Carbon Denominators

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Mitigating climate change demands rapid reductions of greenhouse gas emissions from the construction and operation of buildings. As the design and construction industry improves tools and techniques for adding up buildings' contributions to greenhouse gas emissions it must also consider and critique the methods used to normalize these data for analysis: how to divide them. Using Life Cycle Assessment methods, we accounted for the lifetime global warming potential of four case study buildings, each endemic of a primary structural material: steel, concrete, masonry, and mass timber. To improve the critical understanding of these denominators role in comparisons and decisions, we normalized the absolute totals using spatial (kgCO2eq/m2), temporal (kgCO2eq/year), and human (kgCO2eq/person) dimensions. The expanded analysis and visualization of lifetime carbon using novel metrics more closely associates these impacts with buildings' purpose to shelter people over time. Attributing emissions to people, rather than buildings offers a meaningful and nuanced basis for comparison, for example, normalizing based on occupants shows that as the density increases, carbon intensity per person declines. Attending to the spatial demands of use, dividing emissions by net rather than gross area means emissions intensity decreases as building systems become more spatially efficient, while simultaneously increasing the potential occupant density. In long-lived buildings, the temporal carbon intensity (per year, or per generation) declines with age, and the time value of carbon suggests that future emissions reductions may be worth less than the present emissions to achieve them compared to even the least carbon-intensive new construction, thus emphasizing the urgent need for adaptation of existing buildings. A critical reassessment of the denominators used to normalize emissions complicates short-term considerations of life cycle emissions and militates for an architecture of persistence: designed for human use and reuse, for adaptation and maintenance.

BACKGROUND

As a scientific approach to accurately account for the environmental consequences of buildings, Life Cycle Assessment (LCA) plays a key role in continued efforts to increase sustainability of the built environment, especially as related to climate change. While decades of attention reduced building's operating energy—and the associated greenhouse gas (GHG) emissions—the focus now shifts to the contributions of construction itself, and the Global Warming Potential (GWP) from extracting materials, manufacturing products, and constructing buildings, emissions described as embodied in the building.

GHG emissions measured in terms of total carbon dioxide equivalent can be directly added to the tally of total emissions of the construction industry. This upfront carbon counts against the industry's carbon budget,[1] and perhaps highlights which regions and construction practices demand urgent mitigation. However, nearly all other applications of LCA depend on comparisons: analyzing design options means comparing carbon impact measurement between alternative material configurations for the same building. Assuming all else equal (building size, use, location) building-scale decisions may be compared based on total carbon, however, all else is seldom equal, and decision makers must frequently compare among dissimilar buildings. One increasingly common application of Life Cycle Assessment compares the impacts keeping and upgrading an existing building with those from demolishing it and building new construction. Sometimes sustainability metrics prompt LCA comparisons, for example the Living Building Challenge requires net zero carbon but allows a one-time offset of embodied carbon. The standard also requires a reduction of embodied energy by ten percent compared to a baseline defined by the design team.[2] As with all these examples, the present study emerged from the fundamental question of how to compare unequal carbon equivalents, in this instance in the design of an exhibit about sustainable materials.[3]

METHODS

The ISO standard 14040/44 outlines four primary steps in conducting an LCA: defining goal and scope, inventory analysis, impact assessment, and interpretation of results,[4] this section follows this organization and describes the first three steps of the process.

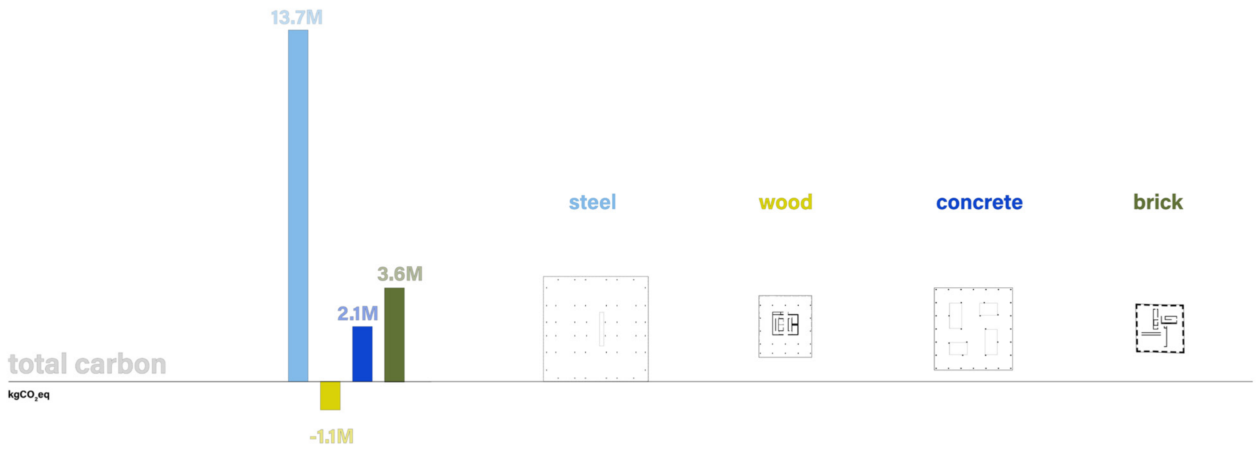

Figure 1. Total carbon equivalent emissions for case studies: Steel (US District Courthouse in Salt Lake City), Wood (Wood Innovations & Design Centre), Concrete (ICTA-ICP in Barcelona), and Brick (Haus 2226 in Austria). Image by authors.

As the longest lasting of building systems, primary structure is both difficult to change and generally constitutes the greatest contribution to embodied carbon in long-lived buildings; so this study focused especially on differentiating among common structural materials. To that end, the research adopted a case study approach, diving deeply into specific example projects—with all their accompanying specificity, complexity, and nuance—to reveal the influence of different bases of comparison. Rather than construct models of an idealized building identical except for structural material, four case study buildings were selected as particularly instructive or didactic examples of using each material as the primary structure. The Research Center ICTA-ICP, Barcelona, Spain, designed by H Arquitectes and DataAE is constructed of tensioned site cast concrete floors with a system of radiant heating and air channels. The United States Courthouse, Salt Lake City, Utah, designed by Thomas Phifer and Partners features a steel structure with moment frames on the exterior designed to resist progressive collapse. Haus 2226, in Lustenau, Austria designed by Baumschlager Eberle Architekten features cellular terracotta masonry exterior walls which provide insulation and support gravity loads. Finally, the Wood Innovation and Design Centre in Prince George, BC, designed by Michael Green Architecture, demonstrates the capabilities of engineered wood, with a structure of glulam and cross-laminated timber (CLT) panels. Although different in many ways, all four projects seek to demonstrate a long-lived building for the future, although that idea is uniquely manifest in each project.

To compile the life cycle inventory of materials and processes, a building information model (BIM) of each case study was developed using Autodesk Revit software[5] based on background information about the design and construction gathered from published and archival sources. Decisions about inventory inevitably require careful consideration about boundaries established in the first step, for example, in some projects the structure is also a finish material, while in others, additional finishes are required for fire protection or to achieve equivalent function. To allow consistent comparisons even though the projects have different uses and locations, all four examples adopted a core-and-shell approach to define the systems boundary: including the structure and envelope, but omitting furniture or equipment. To flesh out the technical information, the researchers conducted structured interviewed the architects of each project,[6] as well as other stakeholders,[7] to fully understand the background, development, and confirm design details.

The Tally plugin from KT Innovations[8] was used to conduct the impact assessment. The assumptions and impacts were carefully reviewed across all projects, especially the expected service life and maintenance of each material, because one purpose of the study is to consider the effect of building lifetime. For example, the default value for the terracotta masonry was changed to “the life of the building” as these units are not exposed to the weather, instead being protected by the lime-plaster exterior finish, for which periodic replacement is accounted in the LCA. Although Tally can assess a full set of possible life cycle impacts, this study focuses only on global warming potential (GWP) measured in kilograms of equivalent carbon dioxide (kg CO_2eq). These values would serve as numerators for this study’s evaluation of various denominators of carbon. The analysis and interpretation of the results are discussed in the subsequent sections.

DENOMINATORS EVALUATED

Even a superficial comparison of these four case studies illustrates an obvious finding: when comparing different buildings, absolute totals of GWP can be meaningless (see figure 01). Constructing large buildings like the Courthouse contributes more GHG than small ones like 2226, but that fact reveals nothing about the different materials, or the use of the buildings. Carbon denominators are thus functional units by which the total carbon emissions are divided to enable meaningful

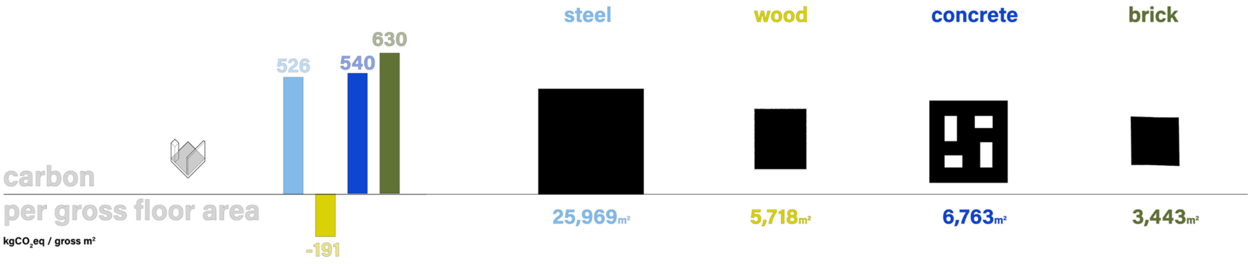

Figure 2. Total carbon equivalent emissions normalized by gross floor area for case studies: Steel (US District Courthouse in Salt Lake City), Wood (Wood Innovations &Design Centre), Concrete (ICTA-ICP in Barcelona), and Brick (Haus 2226 in Austria). Image by authors.

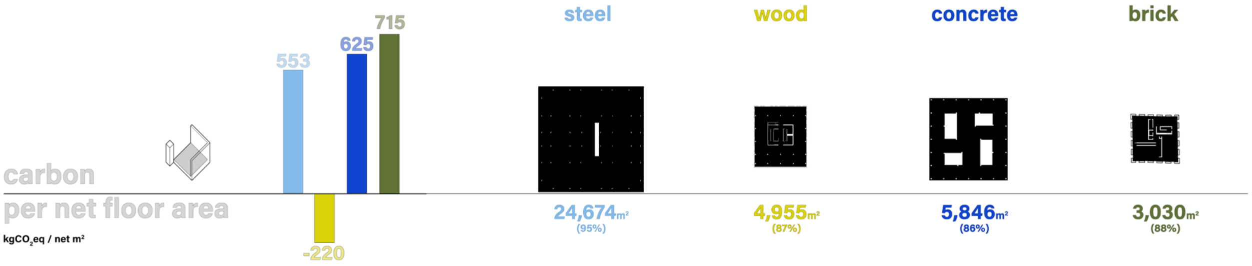

Figure 3. Total carbon equivalent emissions normalized by net floor area for case studies: Steel (US District Courthouse in Salt Lake City), Wood (Wood Innovations &Design Centre), Concrete (ICTA-ICP in Barcelona), and Brick (Haus 2226 in Austria). Image by authors.

Figure 4. Total carbon equivalent emissions normalized per occupant for case studies: Steel (US District Courthouse in Salt Lake City), Wood (Wood Innovations &Design Centre), Concrete (ICTA-ICP in Barcelona), and Brick (Haus 2226 in Austria). Image by authors.

comparisons between different buildings. The term normalization describes the process by which data is cleaned or stripped of other influences, allowing comparisons between different data points or data sources. For example, the normalization of financial data to adjust for inflation converts costs from multiple years to their equivalent values in a single year, making it possible to compare costs. Floor area is a widely used basis of normalization for many aspects of construction, including the carbon emissions produced by the construction of a building. Dividing total GHG emissions by the total floor area enables comparisons between buildings of different sizes (see figure 02). In unit terms, GWP emissions (kg CO_2 eq) are divided by a unit of area (m^2) so that we have normalizing all buildings in terms of kg CO_2 eq/ m^2. This carbon denominator relies on floor area, an objective unit measuring the most important function buildings provide, namely space for some human purpose.[9]

However, when comparing buildings of different primary materials, sizes and programs, the actual amount of usable floor area can vary significantly. These differences between gross area (the total floor footprint inclusive of enclosure and vertical structure) and net area (the total inhabitable area, excluding the enclosure, structure, and in some cases shafts and circulation cores) can be significant. Different construction systems—specifically the primary structural material, the mechanical distribution systems and circulation systems—may occupy a greater or smaller portion of the footprint, a ratio described as efficiency For example, in the four case studies, the difference between gross and net ranges from 86% to 97% (concrete 86%, masonry 88%, steel 94% and wood 97%). To illustrate the effect of efficiency, total GWP for each case study were divided by gross and net area. That difference in efficiency increased the gap between steel and the more massive materials of concrete and masonry, by approximately 10% (see figure 03). Because wood was the most structurally efficient (and it started as negative thanks to carbon sequestration) this calculation amplified the gap between the wood building and all others. Although not a part of this analysis, these differences may be amplified or counteracted by other system spatial efficiencies. For example, the footprint of mechanical distribution systems employing forced air distribution versus those relying primarily on hydronic piping. Tradeoffs in spatial efficiency and specific heat capacity make comparisons more complicated but provide a more nuanced understanding of the initial embodied carbon than gross area normalization. Yet even the best thinking in terms of floor area defines buildings' utility primarily as real estate while ignoring other building purposes, thus militating for other denominators.

When considering denominators, it is helpful to recall that buildings are ultimately for people, who determine, cause, and care about emissions. Attributing carbon emissions to buildings, risks neglecting the connection to people and their use of space, land, materials and energy. Using population as a denominator, i.e. carbon per person or per capita, may prompt questions about justifying the carbon for a particular building, or ascribe individual responsibility for the emissions associate with serving one person's needs. Furthermore, the social and cultural significance of buildings like hospitals and museums correlate with the number of people served, unlike floor-area denominators which ignore investments of material resources to meet occupancy-driven requirements such as life safety. While the analysis of net area in the four case studies considered only structural efficiency, the per person denominator calculated occupancy using the International Building Code area factors for each building's initial use. Among the four case studies (see figure 04), the courthouse serves the greatest number of occupants—not surprisingly as the largest building—and dedicates considerable area to assembly use. The difference was not directly proportional to floor area, because the Courthouse also has the lowest occupant density, roughly half that of the other three buildings. Among other things, courthouses require separate vertical and horizontal circulation systems for different occupants: judges, defendants, and the public. Due to the high-risk nature of the program, the courthouse also required greater structural capacities to resist progressive collapse. These two factors explain how the steel building went from second lowest when normalized by net area to highest when normalized by the denominator per occupant. When combining efficiency and occupancy, a civic building like the courthouse appears to be less spatially efficient in terms of occupants per unit of area and to require higher embodied carbon per occupant. However, just as building codes assign higher importance factors to critical functions or infrastructure such as hospitals, perhaps carbon measurements per person should consider the importance of buildings and the contributions they make to the common weal and human wellbeing, as well as their environmental cost. In the courthouse people become citizens, the accused protected by the machinery of due process, and ordinary citizens come together in the civic duty of jury service. Occupancy, as defined by code for egress, provides a standard measure of population based on maximum density at one point in time, yet, this analysis fails to recognize that although some buildings serve small and stable populations over long periods of time (e.g. housing, offices), other occupancies—such as courthouses and educational facilities—serve more individual people for short cycles of occupancy. Thus, a true denominator for emissions per person, cannot rely on code occupancy, but demands some measure of the total lives touched, and to what end.

Although LCA accounts in the numerator for emissions over the lifecycle of the building, the denominators described thus far fail to consider the dimension of time. That may mean dividing the embodied emissions over the life of the building (see below for the necessary caution about the time value of carbon) but might better be achieved by combining multiple denominators to capture the complexities, for example emissions per person per year. Such an assessment would require knowing or predicting future occupancy, easy enough in fixed typologies, but a challenge for projects with changing uses. Adopting baselines or targets for carbon emissions using such combined denominators would place a greater burden of responsibility for carbon reduction on shorter-lived, or lower-occupancy buildings, while acknowledging a greater allowance of emissions for certain long-lasting and valuable uses.

ANALYSIS AND DISCUSSION

Obviously, the wood structure performed better across all scenarios and regardless of the denominator. Consider too that these assessments compare buildings, rather than merely substituting the primary structure; meaning these numbers account for many non-wood materials (e.g. insulation, glazing, concrete) used in the primarily wood building. The nature of denominators means the GWP may get smaller or larger but cannot change sign, so the wood always remained negative thanks to the carbon sequestered by the growing trees and

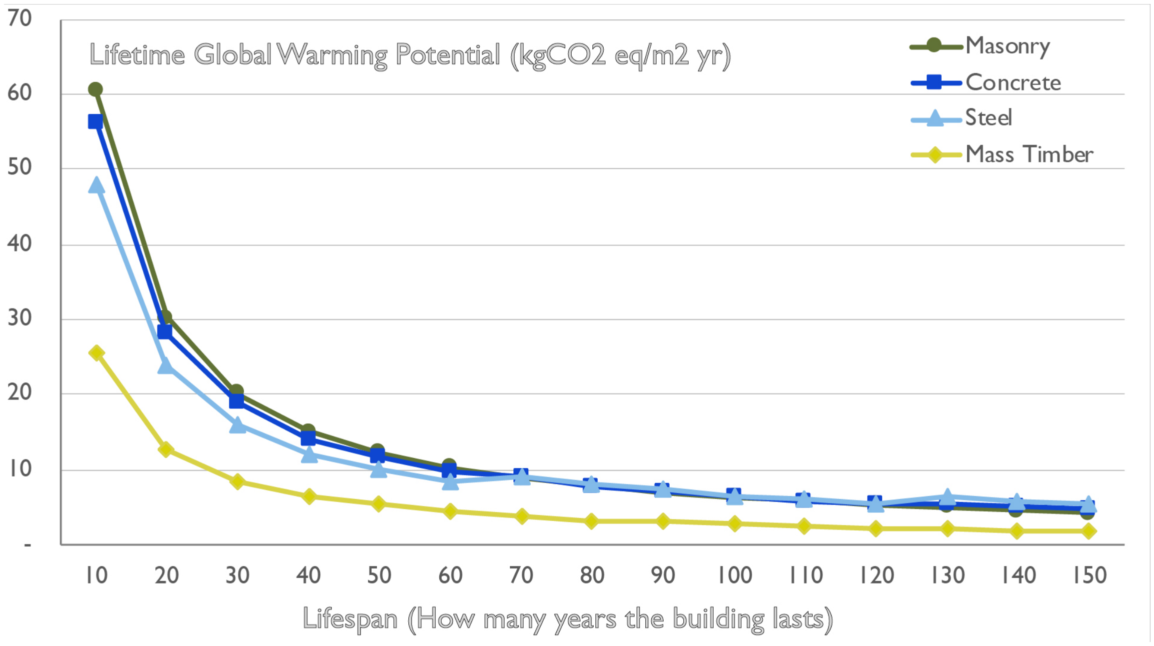

Figure 5. Total carbon equivalent emissions normalized per area per year for case studies: Steel (US District Courthouse in Salt Lake City), Wood (Wood Innovations &Design Centre), Concrete (ICTA-ICP in Barcelona), and Brick (Haus 2226 in Austria). Image by authors.

stored in the mass timber structure. Accurately measuring the carbon sequestration of wood in buildings remains an important area of research for LCA, as does accounting for forest management practices and emissions related to logging, manufacture and transport.[10] Many studies omit harvest-related emissions, for example decaying vegetation left in the forest and the possible loss of soil carbon from ground disturbance. Of course forests offer many co-benefits as ecosystems, so any expected benefits from lumber use depend on good forest management practices.[11] However, given the magnitude of difference between these specific four buildings, even a significant error in the values would leave wood's GWP lower than the steel, concrete and masonry buildings, across all denominators, and even when comparing multiple cycles or repair and replacement over a long life.

The graph of carbon emissions per area per year (see figure 05) shows that the life of the building increases, the differences between materials' initial impacts become less significant. Longer-lasting buildings reduce the import of material decisions, and durability is the ultimate equalizer. Reducing carbon emissions associated with constructing the built environment means preserving or adapting existing buildings and building long-lasting buildings to usefully serve for generations.

The lifespan of wood, and the notion of durability as the ultimate measure of sustainability, raises an important point about the time-value of carbon emissions.[12] Stabilizing global greenhouse gas emissions in the next 20-30 years and limiting the global temperature increase to 1.5°C above pre-industrial levels are essential to avoid the worst economic, health and safety impacts of climate change.[13] Avoiding GHG emissions now—and removing GHG when possible—is therefore more urgent than reducing emissions from operating energy decades in the future (although of course both are desirable and possible). Wood buildings promise to sequester carbon for the life of the building, so both lifespan, and end-of-life issues demand consideration when treating wood construction as long-term carbon storage strategy, since combustion or decomposition release the stored carbon back into the atmosphere. Fortunately, building envelopes typically protect primary structural systems—whether steel, concrete, or wood—and well-protected wood can last essentially forever. Similarly advances in design and testing of mass timber demonstrate good fire resistance, promising long lives, increasing permitted applications, and enabling wider adoption.

Although it cannot solve the crisis alone, incorporating large quantities of wood into long-lasting buildings avoids additional GHG emissions, buying time to reduce and sequester carbon emissions elsewhere. In terms of the contribution of structural resistance to durability, wood has significantly lower capacity than steel, making it a challenging choice for demanding projects like the Courthouse with its requirement to resist progressive collapse. Achieving space-flexibility like the steel moment frames—even if it were possible—would result in unrealistically large wood members. However, when considering gravity loads only, although the difference in cross-sectional area between steel and the equivalent wood columns is large—in the case of the Courthouse the equivalent wood cross-sectional area would have been 10x larger than steel—the effect on useable net floor area is less dramatic.

The structurally efficient, hollow shape of the wide flange steel section, which requires protection from fire, occupies a smaller, but not radically smaller footprint to the solid wood column. Ultimately filling that space with timber may benefit by sequestering more carbon, perhaps even enough to compensate for constructing the larger total building footprint needed to achieve the same net area. Of course, larger building footprints affect land use, density, and transportation-related emissions as well, all critical to total emissions but often outside the scope of whole building LCA.

CONCLUSION

Beyond the complexity of comparisons based on factors like efficiency, expected life, and the number of people served, these carbon denominators illuminate choices about justifying carbon-intensive materials in the urgent short term, not only through projected physical durability, but also through enduring cultural significance. Reuse and adaptation of existing buildings divides the carbon emissions over long lifetimes, and that growing denominator inevitably reduces the result. Far from an argument to thoughtlessly build excess capacity for an uncertain future—which runs counter to the time-value of carbon—future use demands balancing anticipation and indeterminacy, carbon intensity and carbon sequestration. To promote the desire, willingness, and ability to reuse buildings, designers must prioritize strategies to make buildings last as long as possible and remain endlessly useful.

This case study highlights the flaws and limitations of normalization by equalization, yet in so doing, offers some guidance to better meet the need for comparisons across differences. First, when considering real buildings (as opposed to models) a rich and nuanced case-study approach not only captures the combined and conflicting basis of comparison than any individual denominator, but also readily incorporates other LCA indicators to move away from a single numerator. Furthermore, case studies provide a natural frame to incorporate impacts and baselines that might otherwise be dismissed as negative externalities or neglected as non-numeric societal benefits. Absent widely available benchmark data, case effective case-studies remain a time consuming but essential method of analysis. Going forward, the industry must share data to establish baseline performance before establishing numeric codes for embodied carbon or standards for normalization. Consider the mature practice of simulating operating energy, which enjoys a baseline standard for minimum performance (e.g. ASHRAE 90.1); may be validated against direct measurement; and compared to large, long-established dataset for benchmarking (e.g. CBECS). In existing standards and practices for LCA stating assumptions such as building life (60 years? 200 years?) and material durability are good first steps. As comparisons extend to multiple denominators, systematic analysis of the uncertainty and sensitivity of results to these assumptions helps determine if distinctions represent real differences or merely noise. Finally, and perhaps most important, scientists and designers using LCA must compare and report their results using multiple bases of comparison, rather than selecting denominators to yield favorable interpretations.

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