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VSI Editorial - Sustainable and resilient construction: Current status and future challenges

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VSI Editorial - Sustainable and resilient construction: Current status and future challenges**Abstract**

The construction industry globally is one of the most environmentally damaging of sectors. Additionally, the resources consumed and the operational energy requirements of buildings are 'locked-in', potentially for decades. The Intergovernmental Panel on Climate Change has recognized construction as a sector in which significant improvements can, and indeed must, be made. But the industry is often argued to be unique, in its multiplicity of stakeholders, transient organisational structures, avoidance of risk and impact on society. The current Virtual Special Issue (VSI) sought to bring together a collection of papers on progress and potential for improvement in the construction sector, in terms of both sustainability and resilience to the changing climate. A total of 34 papers form the VSI. Insights from social science include the need for more holistic perspectives at multiple levels, from buildings to urban plans, and the centrality of human relationships, through leadership, collaboration and along supply chains. Insights from a technology perspective include BIM applications for green and off-site construction, enhanced estimation of construction waste, and developments in materials. Insights on low-carbon construction include evidence that reducing both costs and emissions in the construction sector is viable. This editorial reviews the VSI papers and makes a number of recommendations including the need to recognize that values and understanding change over time and that leadership and human decision-making are essential factors for transformation. Alongside the progress described on sustainability in multiple areas, the editorial calls for an invigorated research focus on how construction can adapt the built environment to the changing future that is before us all.

Keywords: construction industry, sustainable construction, resilient built environment

Wordcount: 7930 (excluding title, abstract and references); 9262 in total

Highlights:

- Reducing both costs and emissions in construction is viable
- Human relationships (leadership, supply chain, project) essential for transformation
- Business decisions rarely utilitarian but set in social contexts
- Evaluation methods must address temporal nature of value and sustainability
- Insufficient research attention on climate resilience in the built environment

1. Introduction

The construction industry as a sector is resource intensive, wasteful and energy intensive. It consumes over 50% of all raw material extracted globally (Ruuska & Häkkinen 2014), produces 25-33% of waste in the EU (EU 2015), emits the highest level of carbon by sector and is responsible for 40% of global energy use in the buildings it produces (UNEP 2015). The industry is often characterised as unique. A multiplicity of stakeholders come together, including developers, architects, engineers and other consultants, contractors, sub-contractors, individual tradespeople and materials suppliers, in temporary organisations that are the construction project. Beyond the project, individuals, communities and societies are affected, both positively and negatively. Policy, regulation and market forces are seen as critical in influencing higher levels of sustainability but the fragmented nature of the sector, its adversarial nature and avoidance of risk can act as barriers.

Research within the domain encompasses a wide range of topics. Environmental assessment schemes such as BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design) continue to be compared and evaluated in specific settings (Suzer, 2019). In addition, more critical and nuanced perspectives are also informing debate: more consistent assessment in green building rating systems requires consideration of midpoint and endpoint impacts (Ismaeel, 2018). The application of Foucaultian theory to BREEAM has shown how the organisation of the scheme itself shapes understanding of what is meant by green buildings (Schweber, 2017) and the choice of rating system can influence the design and outcome of the building project (He et al., 2017). Work on green management and procurement continues to develop: green business models, particularly those that will facilitate transformation to a more sustainable market, represent an expanding area of research (Abuzeinab et al., 2016). Green supply chain management practices may be enhanced through the application of a multi-dimensional framework, such as that proposed by Balasubramanian and Shukla (2017) which identifies core and facilitating practices, within and external to organisations. Development of methods to aid complex decision-making has widespread application in sustainable construction – from assessment of overall emissions of a planned construction project (Marzouk & Abdelakder, 2019) to seeking a limited set of

viable alternatives at early design stages of infrastructure projects (Shahtaheri et al., 2018) to dealing with the environmentally-impactful design of façades (Moghtadernejad et al., 2018). Previous Special Issues in the Journal of Cleaner Production (including Zhang et al. (2018) Sustainable urban transformations; Zhang et al. (2015) Regenerative sustainability for the built environment) have included cutting-edge research on broader themes relating to the built environment. The topics of interest on sustainable and resilient construction, and the disciplinary perspectives that can inform them, are enormously wide-ranging and cannot be captured in any single collection of work. Nonetheless, the objective of this Virtual Special Issue was to provide a multidisciplinary platform (in keeping with the long-established strength of the Journal) to all researchers with an interest in construction, with the aim of integrating multiple perspectives on this critical sector. It presents a novel contribution in attempting to bring together papers on societal, organisational, technical and economic approaches to the critical issues of making the current and future built environment increasingly sustainable and resilient. The VSI offer an opportunity to readers to read beyond their discipline, to look at other perspectives on the topic and perhaps to identify potential for enriched understanding, for ideas for interdisciplinary work or, ideally, for true transdisciplinary insights.

This editorial is structured as follows. For each of the three themes from the Call for Papers, the theme is briefly outlined and the papers within the theme are summarised. A short commentary on each theme follows, and the editorial concludes with final comments presenting emerging themes and unaddressed gaps in the VSI.

2. Theme 1: Insights from social sciences on sustainable construction

It can be argued that the changes needed to transform construction into a sector in which environmental and social sustainability and resilience are embedded within processes, business models and everyday decision making are ultimately changes in human behaviour. Perspectives which examine technology, planning processes, policy and other aspects contribute useful knowledge but perspectives which focus on the individual actor must surely offer additional valuable insights. Generally, however, the person and the social group (organisation, project, community) are under-researched when it comes to examining sustainable and resilient construction. This sub-theme invited papers which draw on theories and methods from the social sciences to investigate the construction sector.

In their paper entitled *Barriers inhibiting the transition to sustainability within the Australian construction industry: an investigation of technical and social interactions*, Martek et al. (2019) applied the theoretical lens of sustainability transitions in an expert focus group study. Although set in Australia, their argument holds more globally. They point to the inadequate progress towards

sustainability in the built environment, despite showcase buildings and pilot products. They take aim at the focus on energy efficiency, when sustainability has much broader meaning. In their view, the current focus on regulation and rating systems in sustainable construction misses the social dynamics of the 'ecosystems' in the sector. They remind us of the multiple stakeholders in the construction project and emphasise the role of a critical player, often overlooked in research and policy: the building occupant or householder. From their discussion with sustainability experts in the sector, they identify multiple barriers to progress. These include lack of end-user awareness and demand; lack of incentives for buyers in the housing market to consider sustainability; lack of knowledge on how high-performance buildings should work; unwillingness to invest due to the rapid turnover in tenure. At a broader level, there is inconsistency between regions; a reactive approach from central government in place of leadership; lack of ownership, governance, power and vision. They see such absences as facilitating spaces in which vested interests can compete and challenge change toward sustainability. The authors position these failings within the social institutions and social dynamic processes which produce the built environment. Their conclusions are that the technology focused solutions of regulations and rating tools, while valuable, are not enough. More attention needs to be paid to knowledge and awareness throughout the sector and especially for the end-user. At national and industry level, leadership is critical as is determining ownership of the problem and its constituent parts. Finally, without end-user engagement, sustainability transitions will continue to stagger along instead of making the rapid rate of advancement that is necessary.

Heffernan and de Wilde's (2020) paper *Group self-build housing: a bottom-up approach to environmentally and socially sustainable housing* addresses directly the consumer level challenges highlighted by Martek et al. (2019). Heffernan and de Wilde (2020) explore group self-build, in a UK context, as a potentially progressive development model for zero carbon homes and sustainable communities. They applied a Policy Delphi method with sector experts at a national and regional level. Amongst the perceptions of advantages of group self-build, energy efficiency and sustainable communities were most strongly supported. Other advantages noted were quality of build, innovation, meeting occupant needs and affordability. The most common disadvantages in the experts' opinions were finding suitable sites, raising finance and ensuring ongoing commitment. The study showed interesting insights from group self-build expert opinion and, in particular, demonstrated the potential for this development model to address two of the particularly entrenched challenges for low carbon homes discussed by Martek et al. (2019): the performance gap attributable to occupant behaviour and the need to grow consumer awareness and market demand for zero carbon homes. Heffernan and de Wilde (2020) argue that people who commit to involvement in group self-build develop greater awareness of issues of not only energy efficiency but of sustainability

more generally, alongside greater knowledge on the science and technology of low carbon building, and in doing so, become advocates for low or zero carbon building within the wider community.

In *Collaboration between designers and contractors to improve building energy performance*, Xu, Li, Wang and Huang (2019) focus on a specific aspect of the sustainable built environment, that of energy efficiency, and examined an important relationship within the construction 'ecosystem', that between designers and contractors. They review the literature which has found that failure of collaboration between design and build stages of development is a significant factor contributing to the building energy performance gap between design and operation, and their aim was to examine the logic and nature of such collaboration. The authors first drew on expert interviews to identify factors which could influence collaboration behaviour and then applied this using evolutionary game theory to model dynamic behaviour. The modelling showed that decisions on collaboration were influenced by three factors: long-term gain from collaborating, cost of collaborating, and loss due to lack of collaboration. Players were willing to collaborate if loss from collaboration was less than loss from non-collaboration. The paper proposes recommendations for encouraging collaboration between contractors and designers, including government incentives for collaboration such as part-funding of training schemes places or information technology, and identifying responsibilities. The authors recommend that the method be expanded to other critical roles within the construction ecosystem as a way of investigating of the dynamics of roles where access to individuals and the complexity of their daily project work makes such studies difficult. However, the method carries the risk that what is being modelled may poorly represent work or cognitive processes and critical factors may as yet be overlooked. In common with Martek et al. (2019), Xu et al. (2019) highlight the absence of responsibility amongst construction professionals and the essential nature of social interaction and collaboration.

The paper by Killip, Owen and Topousi (2020), *Exploring the practices and roles of UK construction manufacturers and merchants in relation to housing energy retrofit*, looks at a different set of actors in construction: the often-overlooked 'middle actors' – here, the manufacturers and merchants supplying small construction firms. They develop an argument for the critical role of the repair, maintenance and improvement (RMI) market in implementing 'deep retrofit' to existing homes which is essential for achieving the climate change policy aims of the UK government. They note that middle-actors are not simply passive agents responding to policy or market demand but are actively pursuing their own goals. The findings demonstrated a complex web of organisations involved in the supply of products and services to the RMI market. The authors contrast the distance of relationships between manufacturer and end-user in high-volume markets with the much closer links between manufacturers, merchants and users in 'green' RMI. As a result, in the latter context, the middle-

actors maintained interest in the operational performance of the building which, in contrast, was seen by mainstream manufacturers and their merchants as outside of their control and responsibility. The challenges for policy that the findings present are discussed, and an iterative and learning-focused process with engagement of industry actors is proposed as one way to make the significant progress needed on the retrofit of existing homes.

In a different context, the paper by Celentano, Göswin, Magyar and Habert (2020) entitled *The informal city as a socio-technical system: construction management and money distribution in the informal and upgraded communities of Bangkok*, also focuses on central actors in development: householders and local communities themselves. The setting is two informal settlements in Bangkok, Thailand. Noting that informal development is not necessarily chaotic but follows its own organisational principles, Celentano et al. (2020) argue that understanding these is essential before considering how formally organised planning logics can be successfully integrated. Examining the case study settlements on technical features, main construction organisational schemes, their inter-relationship and relationship with distribution of materials, financial resources and labour, they found that – contrary to widely-held assumptions – only 18% of upgrades were self-build. For these projects, materials and labour came from within the community and investment was retained in a closed loop. Self-managed projects drew on community labour whereas materials were sourced from formal Bangkok and investment began to flow out of the area. When external contractors were appointed, materials and labour came from outside the community, which in some cases led to employment of illegal migrant workers who then created their own temporary informal settlements, as well as the loss of knowledge on local materials from local labour.

Continuing with exploration of critical relationships in developing a sustainably built environment, in *Conflicts concerning construction projects under the challenge of cleaner production: case study on government funded projects*, Wang, Ma, Wu, Liu, Gong and Chen (2019) examine a problematic aspect of construction: conflicts between construction projects and external stakeholders. Taking government funded projects in China as a nationally and globally significant domain, they conducted case study research on six projects. Six types of external stakeholder were defined and 17 types of conflict. They found particular difficulties had arisen with utility companies and due to inconsistent government policy. Recommendations to deal with conflict include prevention, active resolution, mediation and compromise. The evidence points to the importance of early and continuous communication, designed to be effective for its audience. Although the empirical setting was government-funded projects in China, the findings apply more widely, at least in part. Conflict in construction projects is seen as almost inevitable (Jaffar, Tharim, & Shuib, 2011) and, as Wang et al.(2019) note, environmental requirements can lead to further contention between

external stakeholders and development. Interestingly, the paper makes fleeting reference to the 'dark side' of construction, noting the absence of illegal activity and the view of one participant that violence is never appropriate "any more" in resettlement. These comments serve as a reminder that much research on construction focuses on the responsible organisations who want to learn, to improve and to minimise their adverse impacts. The built environment however is also produced by individuals and organisations who pursue profit over ethical concerns.

Starting from the premise that business owners and leaders play a pivotal role in transitions towards sustainability, Fontana (2019) examined how executives in the garment industry in Bangladesh make sense of decisions around LEED-certified premises in his paper entitled *Pioneering environmental innovation in developing countries: the case of executives' adoption of Leadership in Energy and Environmental Design*. LEED is an environmental assessment and building certification scheme originating in the US and used worldwide. Bangladesh's garment industry is the second largest in the world after China, and suffered major reputational problems after the Rana Plaza collapse in 2013 in which over 1,100 people died. Applying the theoretical perspective of sense-making and addressing the gap in research focus on environmental innovation in LMIC (low-medium income countries), Fontana (2019) took a qualitative approach with company owners who had sought LEED accreditation. He found evidence of social and collective influence in their decision. Pursuit of business gain as well as environmental goals played a role, with both objectives being important for one third of the participants, and neither being important for another third. For the latter group, they accounted for their decision through reference to avoidance of future competitive loss and to group norms in the sector. The paper concludes that the evidence supports instrumental and normative influences, challenging the view that environmental innovation is purely market driven, and noting psychological factors such as status and emotional payoff as relevant. The paper highlights how business decisions are rarely purely 'rational' or taken in isolation from the culture and social groups in which the decision-makers are embedded. Sense is given by social contexts which enables or hinders particular ways of sense-making. The paper is an excellent example of the theoretical and practical contribution social science perspectives can bring to the study of cleaner production.

Taking a perspective of relationship management along the whole supply chain, Badi and Murtagh's (2019) *Green supply chain management in construction* provides a systematic literature review of green supply chain management. They map existing work onto a matrix of holistic versus functional focus, and generic construction versus specific subdomain. Functional foci included procurement, waste management and decision-making in purchasing. Specific subdomains included cement, timber, aggregate, ceiling tiles, roads and residential construction. The mapping demonstrates the breadth and complexity of construction projects and the need for research at

multiple levels, both topic and subdomain-specific and holistically. The paper offers an updated and comprehensive definition of green supply chain management, distinguishing objectives and constituent activities. The authors argue that different players in the construction project, for example, contractors, sub-contractors and the design team, own different responsibilities on green supply chain management. A future research agenda is proposed which notes that the unique characteristics of construction require bespoke research approaches and an end-to-end perspective along the built environment supply chain. Badi and Murtagh (2019) argue that sustainability cannot be delivered by a single actor in isolation and that integrative approaches such as supply chain management are essential. Finally, they point out the need for more theory on supply chain management in construction and, in particular, the need for more critical approaches.

Also aiming to consolidate earlier research and noting the need for greater integration along the supply chain, Solaimani and Sedighi (2020) examined papers published between 1998 and 2017 in a systematic literature review to assess how lean construction contributes to sustainability, in *Toward a holistic view on lean sustainable construction: a literature review*. They use a causal-loop diagram to depict the multiple inter-relationships between concepts and processes influencing the environmental, social and economic dimensions of construction. They conclude that almost all lean principles and techniques have the potential to make positive contribution to greater sustainability across all phases of construction although trade-offs between different sustainability dimensions remain unavoidable. Solaimani and Sedighi (2020) echo the argument of Badi and Murtagh (2019), that collaborative effort through the supply chain is essential. Lean approaches can help to optimise sustainability performance through the chain and the reciprocal influences between stakeholders should be recognised.

While collaboration within building projects is an important focus, the issue of scale is increasingly recognised across academia. A recently launched open access journal *Buildings and Cities* makes explicit the need to consider the built environment at different levels of scale. In the paper entitled *MS-ReRO and D-ROSE methods: assessing relational uncertainty and evaluating scenarios' risks and opportunities on multi-scale infrastructure systems*, Salas and Yepes (2019) address this domain in their development of decision support systems that can be applied to strategic urban infrastructure planning. Using a decision support framework for strategic decisions on infrastructure, extended with applications which evaluate alternatives and generate policy measures which consider both risk and opportunity, they applied the models to Spanish cities as a case study. The resulting urban infrastructure plans offer guidance to policy decision-makers in evaluating planning alternative's risks and opportunities in the face of extreme scenarios, enriching current conceptualisations of resilience. Although more development of the models is needed to

extend their capacity for optimising multiple objectives and relative weighting of risks and opportunities, this represents a valuable step forward in automated decision support. By incorporating urban vulnerability assessment into urban infrastructure planning, resilience becomes part of planning processes. This begins to address the principle of integrated planning, argued to be crucial for resilient cities (Lloyds, 2017). The proposed methodology enhances the implementation of an integrated infrastructure planning throughout a territory by maximizing the adaptation capacity at local (city) scale while minimizing risks at overall (national) scale. In its mechanisms for addressing the complexity of urban and infrastructure planning, it shows how applied research can address some of the most critical topical issues in a manner that can be of practical use.

Although a focus on cleaner production tends to consider research primarily on environmental impact, the sustainability pillar of social impact must not be overlooked. The paper entitled *Spatial-temporal dynamics of social value: lessons learnt from two UK nuclear decommissioning case studies* by Mulholland, Ejohwomu and Chan (2019) examines social value. They take the decommissioning of two nuclear sites in the UK as case studies and argue that end-of-life of energy facilities is an area that merits more research. They review existing definitions of social value, and the amorphous nature of the concept, despite its incorporation into UK law. They distinguish between social value as a strategic approach from social value as a performance indicator, arguing that both frames can be mutually influential. Their study provides empirical grounding to demonstrate the dynamic and situated nature of social value – its meaning may change over time and may vary by place

Goel, Ganesh and Kaur (2019b) in the paper *Sustainability integration in the management of construction projects: a morphological analysis of over two decades' research literature* examined the status of academic research on the integration of sustainability into the management of construction projects, finding that integration could be at the level of content or of process. Research to date has tended to focus on content such as construction materials and technologies rather than processes. After mapping the literature starting from the 1990s, they apply the method of morphological analysis to identify underlying dimensions. They find seven dimensions in the literature: motivations, stakeholder orientation, organisational context, project lifecycle stage, benefits, barriers and risks, and document 31 variants of the seven dimensions. The method also allows a systematic derivation of areas not covered and over 200 gaps are noted. The paper offers insights for practitioners drawing their attention to the dimensions and variants that may be salient for their context. For scholars in the area, it is a rich synthesis of work-to-date, with many opportunities identified for future research.

Moving to an organisational focus, Mazutis and Abolina (2019) investigated the 'hard work' of sustainability leaders in *The Five I Model of sustainability leadership: lessons from the Zibi One Planet*

Living sustainable urban development. Based on a case study development in the Canadian capital city, Ottawa, they propose a 5I framework for the work of sustainability leadership: inspirational work (setting and communicating a vision), integration work (stakeholder engagement, partnerships, alliances and networks), identity work (acknowledging the differing identities of multiple stakeholders), implementation work (such as aligning work with strategy, securing funding, lobbying government, etc.) and institutional work (moving organisational culture and alliance relationships towards the vision). The contribution of their work is of value to practitioners as well as scholars in its articulation of the specific work of leaders, moving the discussion on from traits of leaders and styles of leadership.

In the paper *Status quo and future directions of construction and demolition waste research: a critical review*, Wu, Zuo, Zillante, Wang and Yuan (2019) addressed the significant issue of construction and demolition waste (CDW), conducting a comprehensive review of the literature from 1994 to 2018. The themes they identify from the literature include: pollutant composition of CDW, environmental assessment methods, the potential for recycling and its use in practice, tracking material flows and life-cycle analysis, economic feasibility and waste reduction in all stages of the design/ construction/ operation/ demolition cycle. While they map progress, they also point to many areas in which further research and progress in practice is needed. The evidence presented shows that reducing the environmental impact of CDW requires technical, managerial, economic and policy changes, underlying the multi-disciplinary challenge of moving construction towards sustainability.

Finally within this theme, in *Occupants' motivation to protect residential building stock from climate-related overheating: A study in southern England*, Murtagh, Gatersleben and Fife-Schaw (2019) focus on occupants of existing homes and examined their awareness and preparedness to deal with climate-related overheating. In a large-scale survey in the south of England, they asked about previous experience of overheating, knowledge of protective actions, and perceptions of the likelihood of threat and of coping, based on the psychological theory of Protection Motivation. Two-thirds of their sample of over one thousand people had already experienced overheating in the home on at least one occasion. Although there was a moderate level of knowledge on adaptation actions, the measured intention to take action to reduce the risk of overheating was very low. While perception of threat was a factor influencing intention to take action, perception of coping (including one's ability to make changes and the perceived effectiveness of possible changes) was the stronger determinant. The implication for policies relating to individual preparation for global heating is that there is little motivation to do so at present in the south of England and that a focus on developing people's ability to cope is likely to be more effective than communicating the level of threat.

2.1 Insights from social sciences on sustainable construction: Theme synthesis

A clear pattern in the papers is the critical nature of human relationships in making a transition to a more sustainable and resilient built environment: the case has been strongly argued in the papers for the importance of leadership, of collaboration, of managing relationships in the supply chain, and of communicating with stakeholders. A critical concept is that of responsibility yet is this a 'red herring'? On a rapidly heating planet, with knowledge that collaboration is essential, the answer to "Who is responsible for sustainable construction?" is surely "Every construction professional".

A traditional focus of cleaner production has been (production) process based, giving rise to a molecular or materials-oriented view. Within construction, as Theme 2 below demonstrates, this is an essential perspective. However, the papers in Theme 1 illustrate the need for more holistic perspectives at a variety of levels:

- the building product (office block, school, single-family home, etc.) from design to construction to operation to demolition and reuse,
- the supply chain comprising all of the actors and flows (materials, information, finance) necessary to produce a final building product
- the urban built environment including strategic infrastructure, planned at levels of complexity over and above the single construction project.

Research on sustainable and resilient construction is required at more abstract levels as well as on detailed and specific questions. The argument of Wu et al. (2019) for CDW applies more generally: to achieve a more sustainable built environment, change is needed at technical, managerial, economic and policy levels. Further, there are particular challenges in dealing with the complexity of greater sustainability: decision support systems dealing with multiple scales have a role to play but there are other cognitive and non-cognitive processes to address.

3. Theme 2: Sustainable technologies in construction

Green building is the practice of improving the building's efficiency considering not only use of energy, water, and materials but also the site on which it will be placed, with the main goal of reducing the impact on the environment and human health throughout the whole building life cycle (design, construction, operation, maintenance and demolition). A further goal is to reduce construction costs and building maintenance. Improving today's conventional design, building practices and standards, extending the building's life by making it more durable and efficient, minimizing its operative cost, increasing its productivity, and giving a healthier living and working environment to its occupants should be the aspirations of those in the architecture, engineering and construction (AEC) sector.

The normative assumptions guiding research on sustainable construction research are increasingly being acknowledged. This is particularly true of research on methods of sustainable construction, which aims to harness knowledge from diverse scientific, built environment and engineering bodies of knowledge. While change is a constant for human society, the breadth and rate of change have intensified in recent decades. Internationally, there has been upheaval economically, politically, technologically and socially. Change has extended even to how information is perceived, accepted or rejected in what has been termed the 'post-truth era'. Nationally too, there have been significant shifts and developments in society. And beyond all this, the changing climate is already impacting individuals and communities, businesses and governments. Research must respond to these rapidly changing national and international contexts while acknowledging its own agentic potential for transformational change.

The paper by Cianciarullo (2019), entitled *Green Construction-Reduction in environmental impact through alternative pipeline water crossing installation* investigates the environmental and social impacts cross-country pipeline construction can generate. The paper offers the reader a best practice construction methodology, from a 'living' project that trades heavy and polluting equipment for simple electrical motors addressing the implementation of cleaner production. It provides a guide to calculate the impact of pollution and to measure the direct gain of this alternative installation process for society. The study of only one construction process achieved the reduction of more than 12 tonnes of CO₂ emissions to the atmosphere. As just one of numerous construction processes taking place every day in every country, the findings invite us to imagine what could be achieved for other construction methods around the world by applying a similar perspective.

The research work of Lam, Yu, Wu, and Poon (2019) addresses the sustainability impact of construction waste in *Methodology for Upstream Estimation of Construction Waste for New Building Projects*. The authors use Hong Kong as their research context, highlighting the issues that non-inert waste still goes to landfill sites and noting that such sites are rapidly reaching full capacity. They argue that in order to manage and reduce construction waste to landfill, adequate quantification of construction waste is essential. They use three case studies to demonstrate how design information in project documentation including tenders and contracts can inform the estimation of waste volumes and how this can have a significant effect on waste generation on site.

In their paper *Characterizing urban building metabolism with a 4D-GIS model: A case study in China*, Wang, Chen, Duan, Yin and Niu (2019) draw on a case study approach to characterise urban building metabolism using a 4D-GIS model. Specifically, they offer a case study from China - Longwu Village in Shenzhen city. Their model showed spatio-temporal urban patterns and how the material metabolism of buildings evolved, drawing on stock analysis and material flows in combination with

geographic information systems (GIS). The authors make the point that the use and development of 4D-GIS models have the potential to improve urban regeneration projects, reducing material consumption and increase recycling rates of construction waste. Further, the approach could be extended to regional and city planning.

Muller, Esmanioto, Huber, Loures and Canciglieri Jr. (2019) in their paper, *A Systematic Literature Review of Interoperability in the Green Building Information Modeling Lifecycle*, examine the role of Building Information Modelling (BIM) in addressing the role of sustainability in the whole life cycle of a building. They argue that projects can achieve greater sustainability through more effective management supported by BIM-enabled interoperability through the lifecycle. As a methodology they drill down into the research data through a systematic literature review which addressed lifecycle stages, interoperability issues and sustainability factors. They make the argument that systematic processes to develop frameworks for interoperability, combined with BIM as a repository of both data and knowledge, can offer much to realising sustainable buildings.

In *Offsite Construction: Developing a BIM-Based Optimizer for Assembly*, Gbadamosi, Mahamadu, Oyedele, Akinade, Manu, Mahdjoubi and Aigbavboa (2019) make the case for offsite construction through the use of modern approaches and technologies. They offer a case study methodology applying a Building Information Modelling – Optimiser for Assembly (BIM-OfA) assessment system to support consideration of and selection from optimised design options. The system can also facilitate the selection of materials and construction methods based on functionality and characteristics. They put forward a concluding argument for the adoption of the appropriate technologies by the AEC sector with BIM offering an increasingly effective platform for design optimization.

Madurwar and Kartare (2020) investigated sustainable materials in *Design and investigation of sustainable pozzolanic material*. Focusing on cement, they investigated the pozzolanic properties of boiler ash. The investigation found it to be a sustainable and cost-effective solution for cement production and has the effect of minimising CO₂ emissions.

Comparing heating tower and air source heat pumps, in *An Exploration on the Applicability of Heating Tower Heat Pump and Air Source Heat Pump Systems in Different Climatic Regions*, Liu, Jiang, Zhang, Zheng, You and Wei (2019) compare HTHP and ASHP systems in four climatic regions of China. After developing mathematical models for the HTHP and ASHP systems, they conducted field experiments to provide empirical validation. Numerical modelling was used to analyse the energy consumption, economic and system efficiency of each system. While the ASHP system was superior in electrical power input across the four regions, other factors varied by region. The paper provides recommendations on the appropriate considerations for different climactic zones.

Saberian, Li and Setunge (2019) offer a paper on the *Evaluation of Permanent Deformation of a New Pavement Base and Sub-base Containing Unbound Granular Materials, Crumb Rubber and Crushed Glass*. This research experimentally evaluated the behaviour of the combination of construction and demolition materials, crumb rubber, and waste glass for pavement base/subbase applications in terms of a permanent deformation test, which is the most reliable test for evaluation of the behaviour of base and subbase layers. In the study, 100,000 loading cycles were applied to the samples of recycled concrete aggregate and waste crushed rock containing both crumb rubber and crushed glass to evaluate the permanent deformation of the samples. The findings showed that the mix of the waste materials could offer a viable and acceptable solution for base/subbase applications, providing a low carbon alternative to existing materials.

In *Performance-based design of 100% recycled hot-mix asphalt and validation using traffic load simulator* Zaumanis, Arrigada, Wyss, Zeyer, Cavalli and Poulidakos (2019) share their research on performance-based design of 100% recycled hot-mix asphalt and validation using a traffic load simulator. Five different modifications of a wearing coarse mixture were tested to determine if the chosen methods were appropriate for the mixture design and how the 100% recycled mixtures performed in comparison to conventional asphalt. This comprehensive study concludes that the demonstrated performance-based methodology can be used for designing 100% recycled asphalt and that it is safe to apply on public roads.

3.1 Sustainable technologies in construction: Theme synthesis

In recent decades, environmental concerns have become increasingly pressing for business and government, especially in light of the more recent youth movement around the world. It is correct that there should be more of an emphasis on broadening from the environmental impact of the building site to consider construction product burdens more generally. Meanwhile, many private enterprises and/or their respective linked research groups have begun to emphasize environmental information, sharing this information in the form of an environmental product declaration (EPD). To address the change agenda, this needs to have more of an impact.

For many people, the term “Green Building” conjures images of ‘eco-bling’ or technological solutions. It is to be hoped that natural materials, green roofs and passive design are also increasingly seen as important contributors to more sustainable buildings. However, such understanding and images may not attract key building stakeholders and decision-makers. Such stakeholders may work first from the business case and only subsequently consider the wider perceptions of the buildings thus the commercial and aesthetic aspects of the green building are critical elements of gaining consensus. The delivery process of green buildings may differ from ‘business as usual’ and may

include non-standard materials or systems. Increasing the efficiency of energy, water and material use and lessening adverse impacts of buildings on human health and the environment can be accomplished through better contextualisation of the proposed building, its design, construction, operation, maintenance and removal at the end of its lifecycle. When holistic and realistic whole-life costs are calculated, a strong business case for green buildings is emerging. As markets develop, social pressure increases and research points to more solutions, the business case will become even more compelling.

4. Theme 3: Low-carbon construction

As one of the highest energy-intensive sectors, the construction industry is seen as a key area in promoting decarbonisation (Lai et al., 2016). Against this background, this theme called for papers concerning the current status of the construction sector, technology frontiers, development trends and environmental impacts from the perspective of low-carbon pathways. Issues of interest included energy consumption and carbon emissions in current and future construction; energy performance standards and measurement of improvement in low-carbon construction; low-carbon consumption behaviours; policy modelling and technology simulation for low-carbon construction.

Understanding the development status of sustainable construction is necessary to provide future guidance. In *Deductive Content Analysis of Research on Sustainable Construction in India: Current Progress and Future Directions*, Goel, Ganesh and Kaur (2019a) used deductive content analysis as part of a systematic literature review. They describe three critical imbalances in the existing research on sustainable construction in an Indian context: a) a disproportionately higher focus on environmental over social or economic impacts; b) predominance of the final project deliverable rather than the sustainability of processes through which the projects are delivered and managed; c) greater representation in the literature of internal project actors such as clients and contractors compared to external stakeholders such as building occupants and construction workers. They note the likelihood that these biases exist in the literature around construction in other countries and regions.

To judge the efficiency performance of the construction industry from comprehensive perspectives, in *Cost-environment efficiency analysis of construction industry in China: A materials balance approach*, Xian, Yang, Wang, Wei and Huang (2019) propose a modified data envelopment analysis (DEA) method combined with the materials balance principle (MBP) to estimate cost, technical and environmental efficiency and total cost efficiency of the construction sector in China. The method can assess the allocation efficiency of energy inputs, and the costs and benefits of alternative fuels. By quantifying the energy or materials flows through construction processes, the

problem of violating the first law of thermodynamics – as has happened in previous research - is addressed, avoiding the biased estimation of efficiency. The study provides an effective way to assess for alternative energy sources in sustainable construction the often unavoidable compromises between environmental and economic outcomes.

In their paper *The Relationship between Heavy Equipment Cost Efficiency and Cleaner Production in Construction*, Carmichael, Shen and Peansupap (2019) dispel the belief that reduction in emissions from heavy equipment entails additional costs and therefore impacts profit margins. Considering specific construction operations, their study shows that minimising unit cost results in also minimizing unit emissions. The conclusion is that more efficient construction processes have lower environmental impact and that unit emissions can be reduced without increasing unit cost. Equally, where minimal unit cost is not achieved, emissions are higher than necessary.

Case studies can provide substantial experience on low energy and emissions buildings. In the paper by Moncaster, Rasmussen, Malmqvist, Wiberg and Birgisdottir (2019) *Widening understanding of low embodied impact buildings: results and recommendations from 80 multi-national quantitative and qualitative case studies*, a case-study-based meta-analysis and synthesis were used to investigate the decrease of embodied energy and greenhouse gas emissions across the building whole life cycle ('cradle to grave'). The paper aimed to address the problems of sizeable gaps in results caused by differences of methodology and insufficient information. Through comprehensive assessment of the build, repair-maintain-improve and end of life stages of both new-build and refurbishments, and of construction materials, specific recommendations are offered for policy makers, designers and life-cycle analysis modellers which will inform and help to achieve reductions in the embodied impacts of buildings over the whole life cycle.

The role of government in formulating policy to promote cities' low-carbon development is examined in the paper *How National Policies Facilitate Low Carbon City Development: A China Study* by Zhao, Gao and Zuo (2019). They assess the promotional effect of government policies on low carbon cities. Using a novel multi-dimensional analytic framework, national policies in China from 2010 to 2019 were critically analysed. The analysis showed the important role of national policies in shaping the low-carbon evolution of cities. Technological innovation played an important part in facilitating low-carbon city-level policies. Taking building science, architecture and technology as examples, successful policies have led to increased popularity of low carbon technologies and products, including prefabricated and green buildings.

In addition to policy, industry itself should also seek effective ways to realise emission reduction. In Zhang and Zheng's (2020) paper *Reducing building embodied emissions in the design phase: a comparative study on structural alternatives*, the embodied emissions of five structural

systems were compared, namely brick masonry, hollow block masonry, reinforced masonry, reinforced concrete frame and reinforced concrete wall structures. The assessment used a process-based method applied to the same building layout and a unified system boundary, ensuring the fairness of the comparison. After a comprehensive comparison of safety, costs and emissions, recommendations are made for practice involving residential building designs in specialised areas, for example, in seismic regions, concrete frame structures and reinforced masonry are recommended over concrete wall structures for multi-story buildings.

Another approach to reducing embodied carbon is prefabricated construction. In their paper *Factors influencing the application of prefabricated construction in China: From perspectives of technology promotion and cleaner production*, Wu, Yang, Li, Bi, Liu, Li and Zhou (2019) identified 21 influencing factors from the literature which they clustered into five groups, relating to government, market, industry, technology and organisation. Based on a survey of 185 construction stakeholders and 15 interviews, the analysis found government to be the dominant actor. The five most important factors found in the promotion of prefabricated construction in China are, in order of importance, technology lock-in, incentive policies, standardization, cost and entrepreneurial mindset, providing useful implications for stakeholders in prefabricated construction in China.

As an important aspect of sustainable construction, dealing effectively and in an economically viable way with construction waste is necessary. Differing from economic performance assessment of construction waste recycling, in the paper *A model for assessing the economic performance of construction waste reduction*, Hao, Yuan, Liu, Chin and Lu (2019) considered the economic performance of waste reduction strategies and measures across the three phases of waste generation, on-site reduction, and waste disposal. Establishing a system dynamics model, four strategies were identified to promote the economic performance of construction waste reduction: improving waste sorting, reducing illegal dumping, introducing government incentives for recycling and increasing landfill charges. This study provides a quantitative basis for strategy choice, leading to more effective consideration of construction waste disposal.

Gas for residential heating is a significant part of operational energy consumption in the built environment. In the paper *Does the knowledge and acceptance of an increasing block tariffs policy strengthen residents' gas-saving intention? Evidence from household-level survey data*, Li, Liu, Fan and Shen (2019) use logit and probit models to examine the changes in residents' gas-saving intention and consumption characteristics due to different knowledge levels on the increasing block tariffs policy for household gas (IBTsPHG). The results show a number of interesting relationships: residents' knowledge of the IBTsPHG is significantly positively related to gas-saving intention; average gas price is negatively related to willingness to accept the IBTsPHG; more affluent households have lower

willingness to accept the IBTsPHG than less affluent households; and households with wall-mounted gas boilers have higher gas consumption and higher gas-saving intention but lower willingness to accept the IBTsPHG. Further, there were significant relationships between gas-saving intention and household characteristics, including education, occupation and floor area.

4.1 Low-carbon construction: Theme synthesis

The papers in this theme demonstrate that reducing both costs and emissions in the construction sector is viable. Lessons learnt from the existing experience of other countries form valuable contributions to inform policies and strategy. To promote the process of low-carbon construction, supportive policy and incentives from government are seen as essential, and innovation in technology and materials and advances in design are necessary. Detailed and specialised investigation and measures for specific processes are more effective in reducing the emissions of construction sector, rather than more generic approaches. In the later stages of the production lifecycle, the behaviours of building occupants carry significant affects and policy should address this impact. To realise low-carbon construction, a comprehensive consideration of mutual effects of different stakeholders, including those involved in both production and consumption, and joint working of government and industry are needed.

5. Sustainable and resilient construction now and in the future

The authors of papers in this VSI have provided valuable and insightful contributions to the field (or fields) of sustainable and resilient construction. The papers represent a snapshot of current activity – we are aware of other important work taking place which could not meet the time window for the VSI. We also acknowledge that a Call for Papers may not reach all scholars in the area and the absence of work represented in the VSI does not necessarily mean the absence of academic work on a topic.

Developing the argument above that understanding of value changes over time, this can be applied too to environmental assessment – as technology, processes and understanding of environmental sustainability continue to develop, an environmental assessment is necessarily of its time. Just as asbestos was once considered a highly useful construction material for fire-resistance, thermal insulation and strength but is now deemed too dangerous to health to use, the time may come when petrochemical-based insulation, currently amongst the most efficient insulation materials, is seen as too detrimental to use. The overriding point is that cleaner production in the built environment is an ongoing process, and our understanding of core concepts such as

sustainability, resilience, environmental impact and social value, and our methods of evaluation must represent these as processes, not static, one-off measures.

A particularly important contribution on leadership and decision-making showed how business decisions are rarely purely utilitarian and are always set within a social context, influenced by competitors, partners and others. This suggests that, as the importance of sustainability in the construction sector grows, so too does the potential of reaching a tipping point at which sustainable practices become the norm, and firms which do not comply will become increasingly isolated.

An important contribution to the discourse is the need to have data and evidence on the effect and performance of the current and future building stock. This should also be led by the community of researchers who have a story to tell about how best to improve the built environment. At all levels there is a need to connect with society and make informed actions aimed at a safer, healthier and more sustainable world.

For low-carbon construction, energy choice could be a significant factor. In the existing state of energy transition, the penetration of renewable energy in the construction industry cannot be ignored. Renewable energy can be used for material production and operational energy consumption. But the particular utilization paths and contribution for both forms should be investigated and quantified. In considering how renewable energy is utilised, the synergistic effect of avoidance of waste in generation and use of renewable energy is worthy of investigation. Further, the different development status and resources in rural and urban areas will decide their different optimal energy choices in construction. Identifying targeted urban and rural energy strategies is helpful for the promotion of development of low-carbon construction globally.

With the provisos on the reach of the VSI mentioned above, one particular gap was evident in the response to the call for papers: that of the resilient built environment. Of the submissions, only two papers specifically addressed aspects of the already changing global climate although the topic was mentioned in other papers. This is a significant concern: the global mean temperature is already almost 1°C higher than pre-industrial times. The incidence and severity of heatwaves, wildfires, flooding, drought and storms is growing. The weather on all continents has already changed – where is the research on how the construction sector will deliver a built environment in the context of, and to deal with, increasingly severe weather events? There are many related topics on which academia can lead - on design for resilience, on management, leadership and collaboration for resilience, on social value, on cost and business models, on education, on governance and policy - and at all levels: from the individual home to the city to the region. We call for an invigorated research focus on how construction can adapt the built environment to the altered future that is before us all.

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Declaration of interests

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