



OPINION ARTICLE

The 'building paradox': research on building-related environmental effects requires global visibility and attention

[version 1; peer review: 1 approved]

Francesco Pomponi ¹, Robert Crawford ², André Stephan ³, Jim Hart¹, Bernardino D'Amico ¹

¹Resource Efficient Built Environment Lab (REBEL), Edinburgh Napier University, Edinburgh, EH105DT, UK

²Melbourne School of Design, University of Melbourne, Melbourne, Australia

³Faculty of Architecture, Architectural Engineering and Urban Planning, Université Catholique de Louvain, Louvain, Belgium

V1 First published: 05 Aug 2020, 2:50
<https://doi.org/10.35241/emeraldopenres.13838.1>
 Latest published: 05 Aug 2020, 2:50
<https://doi.org/10.35241/emeraldopenres.13838.1>

Abstract

The construction and operation of buildings is a major contributor to global energy demand, greenhouse gases emissions, resource depletion, waste generation, and associated environmental effects, such as climate change, pollution and habitat destruction. Despite its wide relevance, research on building-related environmental effects often fails to achieve global visibility and attention, particularly in premiere interdisciplinary journals – thus representing a major gap in the research these journals offer. In this article we review and reflect on the factors that are likely causing this lack of visibility for such a prominent research topic and emphasise the need to reconcile the construction and operational phases into the physical unity of a building, to contribute to the global environmental discourse using a lifecycle-based approach. This article also aims to act as a call for action and to raise awareness of this important gap. The evidence contained in the article can support institutional policies to improve the status quo and provide a practical help to researchers in the field to bring their work to wide interdisciplinary audiences.

Keywords

buildings, life cycle assessment, interdisciplinary research, climate change, global warming



This article is included in the Sustainable Cities gateway.

Open Peer Review

Reviewer Status

Invited Reviewers

1

version 1

05 Aug 2020



report

1. **Antonio Garcia Martinez** , Universidad de Sevilla, Seville, Spain

Any reports and responses or comments on the article can be found at the end of the article.

Corresponding author: Francesco Pomponi (f.pomponi@napier.ac.uk)

Author roles: **Pomponi F:** Conceptualization, Data Curation, Formal Analysis, Project Administration, Supervision, Writing – Original Draft Preparation, Writing – Review & Editing; **Crawford R:** Investigation, Writing – Review & Editing; **Stephan A:** Conceptualization, Investigation, Writing – Review & Editing; **Hart J:** Investigation, Writing – Review & Editing; **D'Amico B:** Conceptualization, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: The author(s) declared that no grants were involved in supporting this work.

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How to cite this article: Pomponi F, Crawford R, Stephan A *et al.* **The 'building paradox': research on building-related environmental effects requires global visibility and attention [version 1; peer review: 1 approved]** Emerald Open Research 2020, 2:50 <https://doi.org/10.35241/emeraldopenres.13838.1>

First published: 05 Aug 2020, 2:50 <https://doi.org/10.35241/emeraldopenres.13838.1>

Introduction

Each discipline has its specialist audience, readership, and journals. It is expected that most of the research done in a field be aimed at those publishing venues and specialist readership. Still, significant advances in most disciplines regularly find their editorial light in top international, interdisciplinary scientific journals^a. This might be due to the breakthrough the research represents for the field^{1,2}, the importance or impact it has on society^{3,4}, its timeliness compared to current socio-political-economic global trends^{5–7} or the wider relevance it has in the overall scientific progress of human kind^{8,9}.

Research on building-related environmental effects is often an exception, although it fits the aforementioned criteria. While this is not a new field^{10–12}, it has relatively recently gained global traction as the growing number of published articles in specialist journals (Figure 1). This should not surprise, as buildings account for around 30–40% of global energy demand, greenhouse gases emissions, consumption of natural resources, and waste generation^{13,14}. Parts of this agenda have been directly addressed by policy and regulation for decades, with the European Union Energy Performance of Buildings Directive first approved in 2002¹⁵, and national regulatory efforts to limit energy use in new buildings going back at least as far as the 1960s¹⁶. Therefore, although some might think it is the relative novelty that keeps research on building-related environmental effects out of the most prestigious journals, this appears to not be the reason.

^a The meaning given to this phrasing within the scope of this article is fully defined, with supporting evidence, in the Extended data.

At the time of writing (July 2019), in the entire suite of Nature and Science journals only 27 relevant entries (*Extended data: Table S4*¹⁷) were found matching the same keywords used for the graph in Figure 1. These cover works on urbanisation and cities^{18–28}, indoor ecosystems²⁹, autonomous architecture³⁰, and building materials and material efficiency^{31–37}.

This is paradoxical, particularly when the Nature journal *Eye* published an article in 2013 titled: ‘The carbon footprint of cataract surgery’³⁸ based on a single component analysis for one patient in Britain, showing that the carbon footprint for one cataract surgery was 181.8 kg CO₂eq. It takes a mere 1 tonne of cement in a building to exceed that amount³⁹, and the sole structural frame of residential buildings can have a ‘carbon footprint’ in the range of 126–498 t CO₂eq⁴⁰—three orders of magnitude higher than the carbon footprint of cataract surgery. Moreover, tonnes of cement produced around the world exceeds the number of cataract surgeries by more than 230 times, globally^{41,42}. Why therefore does research on carbon footprint and environmental impacts linked to or caused by buildings not make it into premiere journals despite the undeniable magnitude of the problem and its wider societal relevance?

A reason, highly unlikely given the enormous pressure to publish that most academics face, is that researchers in this field are uninterested in publishing in these top journals. Or there could be a targeted and selective rejection of articles in this field by prestigious publishers, but we struggled to find any reason why this would occur. So why does this happen? The reasons are several and not obvious—we believe—and both intrinsic and exogenous; we have reflected on them in the following sections.

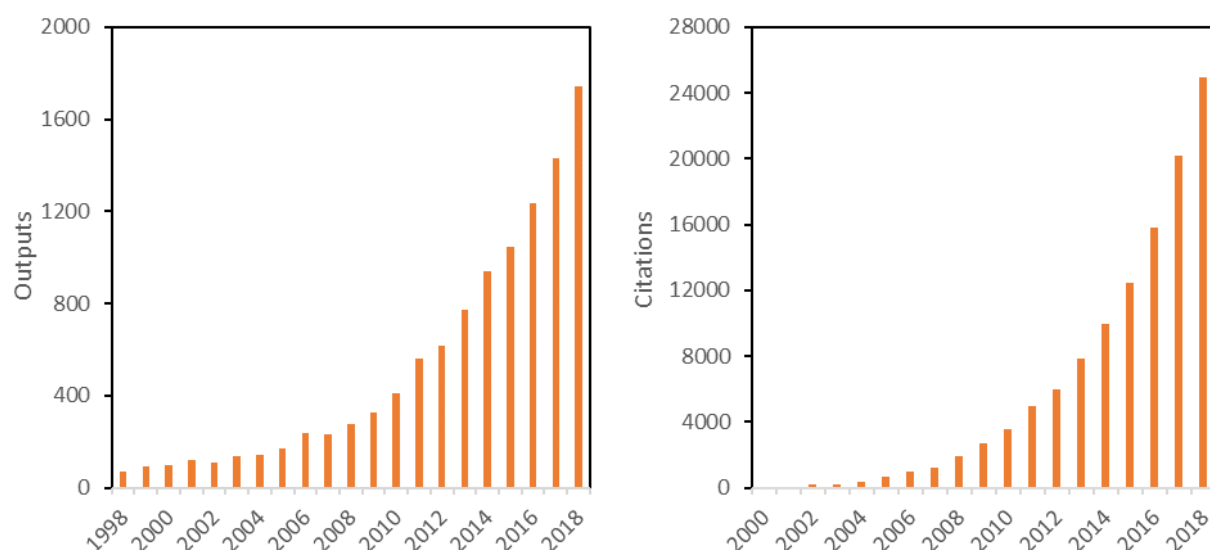


Figure 1. Bibliometric analysis for research outputs (n=10758) matching the keywords ‘life cycle assessment buildings’ OR ‘environmental impacts buildings’ OR ‘embodied carbon buildings’ in the last twenty years (1998–2018): total number of outputs per year (left); and sum of times cited by year (right). Citations start from year 2000 as no citations are recorded in the years 1998 and 1999. [Sources: Web of Knowledge and Dimensions AI].

The uniqueness factor

Albeit focussed on construction materials, one of the few papers that could broadly fit the ‘building-related environmental effects’ category is the recent work of Heeren and Fishman⁴³, which provides comprehensive and harmonised datasets and data structure for material intensity in buildings. This represents an important advance as it collates, validates, and enhances global data on material intensities in buildings. It is also a potentially excellent platform for global collaboration and offers highly sought-after data to many researchers. However, its primary focus is on materials rather than buildings, and if one were to look at the number of case studies behind the dataset (n=33) they would realise that it is well below some norms in other disciplines to produce a global database.

Is it just a data problem then? We do not think so. Buildings are unique entities made of hundreds-to-thousands of components that interact dynamically in space (through global, interconnected, and inter-sectoral supply chains) and time (they enter the life cycle of a building at various moments and stages, and stay for different lengths of time, over decades and even centuries). Grasping a good understanding and a complete picture of what occurs in a building requires a substantial amount of time. Apart from lengthy construction times, buildings require maintenance, repairs, material replacements, minor and major refurbishments, and demolition or dismantling, throughout their life and many decades into the future. This significantly adds complexity to modelling the environmental effects of buildings. More complexity is further added by the myriad of building codes (fire, safety, seismic, acoustic, etc.) and the interlinkages between different building systems that combine and interact with one another (glazing and ventilation, for instance).

The uniqueness of each building also reduces the possibility of bold generalisations of the results. As a consequence, a significant share of building-related research follows a case study approach, which is not, in our experience, widely supported by the publishing world. So much so that in writing, reading, and reviewing papers in this field Yin is always referred to⁴⁴ in order to justify and often *defend* the case study approach. But is this defence necessary? Other methodological avenues are taken for granted and only rarely in other disciplines do authors explain at length why they have chosen a specific technique used in their research. The building-field research community is therefore often looking for more buildings to analyse and strengthen the relevance of their findings. Not only does this require significant time, often beyond what is allowed or acceptable for a research project, but it also incurs an ironic counterargument on the part of some editors and reviewers along the lines of: ‘the number of buildings is appropriate but the buildings are so different from one another that how can they be compared?’.

It is also worth noting that the same approach on diversity of population samples does not seem to apply in other fields. There might be cases in biomedical research where a heterogeneous population (e.g. zebrafish and mice⁴⁵) is well received as it enables a demonstration of whether hypotheses and results hold (or not) regardless of the variation. In other disciplines, a

small but homogenous sample (e.g. n=3 to 8 mice⁴⁶) allows for substantial advancements to be made under the understanding that a bigger sample was not a viable option in that specific research project. But if three mice are a perfectly acceptable number to publish in top journals for biomedical researchers why does the same number not open the same doors for research on buildings? From our perspective, a mouse is not more complicated to monitor and analyse than a building. Further, it is unfeasible that two buildings, identical but for one variable, be constructed to test the influence of that one variable before moving on to the next one. Despite the impressive advancements in simulation tools and digital technologies, it appears unlikely that standard approaches in other fields of science will be fully applicable to research on building-related environmental effects.

Unless and until the uniqueness of buildings is better understood and acknowledged, the lack of large datasets and thousands of data points will continue to impede researchers in this field in the pursuit to have their work disseminated in top international journals. Big data can help, but—apart from some exceptions to date⁴⁷—it seems more easily applicable to certain aspects of a building’s life cycle, such as energy demand through real-time smart meter readings coupled with real-time building occupancy and weather data. However, this is a partial—and increasingly less preponderant^{39,48–51}—aspect of building-related environmental effects, as explained in the next section.

The life-cycle factor

There is indeed an unnecessary and yet unresolved dichotomy in how buildings are seen, and this seems endemic. The IPCC⁵², the Committee on Climate Change⁵³, and several other influential bodies, when focusing on buildings, tend to focus solely on the energy use and greenhouse gas emissions related to the use phase of a building, when it is occupied. This is certainly a large source of global impacts⁵⁴, but with more, and increasingly stringent, regulations driving towards Zero Energy Buildings (ZEB)^b, operational energy will progressively be less relevant, and in fact totally insignificant if the ZEB theoretical targets are ever achieved. What these bodies overwhelmingly ignore is the embodied energy (and the related embodied greenhouse gas emissions) linked to all other phases of a building’s life-cycle: extraction and processing of raw materials, manufacturing, transportation, construction, maintenance, repair, refurbishment and end of life activities such as demolition, recycling and waste processing. In fairness, this energy is not ignored but it gets dispersed and diluted in a wider cluster of ‘industrial sector’ impacts, therefore breaking the functional unity of a building. This is shown in [Figure 2](#).

To understand the paradox of disjoining embodied and operational impacts it is useful to try to apply the same reasoning to a car. It would imply that the petrol used by the car is attributed to the car, but the tyres are not. Does this make sense?

^b We contend this definition and the use of zero when in fact a ZEB is far from having zero energy consumption due to the embodied energy, but have used this definition for the common understanding it has.

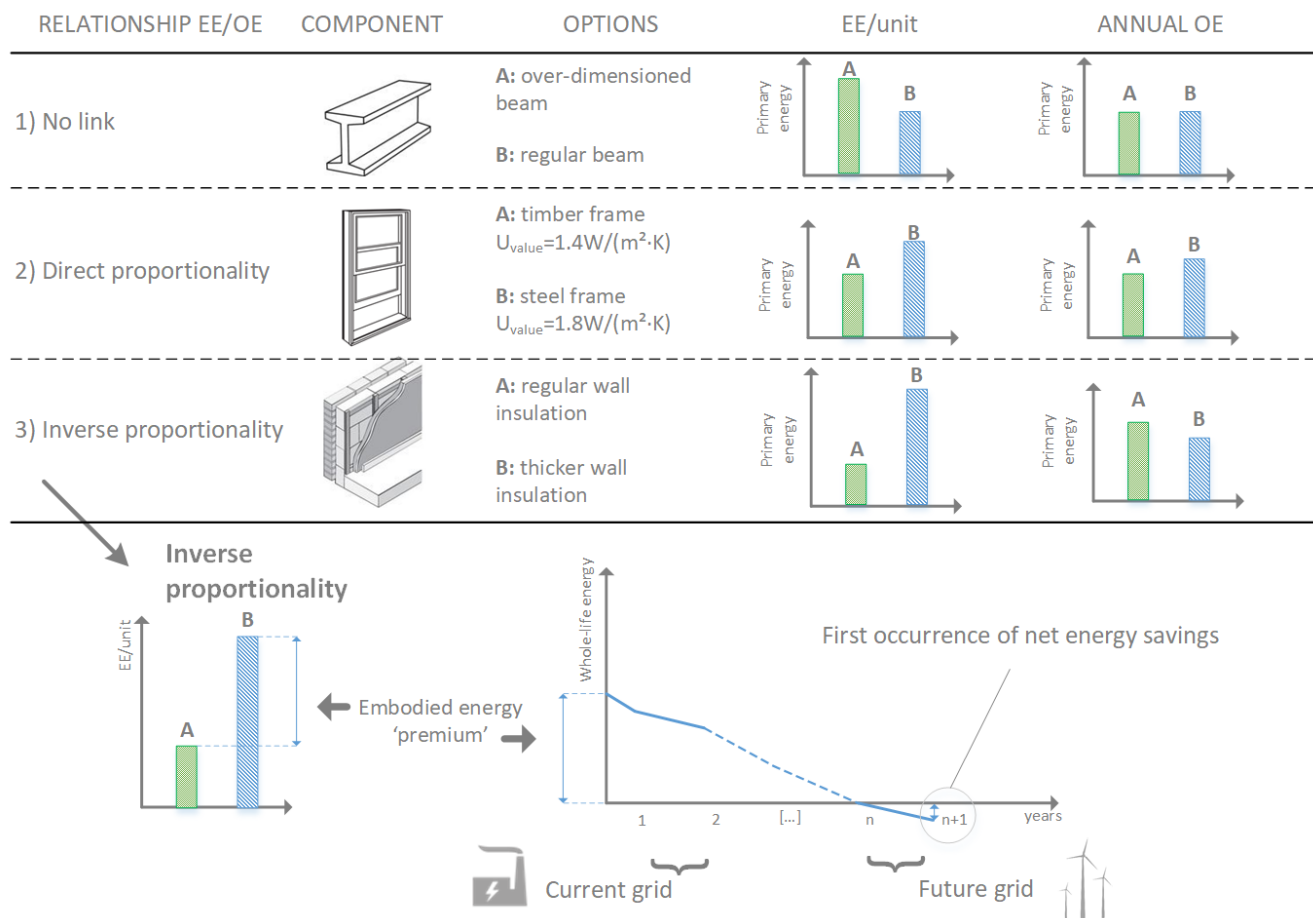


Figure 2. Relationship between embodied energy (EE) and operational energy (OE) in buildings depending on the component under examination. Options are: (1) no link, when a material with higher/lower embodied energy bears no implication over the operational energy consumption of the building; (2) direct proportionality, when a material with higher embodied energy also causes greater operational energy demand due to a worse thermal performance; and (3) inverse proportionality when a component with higher embodied energy reduces the operational energy demand. This latter case would be the only one where an increase in embodied energy can produce beneficial effects on operational energy. However, as the bottom part of the figure shows, operational energy savings do not materialise immediately. Instead, the whole life energy balance starts with the embodied energy 'premium', which is annually compensated by the lower operational energy demand of the option with higher embodied energy. It will take a number of years before the embodied energy premium is recovered. This means that the embodied energy 'premium' is causing a surge in emissions due to the current, carbon-intensive, energy grid to save emissions in the future on a likely decarbonised energy grid. [Source: authors' own].

Can a fully-fuelled but tyre-less car go anywhere? A powered building without walls would be equally useless. As much as the car is seen as the indivisible unit that provides a specific function, so is the building; or at least so it should be. The current mind-set would suggest that the industrial sectors push this energy and materials towards the building, but we would argue that it is quite the opposite. Just as a household pulls the energy demand for heating and cooling, the building—or in fact the people determining its features and construction fate—pulls the energy linked to the manufacturing and other activities related to the cement, glass, steel, and all the other materials it is made of. Until the unnecessary dichotomy of operational vs. embodied impacts gets reconciled, building-related effects will remain distributed and diluted across a number of existing categories and their magnitude will be seldom perceived. A

lack of awareness of the magnitude of building-related impacts will impede appropriately targeted action that would yield beneficial outcomes more quickly and to a greater extent.

The paradoxical decomposition of a building can be observed in one of the most widely used tools for global sustainability analyses and sustainable production and consumption studies: input-output analysis (IOA)⁵⁵. In IOA the physical unity of a building gets broken down into two main components treated substantially differently: the energy we use for heating, cooling, cooking, and hot water goes into the final energy demand of households while everything else linked to the building gets distributed and diluted across many industrial sectors. Recent ground-breaking research has developed the idea of city carbon maps⁵⁶ to allow for the complete and consistent

reconciliation of direct and indirect greenhouse gas emissions from a city. But would it be feasible, or even desirable, to go one step further in this direction and try to develop ‘building carbon maps’ or is there a better way to reconcile impacts caused by buildings? There is already evidence of the successful application of environmentally-extended input-output databases to different scales of analysis, although this is limited to embodied impacts⁵⁷ and mostly focused on either micro (e.g. components⁵⁸) or macro (e.g. nations⁵⁹) scales.

The scale factor

In addition to the mainstream focus on operational energy efficiency, existing research on environmental effects within the built environment seems to fall mainly in two distinct and distant categories. The first could be described as *top-down* and would cover macro-economic and policy related studies that aim to understand current states and future consequences at national or international levels. One example is the work of Ramaswami and colleagues⁶⁰ who investigated cross-sectoral strategies to reduce greenhouse gas emissions from cities in China, finding a 15-36% improvement towards national greenhouse gas emissions targets compared to single-sector strategies. The second could instead fall in the *bottom-up* classification and would include studies in the material research area, and focus on improvements at small scale (nano, micro, or a single material) that would yield improvements given the large quantities of a specific material that are used globally. One example in this category is the work of Miller and colleagues⁶¹ who investigated ways of mitigating the water demand of concrete production. Concrete is however only one of hundreds of materials in a building and while its global impacts are surely significant⁶² they might well be rather modest in comparison to the broad range of impacts attributable to buildings.

Buildings are therefore not just unique, but they are also characterised by a specific scale that does not immediately match mainstream research approaches, mostly focused on macro or micro scales⁶³. A focus on cities seems reasonable and accepted⁶⁴⁻⁶⁷, perhaps because it instantly evokes an idea of utter complexity, but we could argue that a city is a complex conglomerate of buildings much as a building is a complex conglomerate of materials. However, city and material-based research is widely publicised in top international journals, unlike research at the whole building scale. There might be an underlying, unconscious assumption that by working at a problem from both ends—top-down and bottom-up—the research will meet in the middle and the problem would be solved. However, by analogy, we would not feel very comfortable if all medical knowledge was derived from research at the cellular and societal levels. Research on humans is equally fundamental, and so is research on buildings.

A wrongly perceived simplicity of the building scale might also be linked to the fact that many people look at a building and see their home or place of work, with which they might have empathy. Materials are less familiar and not as warming as a thought, as they can harm us and make us ill⁶⁸, and are often seen as parts of the industrial sphere. Cities on the other hand are chaotic, often polluted, interconnected and dynamic⁶⁹, and so the building remains in the middle, often ignored.

The human factor

Buildings are, at least in the large sense, designed not manufactured. Off-site construction can potentially change this⁷⁰ but this is yet to occur at a global scale. In addition, the growth of the concept of mass customisation in construction⁷¹ seems to suggest that users will remain pivotal to defining the key design features, as well as the fate, of buildings. Buildings are quite an intimate thing for us humans. We spend two-thirds of our life indoors⁷², and are keen to personalise our homes, tailor the desk arrangement and layout in our open plan office, create a unique and creative combination of plants, flowers, fruits, and vegetables in our gardens. No two homes are the same. These factors point to a large community of diverse stakeholders that play a pivotal role in the building industry. This seems an innocuous team, which however hides an intricate mix of professions that interact and contribute to the building design process at various and multiple stages. Building actors, broadly defined as those influencing what the finished building looks like, would potentially include owners, developers, architects, civil engineers, structural engineers, geotechnical engineers, building services engineers, interior designers, project managers, site managers and sub-contractors. This ensemble of expertise and professions is the main influencer of the overall environmental effects of a building (together with the user⁷³). Decisions that determine these effects are made from the top down. For example, it is not the decision of the cement manufacturer that dictates how much concrete is used in a building. Rather, the architect decides first if concrete will be used for a specific building project or not. The geotechnical and structural engineer would then influence the amount and type of concrete depending on their approach on rationalisation and material redundancy⁷⁴⁻⁷⁶, but would rarely oversee the procurement and supply of the material, which is left to managers and contractors. Whilst there are obviously rules of thumb developed over decades, and professional bodies and standards that guide best practices, the design process includes elements of unique subjectivity at each iteration and for each project. We believe these multiple human interventions are unique to, and strongly influential for, buildings and the research that is done on them. This should be borne in mind before adopting, suggesting, or promoting a single approach based on repeated iterations of the scientific method followed by rigorous statistical analysis. It might not always be that this is the best approach for building-related research. Interdisciplinary research that follows innovative paths should be encouraged, and the role of social sciences acknowledged and recognised in the pathway to effect real change⁷⁷. Buildings are deeply social, and the solutions that will reduce their environmental effects to within acceptable limits, concordant with the rate of renewal of materials, are unlikely to come solely from technical analyses⁶³.

The systemic social factor

If one reads most PhD theses on building-related environmental effects, there will be few citations to articles in Nature or Science. This should not surprise, given the nearly non-existent body of literature published in such journals that is relevant to this field. However, this possibly also perpetuates the lack of research on building-related environmental effects in such journals and it might be explained by evidence from research on

rational choice and social theory⁷⁸ because real or perceived environmental constraints drive a choice made by an agent (e.g. a person)⁷⁸.

A systemic theory on socialisation also argues that differences in environmental concern are the result of the implicit cultural training received^{79,80}. If a PhD candidate in the field is trained without accessing premiere journals due to the lack of relevant research published in there, s/he might grow accustomed to thinking that such journals are not suitable publication venues for the research s/he does. However, we have already demonstrated this untrue as research on building-related environmental effects does fit the criteria that allows research in other fields to be published in these journals.

This therefore appears to be an endogenous barrier that researchers in the field of building-related environmental effects will need to overcome. Thus action is necessary by the whole community to ensure wider and more powerful dissemination of the work we do and the challenges it entails. It would also spur enormous opportunities for intra-, inter-, and trans-disciplinary collaborations, which would be likely to lead to more widespread and rapid change.

The methodological factor

If repeated applications of the scientific method followed by strict statistical analysis are not always or necessarily the best course of action, then what should be done? The honest answer is that the community is still identifying a course of action. Life cycle assessment (LCA) (in various forms) has been used for three to five decades⁸¹, but its application to the built environment is more recent. LCA standards have initially—and intentionally—been generic and broadly applicable⁸², and the first dedicated standard for the built environment dates back from 2011 only (8 years old at the time of writing)⁸³. It suffered the same issue of broad definition as the first LCA standard and as a consequence national bodies have developed refined methodologies to clarify or adapt it⁸⁴.

Good datasets are few and far between and, without this being necessarily a negative criticism, most published studies are therefore partial and limited in scope⁸⁵. Positive future avenues come from the field of hybrid LCA, whose application to—and usefulness for—the built environment is not new^{86,87} but which has also not seen widespread uptake^{88,89}. The building research community is also fragmented and still divided in the operational vs. embodied debate, and this has slowed progress towards a harmonised methodology that works across the building life cycle. This has also occurred in the Energy in Buildings and Communities (EBC) Programme of the International Energy Agency (IEA): the past annexes have either focused on operational energy efficiency and optimisation⁹⁰ or on embodied energy and greenhouse gas emissions^{91,92}. As demonstrated in Figure 2, this fragmented approach is problematic in the building sector, where building performance is so intrinsically linked across the various life cycle stages.

In addition to the new dataset developed by Heeren and Fishman⁴³, the Annex 72 of the IEA⁹³ is advancing the research

already conducted within EBC Annexes 56 and 57: it broadens the scope of both, and finally reconciles the operational and embodied effects. It aims to produce a harmonised, globally applicable and yet regionally differentiated, methodology to advance the assessment, and consequential mitigation potential, of life cycle environmental effects associated with buildings. There are also other promising avenues that are developing rapidly—in addition to the already mentioned hybrid LCA approach—such as a finer sectoral resolution in multi-regional input-output databases⁹⁴, and over 6,000 Environmental Product Declarations (EPD) for construction products at the beginning of 2019⁹⁵.

Additional observations and concluding remarks

Language is always very important and there could be an issue on the terminology used. The first instances of the term ‘embodied energy’ in academic literature date back more or less to the late 70s^{96–98}. These early studies could all be attributed to the input-output research community, a field of research that unfortunately remains distant from most construction and building related research, as demonstrated in the following sections. To estimate the energy costs of goods and services, Bullard III and Herendeen⁹⁶ [p.268] proposed the idea of ‘conservation of embodied energy’, meaning that ‘the energy burned or dissipated by a sector of the economy is passed on, embodied in the product’. (Interestingly, in the discussion of their method they conclude that their results ‘are less useful for very detailed, micro questions (for example, the energy costs of different building materials)’⁹⁶ [p.268–269] and that for these, specific process analyses should be more accurate.) Arguably though, that energy—as well as the greenhouse gas emissions related to it—is all but embodied in the product. It has been used to generate heat and allow machinery to move and manufacture products, and the greenhouse gases have already been emitted into the atmosphere. Alternative suggestions that have been proposed are along the lines of “upfront carbon emissions”⁹⁹ or “capital carbon”¹⁰⁰. Opponents of the ‘embodied’ terminology rightfully say that the term is misleading, but it is equally true that scientific communities in other fields have successfully used it. Additionally, the term carbon—whilst widely used—is scientifically incorrect to represent greenhouse gas emissions¹⁰¹, and could increase confusion as much as it could ease understanding.

The open challenges are still many, but this is a time for hope. We have shown positive advancements in datasets and methodology, and the number of published studies and its growth rate testifies a global, and very active community, working in this field. However, the challenge of reliably assessing and effectively mitigating the environmental effects associated with buildings remains momentous, particularly in light of global trends of urbanisation and population growth. This is why research in this field must find a way to gain global visibility and attention and build a diverse and interdisciplinary community to orchestrate concerted actions, share and learn lessons, and accelerate impact.

Data availability

Underlying data

No data are associated with this article.

Extended data

Figshare: Extended data for Emerald Open Research, <https://doi.org/10.6084/m9.figshare.12681419>¹⁷.

This project contains the following extended data:

- Table S1 – Top 10 international journals based on H-index values
- Table S2 – Top 25 international journals based on H-index values

- Table S3 – Top 20 journals in the field ‘Construction and Building Technology
- Table S4 – Full list of outputs matching the keywords used for this article in the top interdisciplinary international journals as defined for the scope of this research

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Current Peer Review Status: 

Version 1

Reviewer Report 25 August 2020

<https://doi.org/10.21956/emeraldopenres.14917.r27012>

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Antonio Garcia Martinez 

Department of Building Construction, Universidad de Sevilla, Seville, Spain

The paper investigates the profound reasons that could be found behind the lack of visibility of studies on the environmental consequences of buildings within the scientific world in general and in that of high-impact publications in particular. It provides an original point of view of great value and relevance that will undoubtedly help a better understanding of this complex research object. The authors show a high knowledge of the methodological circumstances, and the theoretical and practical barriers that surround research in this field. Through solid evidence, they construct a well-articulated argument about the factors that determine scientific research in the field of environmental evaluation of buildings and progressively they reach interesting conclusions. From my point of view, the article deserves to be indexed.

Is the topic of the opinion article discussed accurately in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Are arguments sufficiently supported by evidence from the published literature?

Yes

Are the conclusions drawn balanced and justified on the basis of the presented arguments?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Life Cycle Assessment of Buildings. Environmental impacts in Construction Sector.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.
