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OPTIMIZED LOW-EMBODIED AND OPERATIONAL CARBON SOLUTIONS FOR SINGLE-STORY INDUSTRIAL BUILDINGS

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Detailed studies have been performed with the aim of determining optimum low-carbon solutions for buildings, and investigating the complex issues involved in their delivery. The evidence presented below suggests that building envelope specification has reached the point where the embodied carbon of any additional insulation balances, and may even outweigh, the corresponding savings in operational carbon. However, the extra material in the envelope has an inherent strength and stiffness that could be utilized to reduce the embodied carbon in the structure if appropriately designed. An extensive series of analyses was undertaken to (a) quantify the aggregated operational and embodied carbon related to modern envelope systems, and (b) evaluate the opportunities for embodied carbon reduction of the frame through the exploitation of the envelope's structural capability. Particular attention was given to the use of long-span composite panels to reduce the number of supporting structural members. It was found that a considerable saving in embodied carbon is possible compared to traditional construction solutions. The study also suggested the absolute significance of combining operational and embodied carbon analyses, in order to demonstrate the effectiveness of carbon reduction strategies and requirements to shift away from "operational carbon only" methods. The focus of the initial phase of the work has been single-story industrial buildings, but the conclusions are applicable more broadly.

Keywords: Insulation, Building envelope, Low carbon, Sandwich panels, Long span.

1 INTRODUCTION

Energy reduction in buildings is a key part of global responses to climate change, and of meeting the challenges of resource depletion. Forty percent of energy consumption in countries such as the UK is attributable to the operational energy requirements of buildings, and as a consequence there is a sustained drive to achieve better standards of efficiency. Practice for new buildings is very much toward low and zero carbon performance, and there is every anticipation that regulations will continue to move decisively in this direction.

In the 1980s it was estimated that the operational energy requirement of buildings was approximately ten times greater than the embodied energy. However, as energy efficiency standards for new buildings have become more strict, this ratio has shifted to the point where there is far greater parity between operational and embodied energy.

There is, therefore, compelling logic that operational and embodied energy should both be considered when assessing the low-carbon performance of buildings.

Perhaps less obviously, highly-insulated building envelopes possess structural capability in terms of strength and stiffness that could be utilized to minimize materials usage and reduce materials-related embodied energy. Historically, insulation was considered an "add in" material, the sole purpose of which was to minimize conductive heat losses. However, with increasing depth, sandwich panel technology has reached the point where it is capable of spanning significant distances (e.g., from rafter to rafter) without intermediate support from purlins and cladding rails. This has major implications for the supporting structures, which as a consequence can be re-engineered to be lighter or more widely spaced.

Detailed studies have been undertaken with the aims of optimizing the insulation depth within the building envelope in terms of operational and embodied carbon and then optimizing the whole structure-envelope assembly through the utilizations of the envelope's structural capability. The focus of the initial phase of work has been single-story industrial buildings, but the conclusions are applicable more broadly.

2 COMBINED OPERATIONAL / EMBODIED CARBON STUDIES FOR THE BUILDING ENVELOPE

Where low U-values (a measure of heat loss expressed in W/m^2K) are required, the volume of insulation material is such that its embodied energy can begin to outweigh the saving in operational energy. This is demonstrated in Figure 1, which shows the embodied and operational CO_2 for a typical retail building with Polyurethane (PUR) insulation. It can be seen that the minimum total CO_2 occurs at a thickness of 160mm, above which the increase in embodied CO_2 outweighs the operational carbon savings.

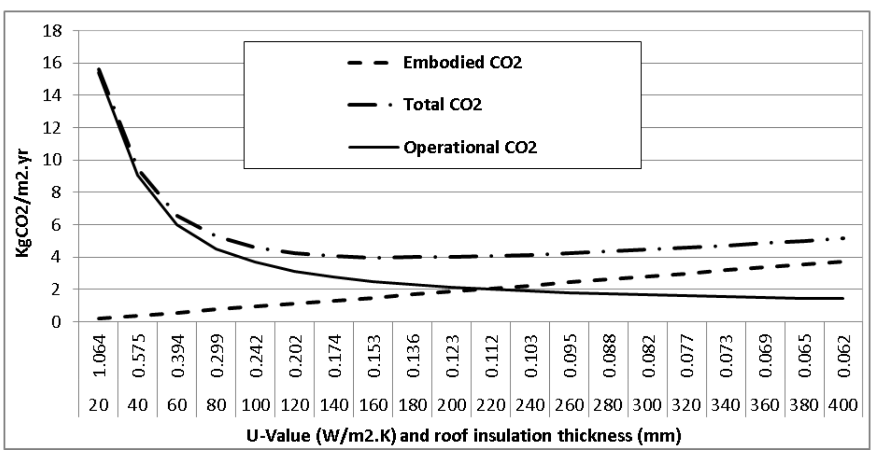

Figure 1. Typical embodied and operational CO_2 with PUR insulation.

It is apparent from Figure 1 that an optimum insulation depth exists, beyond which any further increase in insulation would be illogical and counter-productive. For the first time, this study suggests a sensible maximum level of insulation that should be incorporated into national building regulations and standards and sets limits to the amount by which current approaches to energy thrift can be escalated. This has two major implications:

(1) It will require energy improvements to buildings to focus on wider criteria than simple conservation of heat.

(2) It provides a compelling case for the development of novel insulation materials that combine high standards of thermal insulation with low embodied energy.

The data associated with a standard 4000m^2 single span portal frame retail shed were analyzed. Both buildings were clad with PUR-filled sandwich panels. The analyses assumed the general system parameters, considering 25-, 40-, and 60-year service lives. This is critical to “net benefit” carbon calculations, as the shorter the service life, the greater the impact of embodied carbon.

The results presented in Table 1 were simulated using IES VE software, based on a location west of London (Heathrow). The minimum CO_2 value for each case represents the point of optimum net benefit for the insulation, i.e., the point where the combined operational and embodied carbon is at its lowest level. The ratio of roof-to-wall insulation thicknesses (and hence U-values) is based on current UK building regulations and reflects the higher heat losses through roofs compared to walls. “Current Manufacturing Limits” identifies the generally accepted lowest possible U-values that can be delivered using available PUR solutions. Any increase in PUR insulation thickness above the optimum level shown in Table 1 will result in an increase in embodied energy that will not be recovered through savings in operational energy over the life of the building. Interpretation of Table 1 presents a number of key issues associated with conventional insulation technology:

(1) Factoring embodied energy into an aggregated analysis serves to limit the minimum CO_2 levels that can be justified. Higher embodied-energy insulation materials become more difficult to justify than lower embodied-energy materials, as they more rapidly lead to a CO_2 disbenefit.

(2) The R-value (thermal resistance) of the insulation material is also a significant factor. It indicates how much insulation material is required to deliver any prescribed U-value. The higher the R-value, the lower the amount of insulation material needed, generating a corresponding reduction in embodied energy.

3 EMBODIED CARBON STUDIES FOR THE STRUCTURAL FRAME

The increase in insulation thickness has led to an increase in the structural capability of the envelope for certain cladding types, an opportunity that is currently not fully exploited. This is particularly apparent in insulated sandwich panels, where the strength of the panel relies on the composite action between the insulation core and bonded metal faces. Increasing the panel depth results in a greater bending stiffness, allowing the panels to span further. This presents an opportunity to make greater structural use of the envelope, permitting the removal of some structural elements and reducing the overall level of embodied carbon within the building.

Moutaftsis *et al.* (2015) have determined the structural forms that are best able to utilize the structural capability of sandwich panels, and examined the corresponding potential steelwork savings. Their study concluded that the greatest potential benefit arises from the use of long-span envelope systems. The present research extended this analysis by reviewing the structure-envelope options in terms of their embodied carbon, with a focus on the use of long-span sandwich panels. This was achieved by re-engineering the structural frames for the selected example buildings in such a way that fully utilized the long-spanning capability of the cladding. The steel structural members were sized according to Eurocodes, and the frames were appraised for their embodied carbon based on the index of the World Steel Association (2011). Finally, suitably long-spanning sandwiched panels were designed according to specialist literature (Davies *et al.* 2001) and modern research (Heywood *et al.* 2013).

Four structural frame options were chosen: (a) duo-pitch portal frames with purlins (base case), (b) duo-pitch portal frames without purlins, (c) flat-roof multi-bay re-oriented portal frames, and (d) north light construction using roof trusses. Several frame spacing values were considered between 6.25m and 13.34m to give an integer number of frames for the chosen building geometry and structural scheme. The embodied carbon associated with each structural scheme is shown in Figure 2. These carbon values include the contribution from all of the structural elements, but not from the foundations or building envelope. The sandwich panel depth required to span between the supporting steelwork is also shown.

The results show a reduction of the building frame's embodied carbon for all of the schemes that exploit the envelope's structural capability. Re-orienting the portal frames to run parallel with the ridge and eaves provides carbon savings of up to 54% against the single-bay base case, and 19% against the 2-bay base option, while the north light option produces savings up to 58%. The optimum frame spacing was found to be 8.00m or 8.33m depending on the structural form. Sandwich panels would be required to span this distance, meaning a PUR insulation depth of 170mm or 180mm respectively. Exceeding this insulation depth will not lead to any further reduction in the embodied carbon of the frame. On-going sandwich panel optimization studies undertaken by the authors have shown that even an insulation depth of 135mm can provide the necessary structural capability with modifications to the metal faces of the panel. Structure-embodied carbon values for the base case and optimized buildings are given in Table 2.

Table 1. Minimum aggregated CO_2 burden associated with PUR insulation.

Service life	**Minimum CO2**	**Thickness of Roof insulation**	**Roof U-value**	**Thickness of wall insulation**	**Wall U-value**	**Current manufacturing limits**
(Years)	($kgCO_2$/m2/year)	(mm)	W/m^2 K	(mm)	W/m^2 K	
25	3.97	160	0.15	115	0.21	Lowest achievable U-value: 0.13 for both walls and roofs
40	3.28	220*	0.111*	155	0.15	
60	2.8	280*	0.08*	200*	0.12*	

*Values that cannot be achieved using currently available systems.

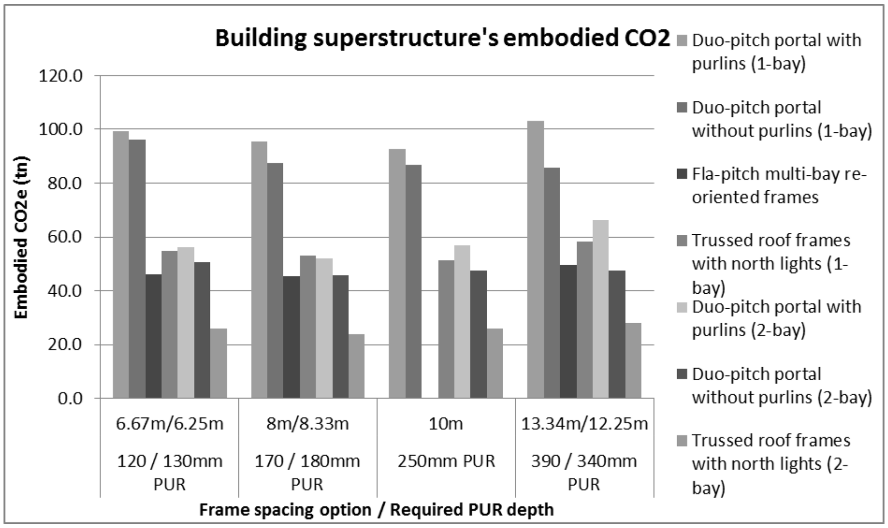

Figure 2. Embodied CO_2 of the superstructure for various frame types and spacing options.

Table 2. Embodied CO_2 of superstructure for selected cases.

Frame type	**Spacing (m)**	**Embodied CO_2 (tn)**	**Embodied CO_2 (kg/m^2/year)**		
			25 years	**40 years**	**60 years**
Duo-pitch portal frames with purlins (base case) 1-bay	6.67	99.3	0.99	0.62	0.41
Duo-pitch portal frames with purlins (base case) 2-bay	6.67	56.1	0.56	0.35	0.23
Flat-pitch multi-bay re-oriented portal frames	8.33	45.5	0.46	0.28	0.19
Frames with trussed roof system and north lights	8.00	23.7	0.24	0.15	0.10

4 REVIEW OF COMBINED ENVELOPE AND STRUCTURE CO_2 ANALYSIS

Figure 3 shows the relative importance of the operational and embodied CO_2 for the example building, and demonstrates the potential benefit of exploiting the structural capability of the envelope. For the conventional building frame, the total CO_2 is minimized when the envelope has a PUR thickness of 160mm. Accounting for the embodied CO_2 of the structural frame adds approximately 25% to the total, but does not change the optimum insulation thickness. However, re-engineering the steel frame, coupled with a modest increase in insulation thickness to 170mm, significantly reduces the embodied CO_2 of the structure, giving an overall saving in aggregated carbon of 18% compared with the conventional frame. In this example, further increases in PUR thickness would not yield any additional benefit in terms of aggregated carbon, but in other cases, the optimum carbon solutions for the envelope and the superstructure can be significantly different.

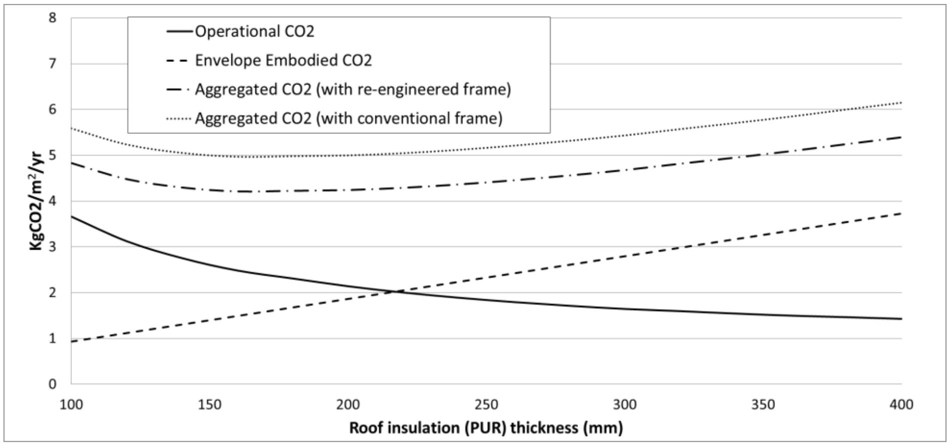

Figure 3. Results of combined envelope and structure CO_2 analysis (25 years of service life).

5 CONCLUSIONS

The study showed that a combined building envelope and super structure analysis is essential to identify true lowest carbon solutions, and represents an essential change of paradigm in terms of carbon analysis and optimization that needs to be built upon in future work. For the case study of retail buildings, it was found that a considerable saving in embodied carbon is possible when the structural capability of the envelope is exploited, and the building frame re-engineered compared against traditional construction solutions. The absolute significance of combining operational and embodied carbon analyses, in demonstrating the effectiveness of carbon reduction strategies and requirements to shift away from "operational carbon only" methods, was ultimately demonstrated.

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