 2a - Portal Frame with Internal Column

FIGURE 9: Portal frame with internal column



Solution 3a - Deeper Steel Beam

FIGURE 10: Deeper steel beam on masonry piers



Solution 3b - Engineered Timber Beam

FIGURE 11: Engineered timber beam

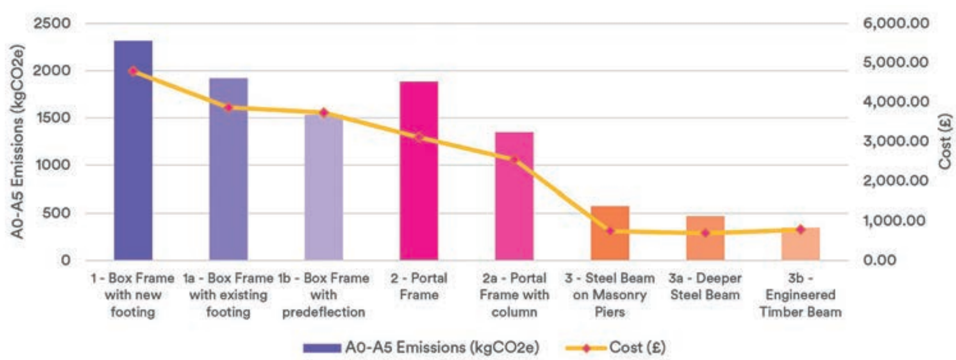


FIGURE 12: Comparison of cost and carbon for all superstructure options

generally more expensive than standard blocks, and the merits of specifying them should be considered against overall project volumes.

All parties need to understand the impact on procurement and programme, and that like-for-like sections may not always be readily available.

1a) Box frame with reused foundations
Assuming the existing foundations show no evidence of subsidence or clay heave, they could be reused without the need for additional strengthening **(Figure 7)**. Trial pits would be needed to verify the existing footing has sufficient depth beneath the proposed steel-concrete encasement (typically min. 600mm below proposed SSL). For large spans, the bearing stress profile of the ground should be considered.

1b) Box frame with pre-deflection
Deflection is often the limiting factor when structures are supporting existing masonry. Pre-deflection of the steels during installation causes the beam to deflect prior to unpropping the wall above **(Figure 8)**. This results in less net deflection once the beam is loaded and therefore members can be less stiff i.e. smaller. Pre-deflection also changes the stress profile in the bottom beam, which typically enables the existing foundation to be reused in the majority of cases. Pre-deflection amounts must be stated on the drawings for the contractor on site.

2a) Portal frame with internal column
The addition of a central column to the box frame can reduce stresses on other members, allowing lighter steels to be used throughout – often leading to a shallower and less carbon-intensive solution **(Figure 9)**. A net increase in concrete volume due to the additional footing is often negligible, as the area of the individual footings can be rationalised to suit the columns carrying lighter loads. The beams used can be shallower, maximising head height, but the full-width opening is compromised.

3a) Deeper steel beam on masonry piers
Concealing structural beams within the floor depth is often preferred, but this increases carbon as heavier steels are required **(Figure 10)**. Lighter steels can be used but would be approximately 100mm deeper and protrude below the ceiling line. Additional steel plates may be required to suit the width of the wall above, which must be accounted for when comparing carbon and cost.

3b) Engineered timber beam on masonry piers
If the head height is available, and a deeper down-stand is acceptable, an engineered timber solution could be considered **(Figure 11)**. Typically, this increases the depth by 250mm. A deep beam can be incorporated as an upstand if the roof flashing can conceal it, and the room above can be redecorated. Additional considerations include fire resistance, moisture shrinkage, and moisture ingress. Biogenic carbon storage is excluded from this analysis as it is an evolving methodology and outside the scope of this study.

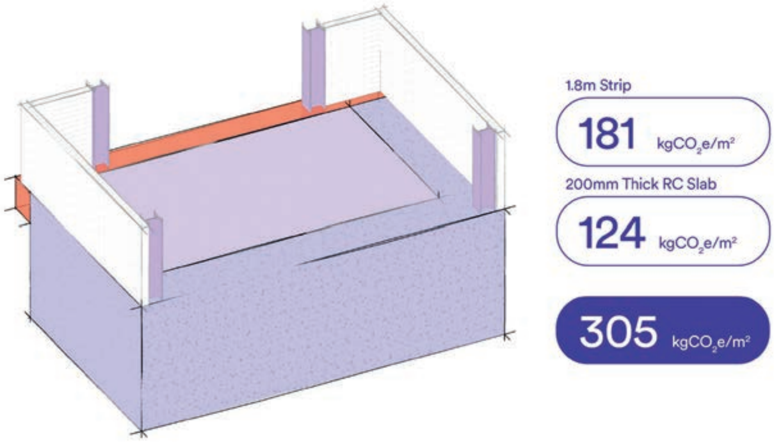
Superstructure summary
A pre-deflected box frame (solution 1b) is more carbon efficient than a portal frame (solution 2) – if combined with the carbon (–382kg) and cost (–£900) savings of reusing the existing footing (solution 1a), the box-frame solution could be up to 40% lower in terms of carbon and cost than a portal frame, and achieve the desired opening width **(Figure 12)**.

Solution 2a demonstrates that having more efficient spans equates to less material overall, even when introducing additional members.

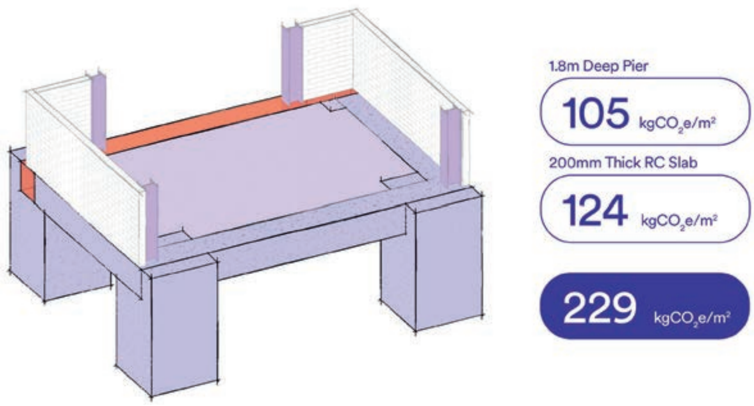
The single-beam solution (3a) will always be more beneficial in terms of cost and carbon following the 'do less' approach.

Each project is unique and the final solution will be governed by several factors, including head height, layout, cost and the capabilities and method of the selected contractor.

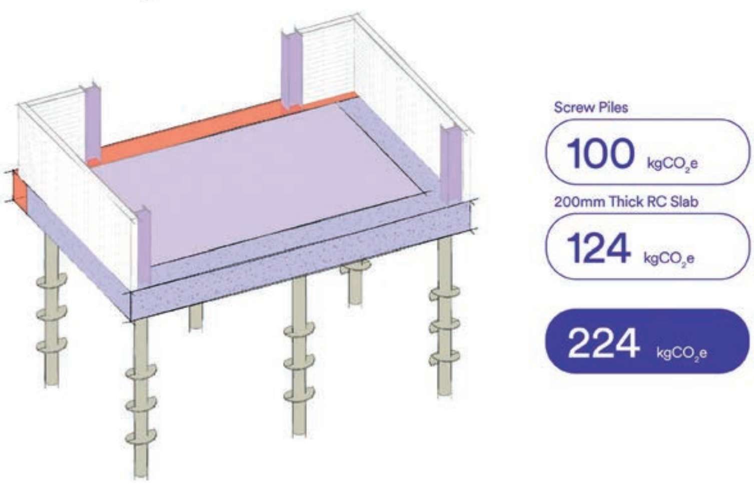
This framing study will often only be one part of the structural solution for



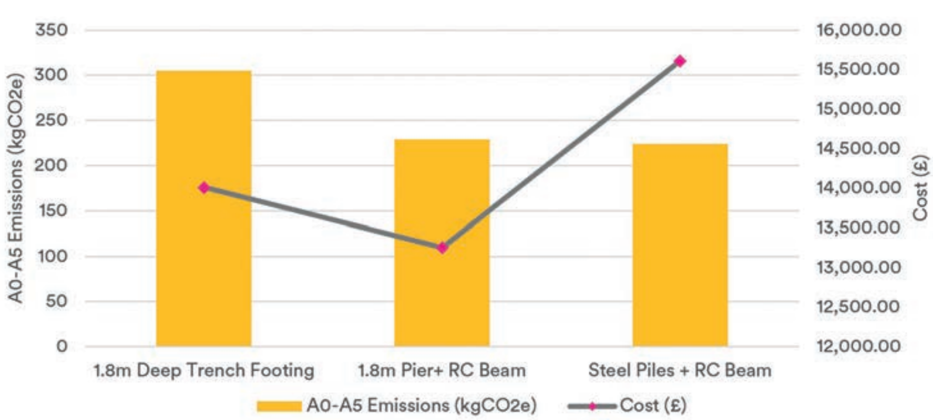
🡐FIGURE 13: Deep trench footing and associated embodied carbon



🡐FIGURE 14: Deep pier + RC beam and associated embodied carbon



🡐FIGURE 15: Steel piles + RC beam and associated embodied carbon



🡕FIGURE 16: Comparison of cost and carbon for typical substructure options with 200mm RC slab

the whole project, and therefore carbon savings must also be considered in the context of the net build.

Substructure study

The depth of foundations for new construction is heavily influenced by the soil type (e.g. presence of clay across London) and its plasticity, and the distance of trees to the new footings.

Design criteria set out in NHBC Standards, Chapter 4.2[2] are considered best practice and are often expected to meet building regulations. These criteria also determine whether the slab can be ground bearing or suspended.

A low-cost plasticity test of the soil will determine savings in the depth of the concrete; a medium plasticity compared with high can save 200–300mm of concrete. Confirming tree species can reduce the required foundation depth by up to a meter if a moderate- or low-water-demand tree is identified.

Case study – substructure

We consider the design of a new slab and foundations to support a 5.0 × 3.0m extension with new masonry perimeter walls and steel framing. Ground conditions and trees dictate the foundations need to be 1.8m deep, and the floor needs to be suspended.

Comparable foundation options, assuming a suspended reinforced concrete slab, have been assessed with carbon ($kgCO_2e/m^2$) and cost data included.

Foundation typologies

1) 1.8m deep trench footing with 200mm thick RC slab

The excavation of a continuous trench along a boundary is straightforward to construct but undermines structures on or near the boundary. Temporary works or a 'hit and miss' sequence may be required to install the trench. *In situ* slabs need to be cast onto collapsible void formers to allow the ground to heave without loading the slab. This study **(Figure 13)** considers collapsible void formers made from cardboard, which disintegrates with the introduction of moisture. Plastic options designed to compress under a specific load are also commonly available; use of these will increase the cost and carbon for this solution.

2) 1.8m deep pier + RC beam with 200mm thick RC slab

This option **(Figure 14)** omits the continuous excavation along the boundary and removes the need for temporary works. The beam can be concrete-encased steelwork or reinforced concrete. Preformed cages for

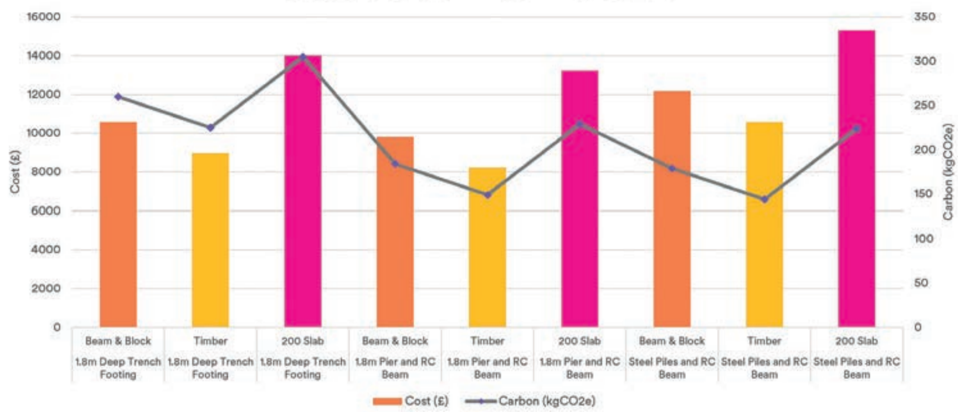


FIGURE 17: Comparison of cost and carbon for substructure floor and foundation combinations

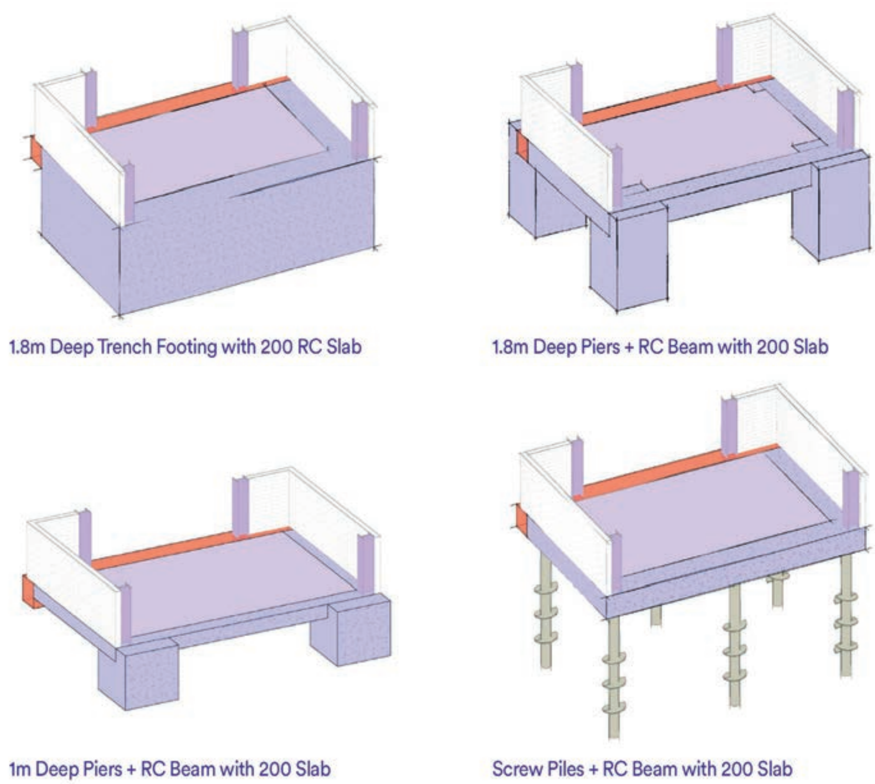


FIGURE 18: Indicative slab and foundation combinations

reinforcement can be delivered to site to reduce installation time. Carbon amounts for either option would be similar.

3) Steel piles + RC beam with 200mm thick RC slab

This option **(Figure 15)** omits the continuous excavation along the boundary and removes the need for temporary works. Screw piles may be required to avoid tree roots if excavation is required within a tree protection zone. A small rig will be required at the rear of the site and so accessibility must be considered. Smaller ground screws can be installed with handheld equipment, but their smaller capacity may not be sufficient for extension applications with higher loads. The beam can be concrete-encased steelwork or reinforced concrete. Preformed cages of reinforcement can be delivered to site to reduce installation time. Carbon amounts for either option would be similar.

Foundation comparison

Costs for the three foundation solutions **(Figure 16)** are impacted by material volumes as well as the labour involved in activities such as excavation and formwork. Therefore, changing from a trench solution to a pier reduces the cost by less than 10%, although the material volumes are considerably lower.

Piling can be expensive due to upfront costs of machinery and installation, but may suit a project where excavation is limited by boundary conditions or tree protection orders. The cost and carbon for piles can increase greatly if a piling mat is required for a heavier rig, adding to the amount of spoil to be removed and material to be imported.

Floor options

The biggest contributor to embodied carbon is the foundation, but floor choice also influences this **(Figures 17–20)**.

Refinements considered include a beam-and-block or suspended timber floor, both of which are suitable for London ground conditions. The timber floor results in the lowest-carbon option; combining beam + pier (foundation option 2) with a timber floor can lead to a 50% reduction in carbon compared with the trench footing + reinforced concrete slab (option 1).

The net reduction in carbon for a piled (option 3) or pier (option 2) solution compared with trenches (option 1) is approximately 30%. By combining this with a lower-carbon floor type (changing slab to timber), the reduction is increased to 50%.

The void below the beam-and-block or timber floor will need to allow for ground heave and ventilation – this could be up to 300mm.

Suspended timber floors are common in historic building stock and, where ventilation and an oversite slab is provided, issues with durability are not a concern.

The preference for tiled finishes on a screed with underfloor heating lends itself to a concrete/beam-and-block solution as shrinkage or creep deflection will not impact the brittle finishes in the long term.

Substructure summary

The chosen substructure solution will be influenced by many factors. Depending on the chosen contractor skill level and supply chain, the 'simplest' yet higher-carbon option of excavating and casting deep strips might be selected. But none of the solutions presented should be unfamiliar or difficult to source.

While every reduction to carbon can be applied, the results show that opting for a timber floor while retaining trench foundations may not provide a clear case for a 'greener' design. The needs of the project and access requirements must be considered when reviewing foundation and floor alternatives.

Further to the options above, the concrete mix should be considered and optimised for the project's needs. The mix for domestic foundations should be optimised to meet the minimum

Slab/Deck Options (A1 - A5)

Ref	GWP (kgCO2E/M2)
Timber joists (+oversite slab)	44
Glasscrete	60
Concrete Beam and Block + Screed	79
120 Slab + A193 (screed and blinding)	90
150 thk Slab + A393 (screed and blinding)	118
200 thk RC Slab (screed and blinding)	124

(75mm screed and 50mm concrete blinding allowed for)
(*combined built up estimated based on available EPD data)

Foundations 1m deep (no tree influence)

Ref	GWP (kgCO2E/M2)
Piers + Concreted encase steel edge beam	75
Piers + RC edge beam	76
450mm strips, 1m	87

Foundations 1.5m deep

Ref	GWP (kgCO2E/M2)
Piers + Concreted encase steel edge beam	93
Piers + RC edge beam	94
450mm strips, 1.5m	151

Foundations 1.8m deep

Ref	GWP (kgCO2E/M2)
1.8m deep piers (no edge beam)	102
Piers + Concreted encase steel edge beam	104
Piers + RC edge beam	105
RC beam + piles 5m deep	100
450mm strips, 1.8m	181

FIGURE 19: Global warming potential of slab and foundation options

Combinations

Foundations 1m - no clay heave, ground bearing slab applicable

Floor	Foundation	Total
Timber Joists (+oversite slab)	Piers + Concreted encase steel edge beam	119
	Piers + RC edge beam	120
	450mm strips, 1m	131
Glasscrete	Piers + Concreted encase steel edge beam	135
	Piers + RC edge beam	136
	450mm strips, 1m	147
Concrete Beam and Block + Screed	Piers + Concreted encase steel edge beam	154
	Piers + RC edge beam	155
	450mm strips, 1m	166
120 Slab + A193 (Screed and Blinding)	Piers + Concreted encase steel edge beam	165
	Piers + RC edge beam	166
	450mm strips, 1m	177
150 thk Slab + A393 (Screed and Blinding)	Piers + Concreted encase steel edge beam	193
	Piers + RC edge beam	194
	450mm strips, 1m	205

Foundations 1.5m - no clay heave, ground bearing slab applicable

Floor	Foundation	Total
Timber Joists (+oversite slab)	Piers + Concreted encase steel edge beam	148
	Piers + RC edge beam	138
	450mm strips, 1.5m	195
Glasscrete	Piers + Concreted encase steel edge beam	153
	Piers + RC edge beam	154
	450mm strips, 1.5m	211
Concrete Beam and Block + Screed	Piers + Concreted encase steel edge beam	172
	Piers + RC edge beam	173
	450mm strips, 1.5m	230
120 Slab + A193 (Screed and Blinding)	Piers + Concreted encase steel edge beam	183
	Piers + RC edge beam	184
	450mm strips, 1.5m	241
150 thk Slab + A393 (Screed and Blinding)	Piers + Concreted encase steel edge beam	211
	Piers + RC edge beam	212
	450mm strips, 1.5m	269

Foundations 1.8m - clay heave

Floor	Foundation	Total
Timber Joists (+oversite slab)	Piers + Concreted encase steel edge beam	148
	Piers + RC edge beam	149
	RC Beam + Piles 5m Deep	144
	450mm strips, 1.8m	225
Concrete Beam and Block + Screed	Piers + Concreted encase steel edge beam	183
	Piers + RC edge beam	184
	RC Beam + Piles 5m Deep	179
	450mm strips, 1.8m	260
200 thk RC Slab (Screed and Blinding)	1.8m Deep Piers with no edge beam	192
	Piers + Concreted encase steel edge beam	194
	Piers + RC edge beam	195
	RC Beam + Piles 5m Deep	190
	450mm strips, 1.8m	271

FIGURE 20: Global warming potential of slab and foundation combinations

compressive strength and durability requirements of BS 8500[3] and BRE *Special Digest 1*[4], while minimising embodied carbon by using the lowest practical cement content, specifying cement replacement materials where ground conditions permit, and avoiding over-specification of strength class.

Case study – typical design

The brief was for a rear extension to an existing house in London (single storey with a partial second storey). The project was designed with the following most commonly adopted principles:

- foundations 1.5m deep, based on ground conditions and trees close by
- 150mm thick reinforced concrete slab
- steel box frame below the rear wall used for vertical and horizontal stability (not pre-deflected)
- new walls of concrete blockwork and clay-fired brick cavity walls
- new roofs of C24 timber joists.

Based on the floor area of the new extension only, the project **(Figure 21)** achieved a SCORS rating (kg/CO_2e/m^2) of G and the UK Net Zero Carbon Buildings Standard (NZCBS) target for 2026 (400kgCO_2e/m^2) was exceeded. The substructure contributed to approximately half the embodied carbon, the steel framing approximately a fifth, and the structural walls a third of the overall carbon.

Case study – lower-carbon design

The principles previously outlined were then applied to this completed project, in conjunction with the Hierarchy of net-zero design, to assess the impact on embodied carbon in a hypothetical case study **(Figure 22)**.

The percentages listed below show the total carbon saving **(Figure 23)** compared with the original case study scheme by making incremental changes.

- Changing foundations from 1.5m deep trench to reinforced concrete beam (450mm × 450mm) and 1.5m deep piers (8No. 600mm × 600mm piers): –**18%**.
- Suspended timber floor (with oversite slab): –**5%**.
- Pre-deflecting box frame: –**2%**.
- Reused steel (assumes 100% of steel, omitting pre-deflection): –**12%**.
- Specifying Greenbloc low-carbon blockwork: –**10%**.

The greatest impact on the scheme is from reducing the volume of concrete used in the foundations by considering a beam and pier. From this study, this option would not incur additional cost.

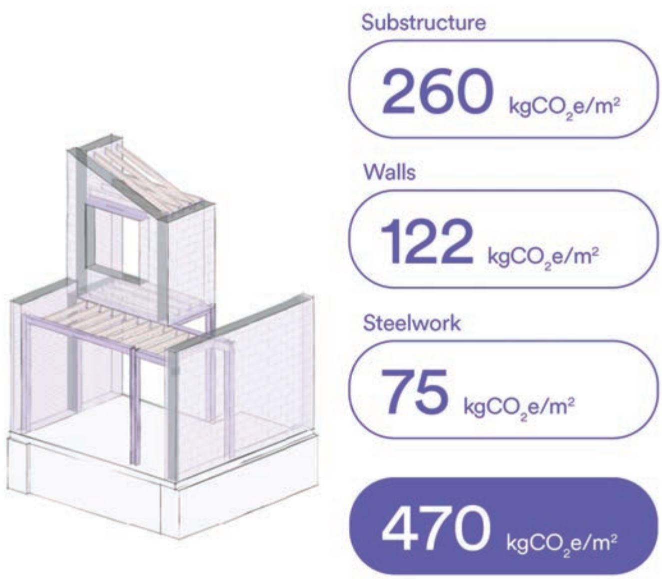


FIGURE 21: Embodied carbon of rear extension case study

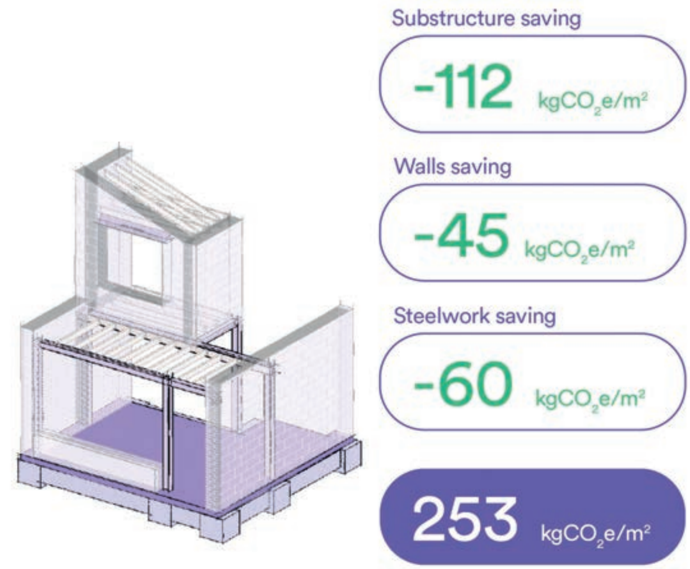


FIGURE 22: Embodied carbon of lower-carbon rear extension case study

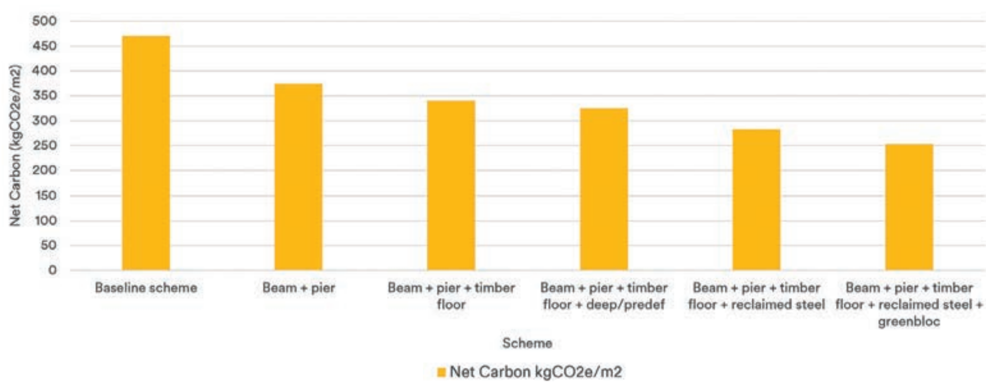


FIGURE 23: Net carbon of incremental changes to case study scheme

Specifying reused steel has a clear impact on reducing carbon; in addition, the cost of materials can often be reduced. This study assumed the same tonnage of steelwork as the original design and that 100% of it is reclaimed. When specifying reclaimed steel, the designed section size may not be available and therefore the overall tonnage may vary. However, even heavier sections will achieve a lower embodied carbon if using reclaimed steel. This option requires the iterative design process between engineer and steel supplier to be understood, and the potential impact on programme communicated to all parties.

The improvements outlined above reduced the SCORS rating to D and meant that the appropriate NZCBS target was met.

Conclusion

Many interlinking factors affect the outcomes of construction. By applying principles of using less, designing efficiently and specifying lower-carbon materials, reductions in embodied carbon can be made for small projects where the carbon outlay per area is typically very high.

Reducing carbon requires the case for 'business as usual' to be challenged. Where the client and design team are motivated to provide lower-carbon designs, this study provides viable solutions for construction works on site.

The implications on site activities should be understood, and if reducing carbon can be married with efficiencies on site, such as reducing the steel tonnage to be brought in or spoil to be removed, together with positive implications on cost, then the case for lower-carbon design is clear.

This study demonstrates that, when considering design changes to reduce carbon, informed choices should be made to have the greatest impact. The aim should be to target high-carbon materials used at volume. The findings from this study can be used to help inform those decisions at the beginning of the project.

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Mike is Director and Co-Founder of SD Engineers, specialising in delivering efficient designs that save carbon, cost and time. He has been the design director on several award-winning projects, notably a 2024 Structural Award for Mary Ward Centre, London.

Harry Furnival-Doran
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Harry is a Senior Project Engineer at SD Engineers. He leads internal sustainability and carbon reduction efforts and is a member of the IStructE Sustainability Panel.

Gemma Sheterline
Gemma is Head of Marketing and Communications at SD Engineers, aiding the practice's growth and reputation through content strategy and creation, brand development, and building strong client and industry relationships.

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