Embodied CO_2 of structural frames

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Synopsis
This paper discusses a study undertaken by Arup on behalf of The Concrete Centre to investigate the embodied CO_2 in typical structural frames for non-residential buildings. The study used the designed and measured schemes produced for the cost model studies published by The Concrete Centre in 2007-2008. The study explored the variations in embodied CO_2 predictions. Two sources of variation were considered: the method of the analysis and the specification. The study found that, within the uncertainties of the available data, there was little difference between the embodied CO_2 of the different types of structural frames, but that once the frame type had been chosen, there was a significant opportunity for the structural engineer to reduce the embodied CO_2 of the final structure by careful specification.

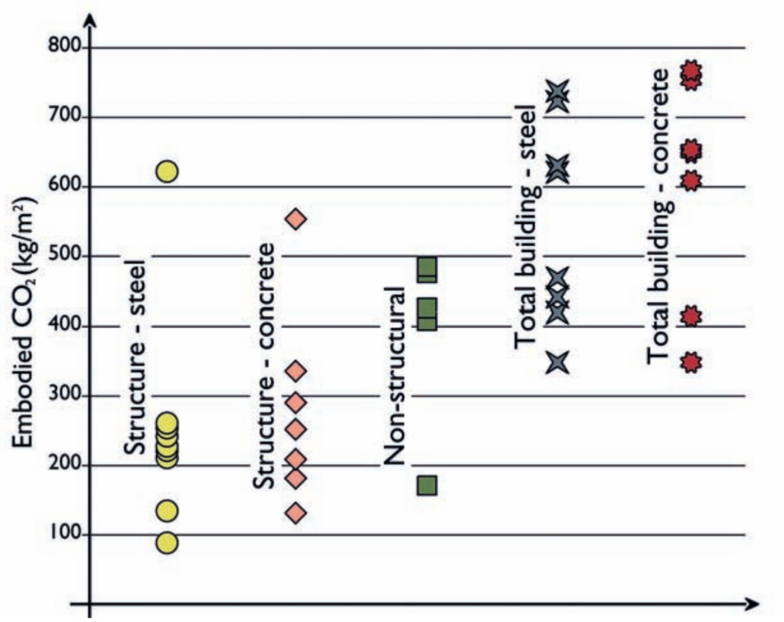


Figure 1
Embodied CO_2 of comparative studies

Introduction

The embodied CO_2 study presented in this paper[1] was undertaken to provide an understanding of the climate change potential associated with three building types. CO_2 is a gas that contributes significantly to climate change. It is also a measure that can be readily combined with in-use impacts when evaluating the whole life cycle impacts of buildings. As buildings become more energy efficient, in-use impacts reduce and embodied impacts become a more significant part of the total. This paper discusses a study undertaken in 2009-2010 by Arup, on behalf of The Concrete Centre, which investigated how the climate change impacts of building materials can be reduced through specification and design.

It is not expected that life cycle assessment (LCA) will become part of the everyday practice of engineers and contractors. However, one important step on the journey to these methods becoming useful is for designers, specifiers and constructors to understand where embodied CO_2 is attributed in construction.

The study focused on the structure of buildings and compared the impacts of different solutions to the structural frame, plus the effect of material specification choices. An assessment was also made of how the structural frame can affect the impacts across the whole building for items such as construction, cladding, substructure and fit-out. The structure was considered to include the foundations, slabs, beams, walls and columns. Non-structural elements included cladding, ceiling and floor finishes.

The study took its boundary as cradle to site, so took into consideration all the impacts of the extraction of the raw material, factory production and delivery to site, but without the operational and end of life impacts of materials. The justification and limitations of this approach are discussed in the paper.

Literature review

A literature review identified existing studies of the embodied CO_2 emissions associated with buildings. Figure 1 divides the embodied CO_2 values from the reviewed studies into steel and concrete framed buildings. The data spanned nearly the same ranges whether the frame was steel or concrete. The embodied environmental impact due to non-structural elements typically did not change based on material choice of the structure. The margin of uncertainty due to the variability in the material impact factors was greater than any margin of advantage these two framing materials appeared to have over the other.

Studies that included services were only found for office and warehouse buildings. Service impacts ranged widely from 0.37% to 24% of the total building impact, with an average of 12%. Transport and construction impacts combined ranged from 0.4% to 20% of the total building impact.

The variability of results in the literature review came primarily from the range and quantities of materials deployed in the building types. However, there were other secondary sources of variability. These included regional differences, fuel type, LCA method, process type, allocation method and treatment of recycling.

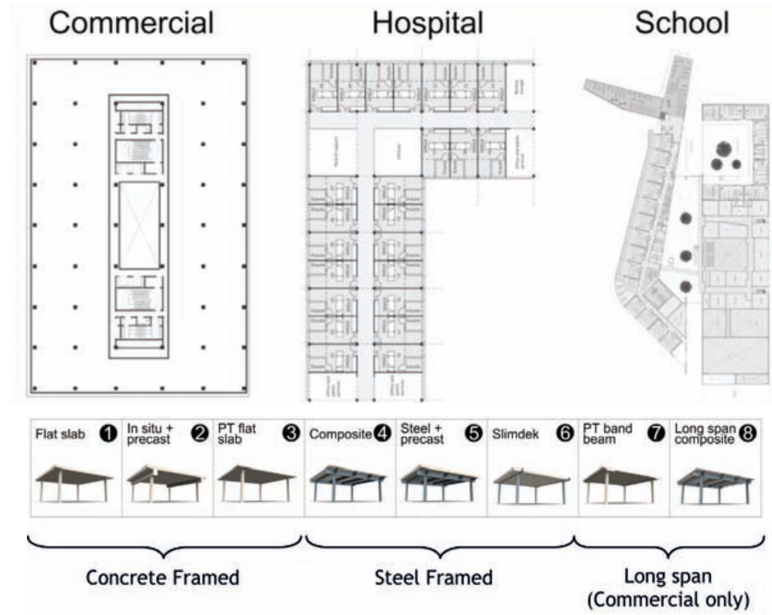
The study

Three building types were considered in the study: commercial, hospital and school buildings. Within each building type different structural solutions were considered but architectural and services solutions were kept the same. The study looked across this broad set of solutions to arrive at typical values for the cradle to site embodied CO_2. To provide clarity, the study did not consider operational or end of life impacts. Adopting this approach provided the opportunity for a rigorous consideration of the sensitivity of the results to variations in cradle to site impact data for materials. Up to nine variances of the 20 schemes were included in the sensitivity study.

By removing many of the variables and unknowns not related to the structural design, the study provided a powerful set of results. These could be used to investigate quite detailed design and specification choices that face designers, specifiers and constructors of the structural frame. The findings should enable them to play their full part in minimising the overall impact of the design.

Standards such as PAS 2050 (2008)[2], and the ISO 14040 series (BS EN ISO 14040:2006[3], BS EN ISO 14041:1998[4], BS EN ISO 14042:2000[5] and BS EN ISO 14043:2000)[6] allowed broad flexibility in approach to the calculation of the materials impacts used in this study. Differences in method were separated

Figure 2
The schemes considered



from material specification choices to show which decisions made by a specifier would change the impact of the element under consideration and how different methodologies would portray the relative merits of solutions.

Method

Case study buildings

To allow clear comparisons to be made, identical specifications were required for which different structural solutions could be developed. Ready made solutions were available in the independent cost comparisons of commercial office buildings[7], hospitals[8] and schools[9] published by The Concrete Centre. These fitted the requirements of the study because for each of the three building types the only variations were directly attributable to the choice of structural scheme.

The study looked across this broad set of solutions to arrive at typical values for the cradle to site embodied CO_2. Plans and structural schemes of the three building types studied are shown in Figure 2.

The 20 schemes that had been developed for the three building types in the cost studies made the findings of the study applicable to a large number of buildings constructed today. Information of outline design stage quality and detailed bills of quantities used for the cost studies were available. All the buildings were medium rise and were reasonably regular in layout. None of the buildings had a basement. Changing these aspects would probably have changed the resulting impacts significantly and also made the study more specialised. The quantities excluded external works, landscaping and mechanical and electrical services so these could not be included directly.

Schemes were developed for flat slab, *in situ* + precast, PT flat slab, composite, steel + precast and Slimdek solutions for all three building types. The first three were considered concrete framed schemes; the second three were considered steel framed schemes. In addition two long span options were studied for the commercial office building, one concrete framed, the other steel framed.

Embodied CO_2 values for materials and construction

The study combined the material quantities with embodied CO_2/t of material. The literature review showed that there was a high level of variability in overall embodied impact/m² between different buildings. The choice of structural material (e.g. steel or concrete frame) was not the source of that variation (see Fig. 1). It was felt a more rigorous approach was needed with stronger agreement between impact factors and method. This study provided such an opportunity and also provided more data points for further studies into embodied CO_2 in construction. The approach to the embodied CO_2 of material was also developed to facilitate investigation of decisions within the control or influence of designers, constructors and specifiers of the structural elements of buildings.

The embodied CO_2 values were chosen to represent both typical impacts in practice and the range of possible values. Most values were taken from the Bath ICE database (v1.6a)[10] or the commercial database GaBi[11]. Two sources of variation were considered separately in the study:

	Cradle to gate embodied CO_2kg/t				
	Specification study			Method study	
Material	Low	Typical	High	Low	High
C32/40 normal weight *in situ*	67	110*	157	as specification study	as specification study
C25/30 normal weight *in situ*	59	95*	133	as specification study	as specification study
Post-tensioned concrete	150	166*	182	119	190
Lightweight concrete	125	168*	215	106	223
* These values are used in the base case for the study and are referred to as the 'typical specification'.					

Table 1 Embodied CO_2 for concrete

Cradle to gate embodied kgCO_2/t			
Element	Base case & specification study	Method study	
		Low	High
Steel sections & PT strands	1770	1360*	2750
Reinforcement	872	430	1770
*Figure is for cradle to gate. Figure taking into account of end of life will be lower			

Table 2 Embodied CO_2 for steel

– the variation due to the specification of the structural materials (specification study)
– the variation due to different methodologies for cradle to site embodied CO_2 calculations that relate to issues beyond a specifier's control (method study). These could be, for example, the energy source used in the production of a material, which would have an impact on the embodied CO_2 of that material.

Impact factors were chosen, where possible, to represent materials installed on UK construction sites.

In order to draw out the variations the study took its boundary as cradle to site without the operational and end of life impacts of materials. These could have been added separately to provide a whole life cycle comparison. The life cycle of most buildings constructed today will span the critical period for achieving global warming reduction targets set by Government so refurbishment and end of life scenarios would need to take account of the necessary change that will occur in this period and should not be based on current construction practice. For example, greater reuse rather than recycling solutions will almost certainly develop over the next 25 to 50 years. The potential variation in the total CO_2 impacts for a building from cradle to grave, introduced by these post-construction scenarios, is very large.

Alongside the findings of this study, the design and detailing of a building can be reviewed in order to minimise operational impacts, maximise the life-span of the building elements, maximise the potential for refurbishment and reuse and minimise end of life impacts.

Concrete embodied CO_2 values

Although dependent on the amount and type, Portland cement (CEM I) can account for up to 90% of the embodied CO_2 of concrete. The embodied CO_2 of concrete, found from a review of world-wide LCA databases and studies, ranged between 59 and 202kgCO_2/t. The variation comes from two sources:
i) For a given concrete strength there was both a range of allowable cementitious content and an allowable Portland cement replacement that could be specified. This means that there was a large range in the embodied CO_2 of concrete that was due to specification. This range was considered in the specification study.
ii) Secondly, there was a variation in the embodied CO_2 associated with the different processes used to make Portland cement clinker. Mostly these varied from: wet, semi-wet, semi-dry to dry kilns as required by the particular nature and sources of raw materials. In addition there were significant variations attributable to the type of fuels used in the kilns, as well as the efficiency of the milling and blending processes required for both raw materials and finished product. None of the cement produced in the UK is made via the wet process method, which is the least fuel-efficient method. Specific production processes are not addressed by specification so these variations were only considered in the method study.

The variations in the values for the embodied CO_2 of concrete in the public domain led to the values for the study being calculated independently from first principles, using figures for concretes collated from practice. The values compare well with figures in the public domain. It was found that the choice of cement production process was not normally as significant as cement type but became more important for lightweight and post tensioned concrete, where the variation of constituent ingredients was more limited. The values used in the study are given in Table 1.

The impacts of the concrete constituents were taken from the CISCF (2009)[9,12]. This fits the chosen geographical study boundary.

The factors affecting the specification of these concretes would probably be common for all concrete elements, so the study investigated the total impact due to all 'low' impact specifications combined, through to all 'high' impact specification choices combined. For example, cold weather conditions may lead to a higher Portland cement content for all elements. In addition, a concrete supplier usually stocks either ground granulated blast-furnace slag (GGBS) or fly ash, so a mixture of these is unlikely to be used on a single project.

The precast concrete industry covers a huge range of products. The hollowcore units included in the building designs were proprietary products, available from a number of manufacturers, which use a specialised production method. Therefore generic impact values for 'precast concrete' from LCA databases, or in situ concrete mix designs were not applicable. Bath ICE database (v1.6a)[10] gave a value of 215kgCO_2/t for 'all prefab'. It is believed that a more realistic value would be 170kgCO_2/t for hollowcore elements. However in the absence of publicly available LCA data, the Bath value was adopted within the study.

Steel embodied CO_2 values

The cradle to gate impact of steel, from a review of worldwide databases and studies[10,11], ranged from 430 to 2750kgCO_2/t, depending on the recycled content of the steel.

Published cradle to gate environmental impacts of steel depend primarily on the amount of recycled material used in the process. Steel markets work across borders and make efficient use of the worldwide supply of scrap. Recovery rates of steel for recycling are very high (>95%) and so the two primary steel production processes cannot be seen in isolation. The specifier does not have influence over the percentage of recycled steel in structural steel sections.

The boundaries adopted for this study included cradle-to-site impacts of UK construction. Hence steel embodied CO_2 values, which included reductions from future recycling of the steel, were not compatible. The values taken for the study are given in Table 2.

The UK construction boundary could not be applied to steel sections because information regarding UK installed (rather than UK produced) steel was not available. The worldwide recycled content was used as a basis for the steel embodied CO_2 value. This probably underestimated the embodied CO_2 of steel sections installed in the UK.

Suppliers have confirmed that the average recycled content of reinforcement installed on UK sites could be as high as 97%. Unfortunately, published LCA data was not available to provide a validated figure. A base case embodied CO_2 value was derived using a conservative 80% recycled content figure. It was found that the total building results were relatively insensitive to this decision. Since the completion of the study manufacturers have published values that confirm that the study was conservative.

Steel industry advice[13] is that a specification that attempts to impose recycled content requirements could pose a threat to the efficiency of the current flows. Therefore no variation was considered in the specification study.

For steel sections the range of possible cradle to gate embodied CO_2 values for the method study was generated using UK through to European Union production figures. For reinforcement the range was generated from the literature search.

Other elements

The variation in quantities of the other elements in the building was relatively small. Their specification is also beyond the control of the structural designer or constructor. As a result, the impact values were simply sourced from the ICE (v1.6a) database[10], with some validation against the commercial database GaBi[11] for materials that generated high impacts.

Variation of these impact values was not included in the method study as this would have masked the findings of the research concerning the effects of the structure. However the whole-building impacts generated by this study could potentially be very different due to the large variations in specification and data sources. The three materials which cause variations between this study and the often quoted Eaton and

	$kgCO_2/kg$		
Material	Eaton & Amato (1998)	This study	Notes
Aluminium section	29	8.2	Study value confirmed by GaBi & Athena[15]
Carpet	20	6	Huge variation in specification possible
Chipboard	2.5	0.5	2.5 seems high; 0.8 is a more likely maximum value based on trade association figures

Table 3 Comparison of values taken in this study for non-structural elements

Element	Method
Wastage rate	‘standard’ factors from WRAP NetWaste Tool[16]
Haulage distances	Department for Transport statistics[17], trade associations or advice from materials experts
Transport CO_2 emissions	DEFRA data[18]
Site work CO_2 emissions	Environment Agency Carbon Calculator[19] & Highways Agency Carbon Calculator for Major Projects[20]

Table 4 Construction impacts

	Measurement	Office	Hospital	School
Primary Parameters	Gross floor area (m²)	16480	10752	13500
	Façade area/floor area	~40%	~60%	~65%
	Number of floors	6	2	2-3
	Foundations	Piles	Pads	Pads
	Number of schemes	8	6	6
	Mean embodied $kgCO_2/m^2$	340	400	409
Results	Mean total embodied CO_2(t)	5600	4300	5520
	Range embodied $kgCO_2/m^2$	300-410	360-490	380-520
	Highest scheme	Slimdek	Slimdek	Slimdek
	Lowest scheme	*In situ* + precast	PT flat slab*	PT flat slab/*In situ* + precast
	Construction impacts	12%	21%	16%
	Structural impact, $kgCO_2/m^2$	205	210	206
	Structure (% of total)	60%	50%	50%
* *In situ* + precast is within margin of rounding errors				

Table 5 Summary of the results

Base case specification and method (embodied $kgCO_2/m^2$)			
Building type	Structure	Superstructure alone	Non-structural*
Office	170-280 Range: 110	110-220 Range: 110	92-98 Range: 6
Hospital	170-300 Range: 130	120-260 Range: 140	105-112 Range: 7
School	180-320 Range: 140	130-280 Range: 150	136-143 Range: 7
* Excludes construction and services			

Table 6 Base case range of embodied CO_2

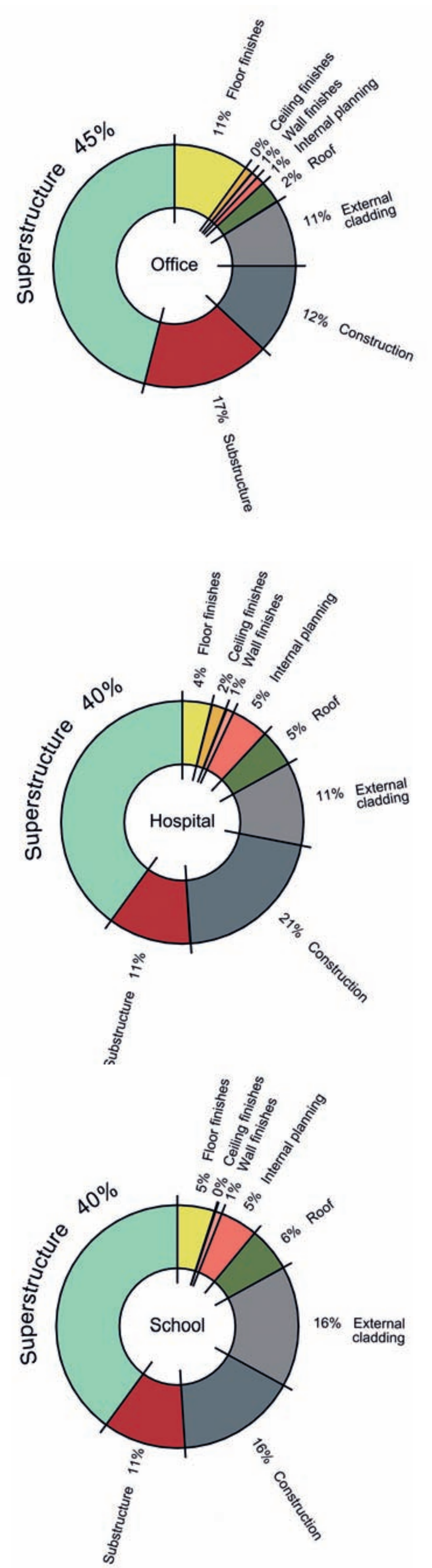


Figure 3
Breakdown of the embodied CO_2 for the different elements

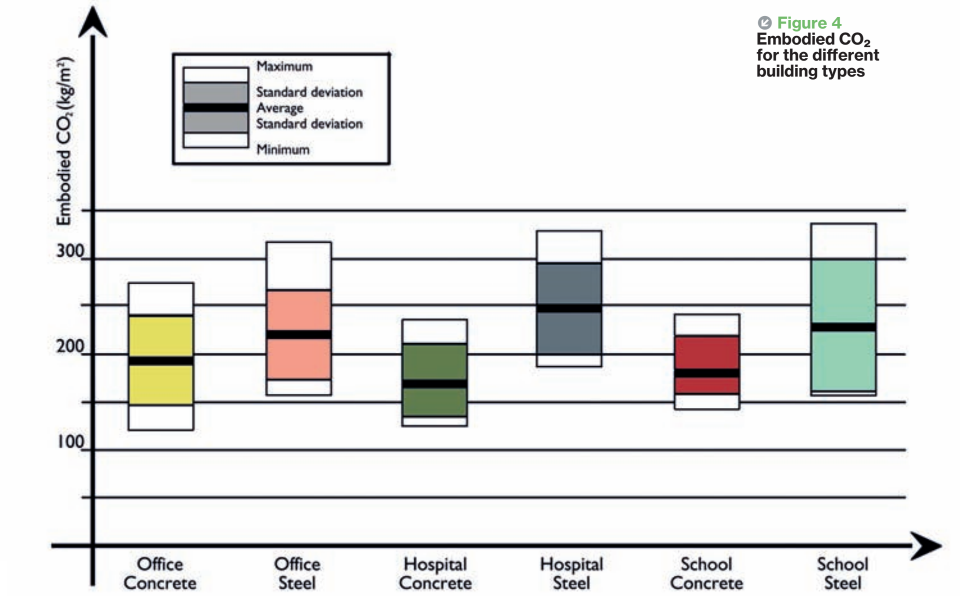


Figure 4
Embodied CO_2 for the different building types

Amato studies[14] are shown in Table 3.

Sources of variation of impact of non-structural elements

As this was a cradle to gate study, the impact of renewing the finishes during the operation of the building was not taken into account. Any possible reduction in the finishes specification due to the frame type was not taken into account in the study.

Construction stage

The construction impacts were added to the cradle to gate values obtained from the sources shown in Table 4.

The formulae used were:

- $E_t = m \times (100 + w)/100 \times (D \times F_{CO_2})$

Where E_t is the embodied CO_2 of transport, m is the mass of the material, w is the wastage rate (%), D is the transport distance and F_{CO_2} is the CO_2 factor for mode of transport.

- $E_s = 6.25 \times d$ (in tCO_2)

Where E_s is the embodied CO_2 site works and d is the duration of project in weeks.

In addition to transport, a minor component of the construction impacts is made up of formwork. A detailed sub-study in conjunction with a formwork system supplier found that formwork impacts were typically 0.1-1% of the superstructure impacts.

Results

Overview of results and comparison with literature study

The structural impacts and construction impacts agreed well with the other studies. The results for the three different building types were very similar. The buildings all had fairly regular grids and similar features. The impact results quoted are averages across all schemes for the typical specification (base case).

The embodied impact of non-structural elements in the buildings was consistently low when compared to other studies. This was due partly to the omission of services and lifts, and the lower impact factors adopted in this study in comparison to previous studies for aluminium, carpet and boarding products. As a result, the structure was found to represent a much higher percentage of the overall building embodied CO_2 than had been shown in previous studies, for example, Eaton and Amato[14].

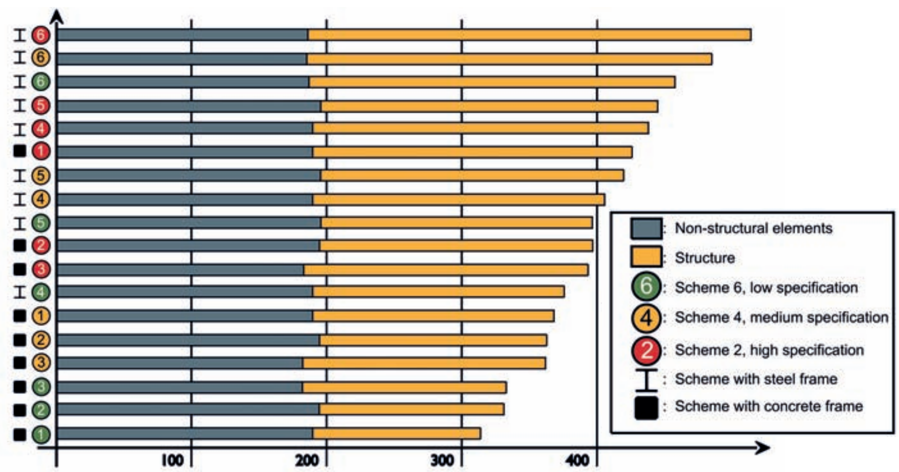
Figure 3 shows the breakdown of the embodied CO_2 by element. These are the average results across all the schemes using the base case or 'typical' specification impact factors.

Choice of scheme: lessons from base case study

Table 5 shows a summary of the results for the different building types for the typical base case.

Figure 4 displays results for the base case study combined with the specification study.

The steel and concrete buildings showed significant overlap. Although some steel solutions performed better than some concrete solutions, and vice-versa the concrete buildings performed slightly better in general. It was found that there was greater potential to minimise the impact of structures through the careful design and specification of the concrete in buildings,



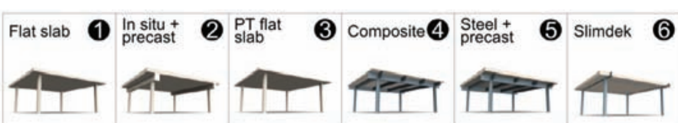


Figure 5 Total impact of hospital building showing all specification choices

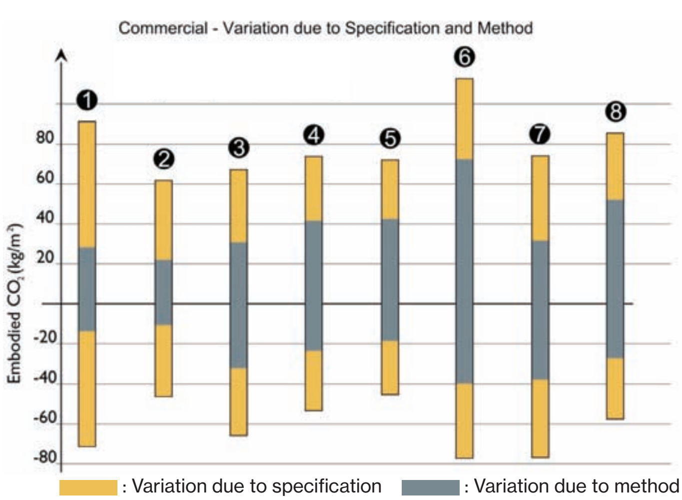
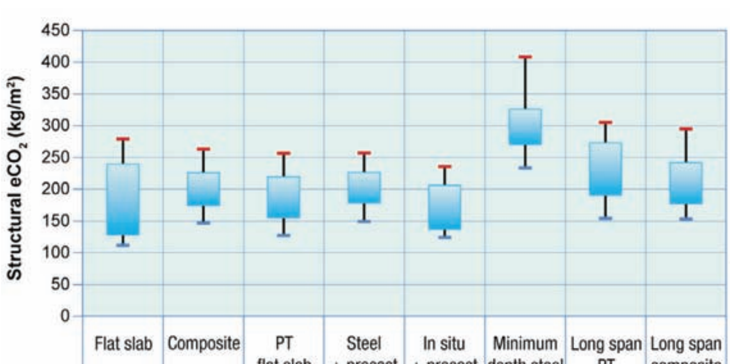


Figure 6 Commercial Building: Possible variation due to method and specification



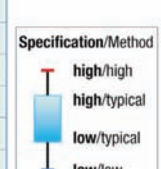


Figure 7 Comparison of framing solutions across all building types

than through the choice of framing material.

The base case study investigated how different schemes performed relative to each other and how the choice of superstructure influenced the embodied CO_2 of other elements in the buildings. Table 6 shows the range of embodied CO_2 in the structure and non-structural elements. The non-structural elements did not show much variation as these were kept the same across the different structural options.

Within the limitations of the calculation, a rule of thumb figure of 200kgCO_2/m² could be considered for the structural impact of medium rise, regularly framed typical buildings without basements. Schemes which are found to have an embodied CO_2 above ~250kgCO_2/m² should be reviewed to see if savings can be made.

No correlation was found between structural depth and CO_2. However, the minimum depth steel solution, Slimdek, consistently had the highest embodied CO_2. Minimum depth concrete solutions such as post-tensioned concrete, which incorporated higher impact concrete than conventional slabs, still provided low impact solutions due to the saving in mass. Also, surprisingly little variation was found in substructure impacts. Long span schemes added ~10% to whole building impacts.

The effect of structural scheme on in-use impacts was outside the scope of this study. If thermal mass is mobilised to reduce in-use impacts for a particular building, then the structural framing scheme solutions which lend themselves to exposed slab soffits will offer significant additional lifetime reductions in CO_2 that have not been measured in this study.

Choice of specification

The specification of concrete caused a large variation in the impact of all the schemes. Although the higher and lower embodied CO_2 values used in the study (values obtained by altering the specification) represent extreme values, the results demonstrate that there is potential to save more CO_2 through efficient scheme design and specification choices than through the choice of framing material (steel versus concrete).

Figure 5 reports data for the hospital building. Similar results were found for all three building types. Changing the specification changed the relative benefit of different schemes. Hence the specification choices should be made early enough for the combined design and specification choices to be evaluated together.

For the office example, the lowest impact scheme is the flat slab option. The specification study for this option provides

Flat slab	Total tCO_2	$kgCO_2/m^2$
Low CO_2 spec.	2000	120
Typical spec.	2900	180
High CO_2 spec.	4000	240

Table 7 Structural impacts (superstructure + foundations) for flat slab (Office)

Slimdek	Total tCO_2	$kgCO_2/m^2$
Low CO_2 spec.	3900	240
Typical spec.	4500	275
High CO_2 spec.	5200	320

Table 8: Structural impacts (superstructure + foundations) for Slimdek (Office)

Flat slab	*In situ* + precast	PT flat slab	Composite	Steel + precast	Slimdek	1 = lowest impact 6 = highest impact
1	3	2	5	4	6	Lowest values for spec. and method
4	1	3	5	2	6	Base case: typical choices
5	2	3	4	1	6	Highest values for spec. and method

Table 9 School method study: ranking of structural and whole building embodied CO_2

the upper and lower bounds found in Table 7. The highest impact scheme is Slimdek. The same investigation was done for this scheme and the results can be found in Table 8. The comparisons illustrate that there was realistic potential to save at least $1000tCO_2$ on the office project though design and specification. A review of the extreme upper and lower bounds of the three building types showed that savings could be as high as $3000tCO_2$ (or roughly $200kgCO_2/m^2$). Specification choice was found to change the ranking of schemes significantly. The study also found that choosing a concrete with high embodied CO_2 causes the foundations to play a much more significant part in the total embodied CO_2 of the building.

Choice of LCA boundary and method

The buildings were reassessed for the method study in order to understand the potential uncertainty within the results.

Changing the method for an environmental impact study will not change the impact of the material that is installed on site. However, choosing a different boundary may help to understand project impacts in the context of broader issues. This is particularly the case for steel, which is highly recycled and a globally traded commodity.

There are a large number of potential combinations of high and low impact choices that can be made, and as many motivations for choosing one method over another. All have different merits and this study method is not proposed as the 'correct' approach. Particular combinations (such as methods which generate relatively high concrete impacts with low steel impacts and vice versa) were not explored. Instead the maximum uncertainty band due to method choices was calculated. This was achieved by combining all high or low impact material values together for the structure.

In the study of the school building only the Slimdek maintained a consistent position. All the other schemes change their ranking based on specification or method choice. This implies that the designers should not choose one scheme over another due to a small difference between them.

The method study revisited the comparison of flat slab and Slimdek. A scenario was considered where a client had set a project benchmark of $200kgCO_2/m^2$ for a structure. If the method associated with that benchmark was not stated, then the Slimdek could be shown to meet the target or the flat slab could be shown to fail. However other choices of method (including the base case) would not yield this result. The use of standards such as PAS 2050 (2008) or ISO 14040 (2000-2006) would not avoid this variation so it is important that developing standards help to reduce the level of potential variation due to method.

Figure 6 illustrates the uncertainty band that was calculated. The variation shown is from the base case for each of the framing types.

The results of all the studies across the building types are summarised in Figure 7.

Conclusions

This study only varied the structural frame. Variations in quantities of other elements came as a direct result of superstructure changes. This comparison is useful for structural designers to understand how to incorporate sustainability into their practice and how to work with other team members to reduce impacts.

The results for the structural embodied CO_2 were remarkably consistent across all three building types and thus rules of thumb can be drawn from a very large data set for medium rise buildings of regular geometry with no basement. A typical embodied CO_2 value of $200kgCO_2/m^2$ can be considered for similar buildings. Schemes that have an embodied CO_2 value above ~$250kgCO_2/m^2$ should be investigated to see if CO_2 reductions can be achieved. Several important conclusions can be drawn:

- Concrete and steel framed buildings embody similar levels of CO_2.
- Contrary to popular belief, the embodied impact of the structure is a significant part (50% and above) of the total building embodied impact. Significant savings are possible through choice of appropriate scheme and good design. The least favourable choice of scheme adds roughly $2000tCO_2$ (~140 $kgCO_2/m^2$) to the lowest impact alternative.
- Knock-on effects on embodied CO_2 of non-structural elements from changing the structural scheme are relatively small.
- Potential for the design and construction team to change the embodied impact of non-structural elements independently of the structure is far greater than had been expected.

Structural engineers can work with the rest of the design team to drive down the total building impact. Minimising the structural impacts will lead to the lowest embodied CO_2 solution if other design team members also minimise the impacts under their control.

The study looked at the choices available to designers, specifiers and constructors at different stages of a project in order to see where the maximum embodied CO_2 reductions could be achieved:

- No structural scheme gave the lowest impact consistently. The minimum depth steel solution was consistently the highest impact solution by a significant margin. Concrete schemes were consistently the lowest impact solution when combined with low impact specifications.
- The choice of framing material: steel to concrete was not the most significant decision.
- The concrete deployed in the buildings provided significant potential to change the embodied CO_2 of a building through specification combined with choice of scheme. A saving of more than $1000tCO_2$ was demonstrated to be a realistic possibility for the commercial building.
- As a general rule the embodied CO_2 of the structure can be optimised without adversely

Figure 8
Equivalent value of $1000tCO_2$

affecting the whole building impact.
• Variation of LCA method for embodied CO_2 calculations makes a difference of roughly $30kgCO_2/m^2$ to the overall impact of the structure. This uncertainty band should be considered when comparing studies.
• Formwork does not make a significant contribution to the overall impacts.

A number of the lower impact schemes also offered opportunities for reduction in operational impacts but were not considered in the study. The results of this study could be expanded with scenarios for extended life and end of life outcomes for the building.

The savings found in the base case and specification study are real and significant. The identified potential for saving more than 1000t of embodied CO_2 (for the school building in the study) per building can be compared to the impact of other activities. A time frame of 10 years for achieving CO_2 reductions is relevant in terms of controlling climate change.

The potential saving can be compared to operational impacts. Design operational emissions for modern UK offices are now reducing significantly; making the embodied impacts a much more important part of the whole life emissions. However, currently for commercial buildings, measured emissions can be $60kgCO_2/m^2$/year for an air-conditioned building. This shows that the potential saving in embodied CO_2 that can be made by specification, is equal to approximately one year of the operational energy required for a typical air conditioned office of the size considered in this study. It is therefore worth choosing the structural frame to ensure that the operational impacts are minimised, by providing thermal mass to reduce the need for air conditioning.

On a more human level, these potential savings can be compared to emissions of CO_2 from domestic activity as shown in Figure 8. On a typically sized non-domestic building, through careful specification, a structural engineer could save their lifetime's personal carbon footprint.

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