Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure

Will Hawkins[a], Samuel Cooper[b], Stephen Allen[a], Jonathan Roynon[d], Tim Ibell[a]
[a]*Department of Architecture and Civil Engineering, University of Bath, UK*
[b]*Department of Mechanical Engineering, University of Bath, UK*
[d]*Buro Happold, Bath, UK*
wh604@bath.ac.uk

Abstract

The enormous environmental impact of construction is becoming increasingly apparent and unacceptable to many structural engineers, whose designs typically account for the majority of a building's embodied carbon. It is timely, therefore, that consensus is forming around a methodology for calculating embodied carbon. This encourages the inclusion of all life cycle stages, from material production and construction, through use and eventual demolition, disposal and reuse. In practice, however, end-of-life processes are fraught with uncertainty and often ignored, despite the potentially large associated carbon fluxes. Further uncertainty exists when considering bio-based construction materials, which store carbon during use. There are no widely-accepted means of accounting for timing of these carbon fluxes, despite the long service life of most buildings. Could we consider whole-life carbon in a more holistic and climate-focused way?

This article uses dynamic life cycle assessment to convert greenhouse gas emission histories to key climate impacts using a simple dynamic model. The implications for structural design decisions are explored by comparing concrete, steel and timber options for a typical medium-rise building structure. Concrete is found to have a higher impact than steel, with the climate response of both options dominated by the large initial emissions of material production and construction. Timber has the smallest impact, for this example, under a typical scenario with sustainable forest management and re-emission of sequestered carbon at end-of-life. The analysis takes a forward-looking approach to sequestration, with timing corresponding to the growth of replanted trees. An optimistic timber scenario, whereby future carbon-capture technology avoids most end-of-life emissions, demonstrates the possibility of structures with small long-term climate cooling effects. Conversely, in a hypothetical worst-case scenario where no replanting or subsequent sequestration occurs, the long-term warming effect of the timber structure is increased by the net emission of biogenic carbon.

Although end-of-life processes are important in the long-term, particularly for timber, the analysis also highlights the importance of the initial emissions from material production and construction. These cause high rates of short-term temperature increase and prolonged accumulation of radiative heat for all the buildings, but the impacts are again lowest for timber.

Most importantly, the investigation shows how dynamic life cycle assessment can be used to explore climate impacts in a comprehensive, graphical and unbiased way. As a simple extension to established methodologies for calculating embodied carbon, it is a powerful decision making tool in the climate emergency.

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1. Introduction

1.1. Life cycle embodied carbon: standard practice

Structural engineers are becoming increasingly familiar with calculating embodied carbon, thanks to a growing consensus around a life cycle assessment (LCA) methodology based on EN 15978 [1]. Indeed, the recent guidance from the Institution of Structural Engineers (IStructE) [2] provides a concise, clear and thorough interpretation which makes this easier than ever, and adds to a chorus of similar industry focused guidance from RICS [3] and LETI [4].

EN 15978 [1] breaks a building's life into various stages, or Modules: product (A1-3), construction (A4-5), use (B), end-of-life (C) and re-use/recovery potential (D), with the latter accounting for benefits outside the system boundary. As more of these stages are considered, a more comprehensive picture of environmental impact is given. In practice, however, LCAs often do not include every stage, but instead define boundaries of a given scope. This might be cradle-to-gate (A1-3), cradle-to-completion (A1-5), cradle-to-grave (A-C) or cradle-to-cradle (A-D). Assessors are frequently reluctant to consider Modules C and D due to the uncertainty surrounding end-of-life and recovery activities occurring far in the future; the standard building lifespan recommended by RICS is 60 years [3].

The clarity and standardisation provided by EN 15978 [1], and guidance based upon it, is undoubtedly of critical importance to achieving adoption in the industry. However, the method is not without its shortcomings. Firstly, the choice of LCA scope impacts materials differently. For example, Module D benefits are much higher for steel, which can be readily recycled into a high-value material, than for concrete, which cannot. If structures of varying material are being compared, this means that the lowest carbon option can depend on the choice of LCA scope.

Secondly, the effects of carbon sequestration and storage in bio-based materials such as timber are difficult to give credit for accurately, and can be a source of confusion. There is considerable variation in the way biogenic carbon is treated in LCAs, with results and conclusions being highly sensitive to methodological choice [5]. According to RICS [3], biogenic carbon should only be included only when end-of-life processes, which typically include a partial release of stored carbon upon combustion or decomposition, are also included. Sometimes, the biogenic storage is reported separately as a negative emission, and this is now required in the latest version of EN 15804 [6] for Environmental Product Declarations (EPDs), but it is then unclear how this value should be interpreted. Biogenic storage can be the largest flux associated with a timber product, and has a dramatic effect on cumulative carbon values. When included within Module A, as is standard practice [7, 8, 3], this typically gives a negative embodied carbon value which may discourage resource-efficient design.

A third limitation is that, whilst every life cycle stage can be included, there are no widely-accepted ways of accounting for the time at which each emission occurs, and the subsequent climate impacts. According to EN 15978 [1], carbon emitted at end-of-life is given as much weighting as that during construction, thus ignoring the differing duration over which greenhouse effects can occur. A carbon emission followed by re-absorption (cement production and carbonation, for example) is treated in the same way as carbon sequestration followed by re-emission (such as biogenic storage), with no way of accounting for the potential climatic benefits of temporary carbon storage or delayed emissions. These benefits include a reduction in cumulative climatic energy input, buying time for adaptation, delaying or avoidance of tipping points, and even the possibility of permanent storage through future technological changes [9].

A number of methods exist which attempt to account for carbon storage or delayed emissions [10]. For example, the International Reference Life Cycle Data System (ILCD) Handbook [11] and the British Standard (PAS 2050) method [12] use a linear reduction factor for delayed or stored emissions which reduces to zero at 100 years, and ignores emissions beyond this. In this way, future emissions are discounted using a fixed time horizon. However, when considering the climate impacts of temporary carbon storage or delayed emissions, the choice of time horizon has been shown to significantly influence results [13]. Choosing a time horizon for LCA is inherently subjective and value-laden; the current global consensus around a time horizon of 100 years for climate impact assessment has been described as "inadvertent" [14].

Finally, conventional LCA practice favours the use of a single metric to assess climate impacts: Global Warming Potential (GWP), which is a measure of cumulative warming over a given fixed time period. Alternative metrics have also been proposed, including Global Temperature Potential (GTP), which is defined as the global temperature change at a given time horizon following an emission [15]. However, it has been argued that the choice of any single climate impact metric risks promoting sub-optimal, or even counterproductive strategies [16]. In order to comprehensively assess the temporal influence of emissions, we must look further and consider the climate's response and subsequent impacts on human and ecological systems.

1.2. Dynamic life cycle assessment

Greenhouse gas emissions are a cause, or start-point, of anthropogenic climate change. The negative outcomes, or end-points, of this are numerous, and include habitat loss, sea level rise, ocean acidification, and increased frequency and severity of heatwaves, hurricanes and drought.

Defining links between climate change start-points and end-points is a highly complex scientific endeavour, not least due to the unpredictable nature of the consequences being considered. However, a number of mid-point indicators are also used by the climate science community, which may be generally related to specific end-point outcomes. For example, increased temperatures are associated with severe heat-waves and extreme weather, the rate of temperature change impacts the ability of ecological and human systems to adapt, and the cumulative effects of increased temperatures are associated with sea level rise [10, 17]. Unlike end-point impacts, mid-point indicators can be calculated directly from any emission history using a dynamic climate model, using dynamic life cycle assessment (DLCA) [18].

In a review on carbon sequestration and storage in the built environment, Arehart et al. [5] note a growing recognition of the need for dynamic methods to adequately capture climate impacts. Breton et al. [19] found that, compared to other methods for life cycle assessment of bio-based products, DLCA is more comprehensive and provides greater consistency in the accounting of impacts associated with all carbon fluxes. However, the increased complexity of DLCA approaches were identified as obstacles to its wider adoption in building design practice. Indeed, previous application of DLCA to buildings or building materials [20, 21] has relied upon relatively complex software workflows requiring specialist knowledge.

This paper uses an easily implemented open-source spreadsheet tool for DLCA [22], which can be used as a straightforward extension to a typical embodied carbon calculation based on EN 15978 [1]. This is broadly similar in its approach to the DynCO2 tool [23], albeit with a more extensive results output which generates time-history data for multiple mid-point climate impacts. The result is a comprehensive and visual means of informing early-stage design decisions.

2. Methodology

2.1. Climate model impulse functions

The DLCA carried out in this investigation uses impulse functions to convert greenhouse gas emissions to mid-point metrics. The functions are those adopted by the IPCC [24] and described by Joos et al. [25], and are implemented using an open-access spreadsheet [22].

From an initial pulse emission, the mass of a gas in the atmosphere subsequently decays as it is either reabsorbed or broken down into other molecules. The atmospheric mass is directly proportional to radiative forcing, which is the marginal change in gross heat flux (in units of power per unit area). Its integral, integrated radiative forcing (IRF), is therefore the total energy input per unit area and increases for as long as any gas remains in the atmosphere. There is some inertia as this power input is manifested as an absolute temperature change, and this is also captured in an impulse function. The rate of temperature change can then be calculated through differentiation.

Figure 1 shows how 1 kg of carbon dioxide, 1/28 kg of methane and 1/298 kg of nitrous oxide, released instantaneously, affect each of the mid-point metrics described above. These gasses are the three main contributors to anthropogenic climate change, and their relative proportions are chosen to have an IRF equal to that of a 1 kg pulse emission of CO_2 after a time period of 100 years, as highlighted in Figure 1. The IRF is a measure of gross additional heat input into the atmosphere and is the metric used when calculating CO_2 equivalence (CO_2e) based on global warming potential over a 100 year period (GWP_{100}).

Although having an equal GWP_{100}, each gas affects the climate differently. The maximum temperature change is caused by CH_4, however this is 99% reabsorbed after 60 years. N_2O is also fully absorbed, albeit over a much longer time period. CO_2 is unusual, however, because around 23% is retained in the atmosphere and has a permanent warming effect. It is also the main contributor to global warming at 76% of total GWP_{100} in 2010, compared to 16% for CH_4 and 6% for N_2O [26]. The majority of CH_4 and N_2O is released from agriculture, making CO_2 the dominant emission in the construction and operation of buildings, and the focus of this article hereafter.

The simplified model presented here is a linearisation of complex atmospheric systems, based on a 'standard-impulse' CO_2 emission of 100 Gt at 2010's atmospheric concentration of 389 ppm [25]. It is, however, also accurate for smaller emissions associated with a building project.

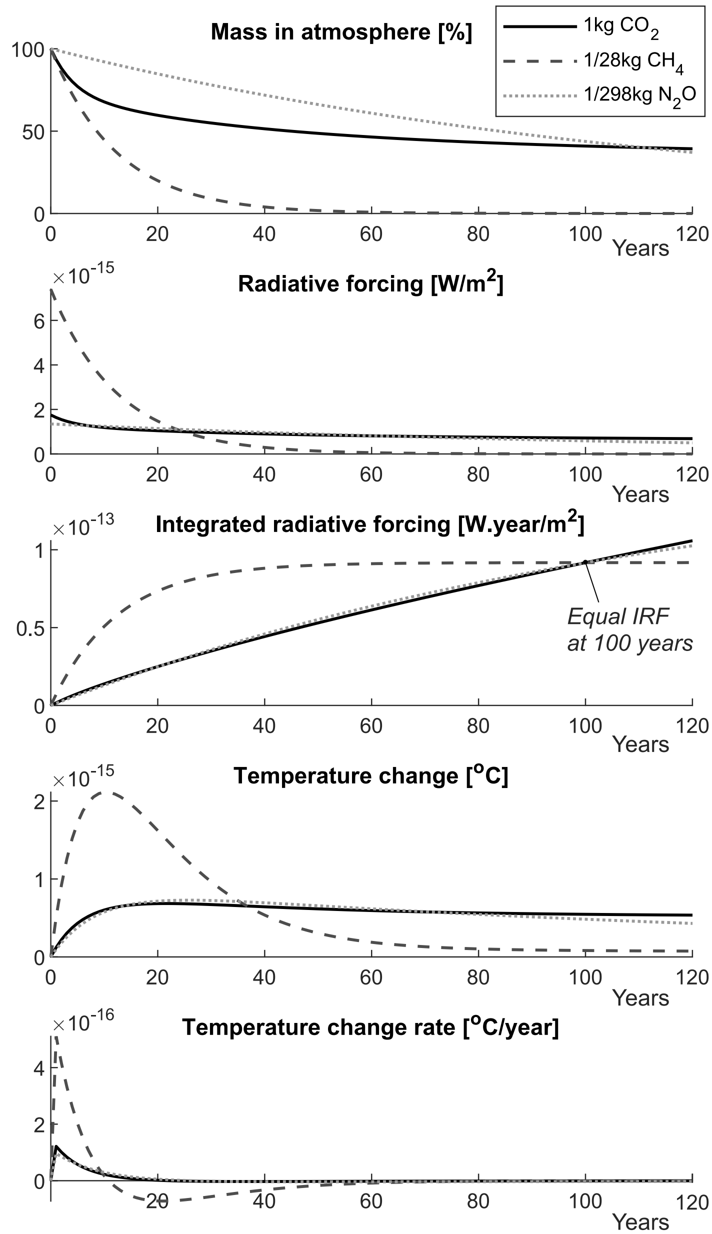

Figure 1: Climatic effects of the instantaneous release of 1kg of carbon dioxide, 1/28kg of methane and 1/298kg of nitrous oxide, from [25]. Each results in an equal IRF after 100 years.

2.2. Case study building structures

This investigation compares the climate's response to the construction of three versions of a simple building structure, using concrete, steel and timber as the primary structural material. The designs are taken from Buro Happold's Embodied Carbon: Structural Sensitivity Study [27]. The building has six storeys with spans of 9 m and an imposed loading of 5 kN/m^2. The concrete structure features in-situ columns and flat slabs (400 mm), the steel option has composite decking (120 mm) with a steel frame, and the timber building uses a glulam frame with primary beams, secondary beams and CLT floors (100 mm). All designs include a concrete core and pad foundations. The total material quantities are summarised in Table 1.

Table 1: Total material quantities for three equivalent building structures with concrete, steel and timber as primary structural materials.

	Material quantity [t]		
	Concrete	**Steel**	**Timber**
C20/25 concrete	5450	5243	3082
C32/40 concrete	9100	2911	839.8
Reinforcement	499.4	35.5	18.1
Profile decking	0.0	107.6	0.0
Hot-rolled section	0.0	543.6	40.3
CLT	0.0	0.0	388.8
Glulam	0.0	0.0	716.5

2.3. Carbon emission values and timing

For each structural design option, the embodied carbon was calculated following the Institution of Structural Engineers guidance [2]. Table 2 summarises the embodied carbon factors associated with each material at each life cycle stage.

Module A4 (transport) carbon was calculated using a factor of 0.1065 $kgCO_2/km$ [28], for road haulage. A constant value of 0.006 $kgCO_2/kg$ for transportation after demolition was assumed [3]. For concrete, the effects of carbonation were included as 2.5% of Module A1-3 emissions throughout Module B1 (use) and a further 5% in Modules C3-4 (disposal) due to crushing and subsequent exposure [29], in line with IStructE guidance [2]. In addition to the material specific values given in Table 2, 140 tCO_2 was included for Module A5a (site activities, using 700 $kgCO_2$ per £100,000 [2] with an estimated project cost of £20m) and 27.2 tCO_2 for Module C1 (demolition, using 3.4 $kgCO_2/m^2$ [3] over a gross internal area of 8000 m^2).

Table 2: Key assumptions and carbon factors for each material and lifecycle stage.

			Embodied Carbon [$kgCO_2/kg$]							
	Waste rate	**Travel dist. [km]**	**Seq.**	**A1-3**	**A4**	**A5w**	**B1**	**C2**	**C3-4**	**(D)**	**References**
C20/25 concrete	5%	50	0	0.094	0.0053	0.0060	-0.0024	0.006	0.0083	0	[7] (A1-3), [29] (B1, C3-4)
C32/40 concrete	5%	50	0	0.120	0.0053	0.0073	-0.0030	0.006	0.007	0	[7] (A1-3), [29] (B1, C3-4)
Reinforcement	5%	300	0	1.99	0.0320	0.1074	0	0.006	0.013	-0.79	[7]
Profile decking	10%	300	0	2.74	0.0320	0.3101	0	0.006	0.013	-1.15	[30]
Hot-rolled section	1%	300	0	1.55	0.0320	0.0162	0	0.006	0.013	-0.34	[7]
CLT	1%	1500	-1.64	0.437	0.1598	0.0061	0	0.006	1.64	-0.524	[7] (A1-3), [31] (C3-4, D)
Glulam	1%	1500	-1.41	0.512	0.1598	0.0092	0	0.006	1.64	-0.524	[7] (A1-3), [31] (C3-4, D)

The timing of carbon sequestration is of critical importance when using a dynamic climate model because, unlike emissions associated with manufacturing and construction, the uptake of carbon by trees occurs gradually over a period of a number of years between planting and harvesting. In a typical static analysis, carbon sequestration is included in Module A [7, 8, 3], effectively modelling sequestration as instantaneous. This approach is not generally considered appropriate for a dynamic analysis [32, 33, 34], but is consistent with the assumption that the supplying forest is in a steady-state; timber harvesting causes no net carbon loss to the forest. However, it does not consider forest regrowth time, which, according to Cardellini et al. [21] and Cherubini et al. [35], has a significant influence on the climate impacts of long-life wood products and fuels, respectively. Furthermore, Ceccherini et al. [36] emphasise that rates of European forest biomass loss due to harvesting are not constant, but appear to have increased significantly alongside growth in demand since 2015.

Two alternative approaches to the timing of sequestration are typically used in DLCA: "backward-looking" and "forward-looking". The backward-looking approach models sequestration over the period leading up to the harvest of timber, following the carbon physically present in the timber product, whilst the forward-looking approach follows carbon sequestration in the newly planted trees which replace those harvested. Results vary considerably between these two approaches [34, 32, 33].

Whilst an in-depth consideration of the relative merits of backward and forward-looking approaches is outside of the scope of this study, it is noted that many dynamic life-cycle assessments of bio-based products adopt the forward-looking approach [37, 34, 21, 38, 35, 39]. However, Sedjo [40] argues that a backward-looking approach is justified in biomass consumption for energy production because forest planting decisions are made taking into account anticipated future consumption. Levasseur et al. [34] further explore the question of forward vs. backward-looking sequestration approaches as a "chicken and egg" causality dilemma, but argue that a backward-looking approach may be appropriate in cases where timber is harvested from forests planted as part of afforestation initiatives, whilst a forward-looking approach may be appropriate in cases where timber is harvested from existing forests which are subsequently replanted. Hoxha et al. [33] argue that a forward-looking approach is preferred from a sustainability perspective due to its focus on regrowth.

The analysis in this paper takes a forward-looking approach, based on the observation that carbon fluxes associated with past forest sequestration have already occurred, and that the climate effects of these therefore apply equally to all conceivable design options (including non-timber designs). A forward-looking approach captures the climate effects of additional future sequestration enabled by the harvest of timber, when combined with replanting. It also highlights the role of future forest management practice in maximising climate benefits, and captures the benefits of using tree species with shorter rotation periods. In contrast, the backward-looking approach inappropriately rewards the use of slower-growing species by assuming an earlier start to historical climate benefits.

In this study, sequestration is assumed to occur between year zero and a crop rotation period of 50 years. The non-linear rate of carbon uptake is modelled on the analysis of a Sitka spruce plantation on peaty gley soil, typical of Northern Britain, published by the Forestry Commission [41]. The final quantity of sequestered carbon is that stored in the structure only, using values given by Jones and Hammond [7] and summarised in Table 2. The biogenic carbon associated with the unused parts of the tree are thus considered outside of the system. This is typical practice for standard LCAs [6] and certain published dynamic LCAs [39, 38], whereas some also account for waste wood burnt at harvesting [34].

The baseline end-of-life scenario for timber assumes 55% recycling to products such as animal bedding or panelboard, 44% incineration for energy recovery and 1% landfill [31]. According to EN 15804 [6], the result is that all biogenic carbon leaves the product system instantaneously in Module C, and this is the approach taken in this analysis. Whilst this is consistent with the incineration scenario from a dynamic perspective, recycling would likely result in a delayed re-release of biogenic carbon. However, the impact of this will be minimal if the recycled products are short-lived. Landfilling can significantly slow down re-emission [42], but the effect is considered negligible when applied to only 1% of timber at end-of-life.

Module D gives credits (negative emission values) if waste products can offset virgin materials with a higher carbon intensity; it is a measure of circularity, or re-use potential. Since it considers processes outside of the system boundary, Module D is reported separately according to EN 15978 [1] and EN 15804 [6]. In line with this, only Modules A-C are included within the DLCA in this investigation.

2.4. Additional timber scenarios

Two additional scenarios are included for timber, alongside the approach already described. An optimistic "BECCS" scenario explores the potential impact of carbon storage at end-of-life, for example through bioenergy with carbon capture and storage (BECCS). The deployment of this technology at scale is by no means guaranteed, although it forms a significant part of the Climate Change Committee's plans for the UK to reach net zero [43]. The technical characteristics and economics of waste wood make it an attractive feedstock for BECCS [44], and if implemented, this could capture 90% of the carbon produced in combustion at end-of-life (Modules C3-4) [43]. A similar reduction factor is therefore applied in this case. A similar partial avoidance of end-of-life emissions for timber might be achieved through continued re-use of timber elements. It is important to note, however, that the allocation of life-cycle impacts associated with the reuse of building elements over multiple service lives presents significant methodological challenges, as discussed by De Wolf et al. [45]. The consideration of permanent carbon storage is prohibited in current LCA standards [6].

A pessimistic "no replanting" scenario considers the case where harvested trees are not replanted, and sequestration is therefore not accounted for [3]. This worst-case scenario represents timber which is not sustainably certified, and would be illegal for a timber product sold under the European Union Timber Regulation (EUTR). Whilst the harvesting of construction timber without replanting is highly unusual, this hypothetical worst-case scenario also accounts for the potential risk that sequestration is prevented by wildfire or pest incursion, for example. It does not reflect the approach described for "native" forests in EN 15804, which ignores biogenic carbon at all life cycle stages.

3. Results and discussion

3.1. Cumulative carbon flux

The life cycle emissions (Modules A-C) for each building are presented as cumulative CO_2 over time in Figure 2, representing a typical static LCA. Module A occurs all at year 0, Module B from 0-60 years and Module C all at the assumed building lifespan of 60 years. For this case-study, cradle-to-completion (A1-5) emissions are greatest for the concrete structure (373.4 $kgCO_2/m^2$), followed by steel (294.5 $kgCO_2/m^2$) and timber (175.0 $kgCO_2/m^2$). End-of-life emissions are much more significant for the timber option, however this is mostly offset through sequestration.

3.2. DLCA: comparison of climate impacts

Figure 3 compares the climate impact of each carbon emission history over a time period of 120 years. A continuation to 1000 years can be accessed though the dataset which accompanies this publication [46].

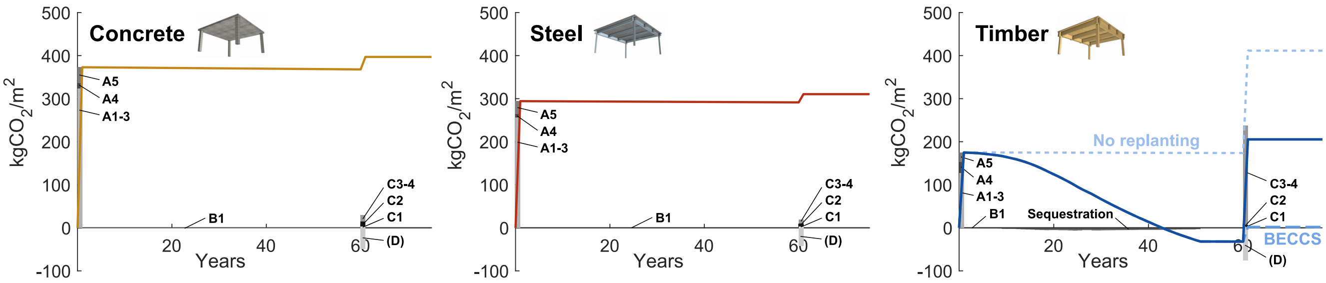

Figure 2: Cumulative cradle-to-grave CO_2 emissions for equivalent concrete, steel and timber buildings based on designs from a previous study carried out by BuroHappold [27].

For all structures, the mass of carbon in the atmosphere, which is proportional to radiative forcing, reduces rapidly from the initial peak before becoming increasingly stable. A second rapid change in atmospheric carbon occurs at end-of-life, which is most significant in the case of timber (without BECCS). After this, the total mass stabilises into the long-term, permanent value. The IRF increases steadily in proportion to the total atmospheric mass. The emissions at the start of the project spend more time in the atmosphere, and therefore have a greater impact on IRF. In contrast, the temperature response follows a similar pattern to the atmospheric mass, albeit with a delayed response to any instantaneous carbon releases. The maximum rate of temperature change is proportional to the size of the largest instantaneous carbon release, which is at year 0 for the concrete and steel buildings but at end-of-life for timber (without BECCS).

The timber building causes the smallest temperature increase throughout the full life cycle, providing that replanting occurs. Sustainable forest management is therefore key to timber's potential as a lower-impact alternative to concrete and steel [47]. in this case study, there is a period of time during which the net cumulative CO_2 emissions, radiative forcing and temperature change are negative for the timber building. This ends abruptly, however, if the building is demolished and the materials are subsequently processed, re-used or disposed of, except where these emissions are avoided (e.g. using BECCS or with continued re-use).

It can be inferred from Figure 3 that the lifespan of the timber building directly impacts the duration of this period of carbon removal, which could be prolonged by delaying or avoiding demolition. Considered another way, the quantity of carbon removed from the atmosphere and stored in the timber building stock can accumulate if the lifespan exceeds the forest rotation period. The importance of lifespan for timber buildings is similarly highlighted by Churkina et al. [47].

This analysis also shows how eliminating the re-emission of biogenic carbon at end-of-life can allow climate cooling effects to persist indefinitely regardless of building lifespan. This might be achieved using BECCS, or by re-using timber elements over multiple service lives. However, since significant uncertainty surrounds end-of-life scenarios, highly optimistic assumptions cannot be relied upon for present day design decision-making. Until timber production emissions (A1-3) are significantly reduced, or carbon-storage at end-of-life becomes commonplace, achieving reliable climate cooling effects through construction is likely to be difficult. It should also be noted that a building's operational carbon emissions would also need to be close to zero to achieve an overall cooling effect.

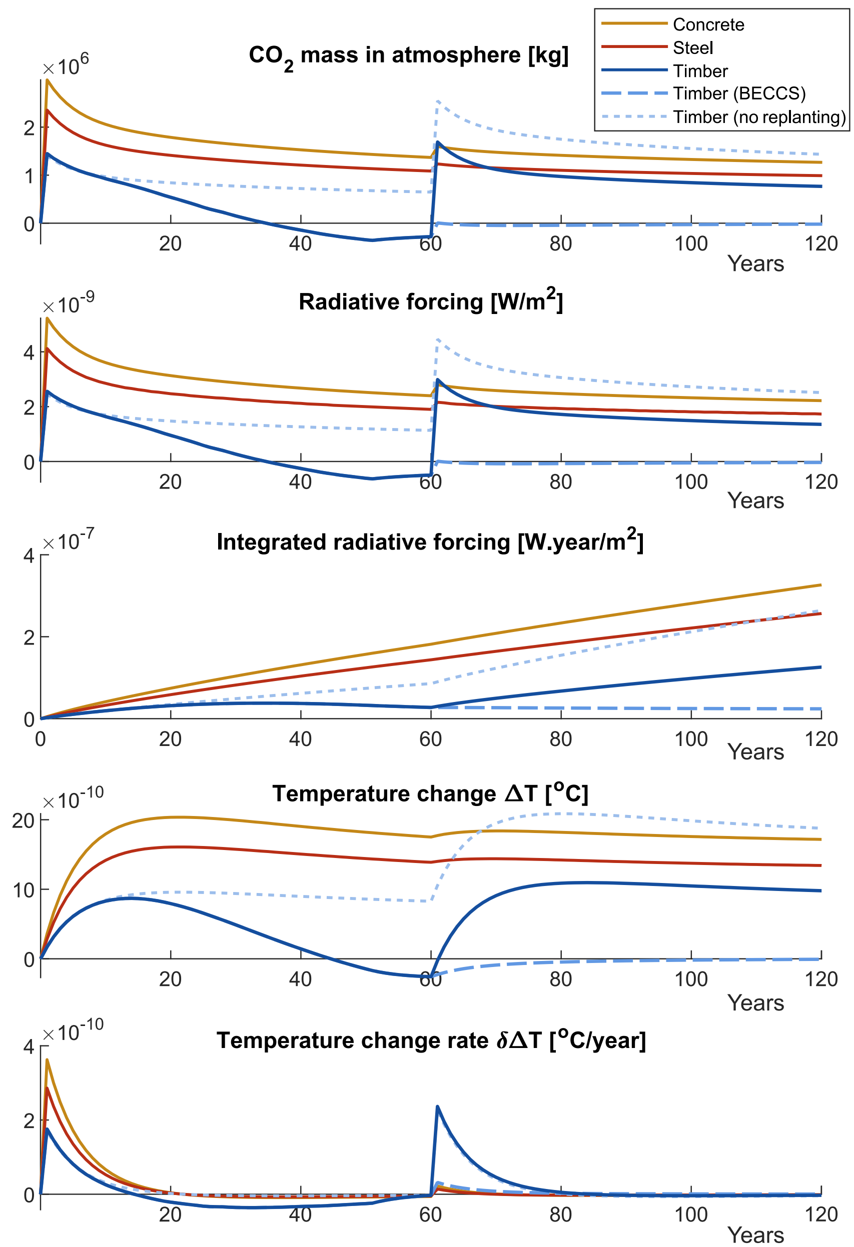

Figure 3: A climate impact comparison between equivalent concrete, steel and timber building structures from their construction (0 years) to demolition (60 years) and beyond. Benefits outside the system boundary (Module D) are not included.

3.3. Fixed Time Horizon Metrics

The time histories given in Figure 3 present a detailed visual representation of climate impacts. In conventional LCA, however, single metrics are used to inform decision-making. Figure 4 compares a variety of different metrics for each structure, beginning with the four typical LCA scopes from EN 15978 [1]: cradle-to-gate (A1-3), cradle-to-completion (A1-5), cradle-to-grave (A-C) and cradle-to-cradle (A-D). In most cases, the concrete building has the largest impact, followed by steel and timber. With BECCS, however, the total life cycle carbon is negative at cradle-to-cradle (A-D), but otherwise positive, highlighting that the conclusions drawn using a typical LCA can be scope-dependent.

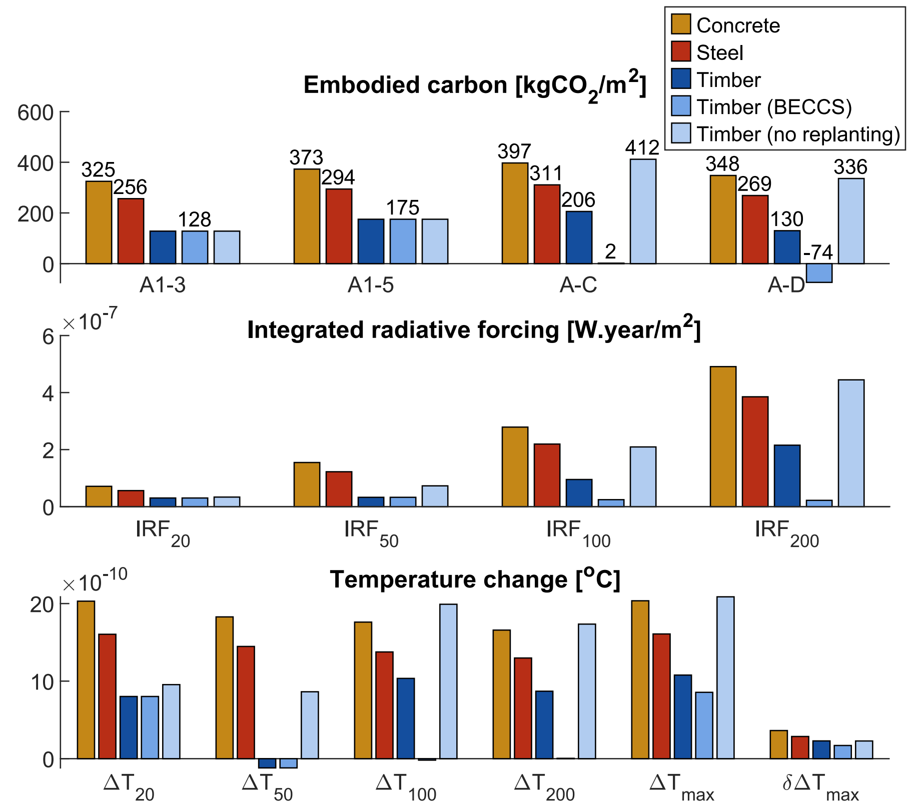

Figure 4: Comparison of metrics across various scopes and time horizons for each structure.

The IRF and temperature change are also compared in Figure 4 using time horizons of 20, 50, 100 and 200 years. The choice of time horizon for comparison, as previously noted, is subjective, and also has ethical implications; will our society become better able to manage changing temperatures in future, or worse? Emissions at the start of the project (Module A) spend more time in the atmosphere, and therefore have a persistent impact on IRF. It is only in the longer term, at 100 years and beyond, that the effects of sequestration and end-of-life become significant. The perceived importance of end-of-life processes therefore depends on the chosen time horizon.

The relative temperature changes caused by the concrete and steel options are similar at any time-point, whereas the timber option diverges significantly depending on replanting and end-of-life scenario. At 50 years, the baseline timber option causes a negative temperature change, but this result is inverted again at 100 years unless end-of-life emissions are eliminated (e.g. through BECCS). Again, this shows that the use of a single time-horizon is potentially misleading, and could be used to mask the temporary nature of a climate benefit.

The long term temperature change (ΔT_{200}) is proportional to the total life cycle emissions (A-C). The largest rate of initial temperature increase ($\delta\Delta T_{max}$) occurs for the concrete structure. Its emissions are largely concentrated in a single spike at Module A, whereas timber's impact is two-stage at Modules A and C, if biogenic carbon is re-released. Assuming that global emissions reduce in the coming decades, then warming rates will be smaller in 60 years than they are now, making Module A emissions a priority in terms of their contribution to peak rates of global temperature change.

3.4. Benefits of DLCA for design decision-making

Presenting an embodied carbon analysis using DLCA, as in Figure 3, provides complete time histories for all key climate responses. This approach is agnostic with regards to the choice of time horizon, reducing the likelihood of making decisions with poor climate outcomes as a result of using fixed time horizon approaches.

Similarly, by including climate responses related to all key mid-point climate response metrics [10], this comprehensive approach reduces the risk of oversight which could arise using a single metric only. Furthermore, the visual representation of these time histories can strengthen a designer's intuition regarding the impacts of their decisions on the timing, magnitude, and evolution of carbon fluxes and climate impacts related to their building designs.

Whilst previous work has demonstrated DLCA tools for buildings and building components [20, 21], the simplified method presented here using an open-source spreadsheet [22] is likely to be easier for structural engineers to adopt and flexibly integrate into their design workflows in practice, without requiring any specialist skills or software. It is a direct extension to the increasingly familiar guidance provided by the Institution of Structural Engineers [2], and others. Despite this ease of implementation, DLCA is a powerful tool which can facilitate detailed sensitivity studies.

3.5. Limitations, future work and implications for design and research in timber construction

This analysis features a case study of a single, generic building structure. It is an illustrative example, rather than a definitive comparison of structural materials, and the relative embodied carbon of each depends on the span, loading, material specification and the layout (or addition) of beams [27]. The timber design in this instance is already highly efficient, featuring 100 mm CLT floor slabs, whilst 400 mm thick concrete slabs are required to achieve the 9 m span.

Furthermore, only one set of carbon factors were considered for each material, following IStructE guidance [2]. In reality, these values vary widely due to differences in raw material supply, manufacturing processes, regional energy generation, and even LCA methodology [48]. A more comprehensive approach, particularly at an early design stage, would be to account for the variation in carbon factors using a statistical approach such as a Monte Carlo simulation [49].

The results strongly suggest that a widespread adoption of timber over steel and concrete in buildings could substantially reduce climate impacts, a conclusion which is in-line with similar comparative LCA studies [50, 51, 52, 53]. This raises the question of resource availability: what are the wider potential impacts of increased timber demand? Planting new forest may be appropriate in some locations, but competing land demands for food production, urban space and biodiversity should not be overlooked. Conversely, neither should the potential benefits of reducing demand for concrete, steel and the land damaged by mining and dredging. Ramage et al. [54] have suggested that changes to forest management and timber processing practices could increase supply without new forest, while Churkina et al. [47] estimated that significant quantities of viable, sustainable timber goes unharvested. Pomponi et al. [55] noted, however, that many developing countries where most new construction is anticipated are also those where sustainable timber supplies are already under most pressure, so an understanding of local timber supply chains remains a key priority.

The analysis also highlights the significant influence that lifespan and end-of-life scenario has on the long-term climate impacts of timber structures. Whilst designers arguably have limited influence over events which may occur in many decades, this result clearly justifies consideration of longevity and re-use at the design stage. For example, irreversible adhesive interfaces with non-timber materials, such as those often found in timber-concrete composite floor systems, should be avoided [56]. Future research and design innovation should aim to maximise the likelihood of continued carbon storage at end-of-life.

Forest carbon sequestration significantly affects timber's overall climate impact. The demand characteristics of timber products, partially driven by construction use, influences forest management practices and the total carbon stored in them [36]. Climate change is expected to result in greater frequency and severity of forest disturbance events such as wildfire, disease, insect attack, and wind damage from severe weather [57]. These can not only cause loss of habitat, but also emission of sequestered forest carbon. Forests conventionally managed for the production of timber may be less resilient to such disturbance events [58], whereas selective timber harvesting of specific low-value trees could potentially improve their resilience [59]. Researchers and designers in the construction sector should therefore engage more closely with forest managers to develop context-appropriate timber structures, systems, and supply chains which respond to diverse regional sustainable forest management needs.

A relatively simplistic model of sequestration dynamics was used in this investigation, however the same DLCA methodology could be used to explore this in more detail. For example, future investigations could model entire forest carbon stocks, accounting for soil and woody debris [60]. Albedo changes during forest disturbance or regrowth also influences radiative forcing [61, 62], and could be straightforwardly integrated with the methodology used in this investigation. Alternative counterfactual forest reference scenarios might also be considered, such as a "no-use" scenario where unharvested forest continues to mature and sequester carbon, or the alternative use of timber in short-lived products or as biofuel.

This article has considered multiple scenarios for timber, but DLCA could also be used to explore the full range of possibilities for concrete and steel. For example, the timing and magnitude of CO_2 absorption due to carbonation of concrete depends heavily on the exposed surface area and concrete characteristics [63], and is potentially significant. Furthermore, carbon emissions for steel are highly dependent on production methods and recycled content [7].

4. Conclusions

This article has applied dynamic life cycle assessment to an embodied carbon analysis of a case-study building structure, as an extension to familiar methodologies based on EN 15978. Complete time histories for key climate responses were generated, and used to compare the impact of three equivalent structures for a generic building using concrete, steel and timber designs. This approach enables uncertainties surrounding timing of emissions to be explored, and was found to be particularly useful when comparing materials with high production emissions, such as steel and concrete, with carbon sequestering bio-based materials.

Three scenarios were considered for timber, exploring the impacts of carbon sequestration in sustainably managed forests (via replanting) and the release or permanent storage of biogenic carbon at end-of-life. It was found that, in this case-study, the timber building has the smallest overall climate impact under typical LCA assumptions. However, under a hypothetical worst-case scenario where harvested trees are not replanted, sequestration is subsequently ignored and biogenic carbon is released at end-of-life, the long-term impact can be greater than concrete or steel. Conversely, an optimistic scenario where sequestered carbon is permanently stored raises the possibility of building structures with a long-term climate-cooling effect. A number of key conclusions and recommendations were identified:

- This analysis reaffirms that any form of construction is likely to warm the climate. Thus, the primary aim of researchers and practitioners in the construction sector, in the context of the climate emergency, remains to avoid new construction unless the societal benefits are clearly justified.

- When construction must proceed, this analysis suggests that timber building structures are likely to have smaller short-term climate impacts than concrete and steel equivalents. Over the longer-term, carbon sequestration can further reduce the impact of long-lived timber structures due to replanting and regrowth of harvested trees.

- For the timber building considered here, the analysis shows a temporary climate cooling period after tree regrowth and before end-of-life. This effect could continue in the longer-term, but only under optimistic end-of-life scenarios which avoid re-emission of biogenic carbon, such as continued re-use or the large-scale future deployment of BECCS. These scenarios should not be relied upon in early-stage design, but the result nevertheless strengthens the case for using structural timber in place of concrete and steel.

- The climate benefits of timber components improve the longer that their stored biogenic carbon is prevented from re-entering the atmosphere. Structural engineers should therefore exert whatever influence they can to maximise longevity of building structures and create opportunities for reuse, whilst also reusing existing buildings wherever possible.

- The carbon emissions of production and construction (Module A) is significant for all structural materials, and is associated with peak temperatures and high rates of temperature rise. Respectively, these directly impact extreme weather and the ability of natural and human systems to adapt. Early emissions also remain in the atmosphere for longer, and therefore have the greatest influence on IRF, which is linked to sea-level rise. Initial emissions should therefore be prioritised when interpreting the results of a static LCA.

- DLCA is a simple yet highly effective means of determining the climate impacts of products with long lifespans, such as buildings, particularly where bio-based materials are considered. Compared to single-point metrics with fixed time horizons, DLCA allows a comprehensive, graphical and climate-focused comparison to be made, highlighting key design decisions and, crucially, facilitating effective decision making in the climate emergency.

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Data access statement

All data created during this research is openly available from the University of Bath Research Data Archive at doi.org/10.15125/BATH-00908 [46].

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