Lean and Sustainable Construction: State of the Art and Future Directions

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Introduction

Only rapid and drastic reductions in greenhouse gases can prevent ever more widespread devastation and extreme weather events. Every increment in global heating is likely to compound the accelerating effects, according to the International Panel on Climate Change (IPCC), the world's leading authority on climate science (IPCC, 2021). The aim of this special issue is to boost sustainable performance improvements in the construction sector, through raising discussions on advances and future directions of lean and sustainable construction theories and practices.

The construction sector is known to be one of the largest environmental polluters, physical waste producers, and energy consumers throughout its lifecycle. The global construction market was forecast to grow by up to 70% between 2013 and 2025 (HM Government, 2013). The existing built environment is subject to growing global challenges, including decarbonising heating and cooling as well as the construction process, rapid population growth, anthropogenic climate changes and resource scarcity. The Covid-19 crisis further compounds these challenges by creating additional unprecedented social and economic pressures on the sector. This means that sustainability must become an integral part of our day-to-day practice, not an add-on. It is imperative that development, design and construction professionals consider whole-life costs throughout the life of our built environment. There is significant evidence that integrating approaches to lean and sustainable construction can yield substantial benefits to the sector, and that the resulting synergy from combining the two approaches can fulfil the distinct objectives of each. The papers in this special issue are only a small beginning. Much more work is needed.

Sustainable Construction (SC) is the response of the construction sector to the challenge of sustainable development (Huovila and Koskela, 1998). Whilst the focus of the traditional approach to construction project delivery is on cost, time and quality objectives. Sustainability in architecture and construction expands on these criteria to include minimisation of resource depletion, minimisation of environmental degradation, contextual, social and cultural considerations and creating a healthy built environment (Elnokaly and Vyas, 2014). At the same time, it has been argued that Lean Construction (LC) has the potential to contribute towards helping the sector to meet the challenges of sustainable development. LC is mostly attributed to the application of the Transformation-Flow-Value (TFV) theory of production to the construction environment (Koskela, 2000). There are several empirical evidences that, through the focus on the concept of 'waste-minimisation', LC can contribute towards the reduction of pollution, material and energy wastes during design, construction and operation. Similarly, through the concept of 'value', LC could be useful to clients aiming for both business and environmental and social excellence simultaneously.

For these reasons, amongst others, a growing number of studies have been conducted in mainstream construction literature to promote and explore the integration of the two approaches. Recent reviews of studies published over the last three decades have revealed the slow up-take, relatively limited amount of existing research on the topic, significant gaps in knowledge, and the opportunities for improvement that remain unfilled (see for example, de Carvalho, Granja and da Silva 2017; Sarhan, et al., 2019; Solaimani and Sedighi, 2020). Therefore, this special issue provides

a much-needed platform for bringing together the innovative, up-to-date research on trends and developments in lean and sustainable construction.

Research Problem and Context

The relation between lean and sustainable construction has been subject to some attention in both academia and practice. Both initiatives seek to maximise value and reduce waste in construction, but in different ways. From a production management perspective, it has been argued that LC is an innovation in the design process, in the design of the production management system and in the management of production (Koskela, et al., 2010); integrating SC within this framework – in design, in production system design and in production management – will reduce the climate impact of the new, refurbished or retrofitted facility. The lean approach in construction changes the socio-technical system used, in order to create processes that reduce all sorts of resource waste and process waste by improved relationships and practices within the design and delivery itself. These project delivery systems include the Integrated Project Delivery (IPD), Alliancing, Target Value Delivery (TVD), and the Last Planner® System (LPS) for example, as well as other manufacturing-led techniques such as visual management, Just-in-time (JIT) delivery, 5Ss and so on. This is relatively different to the sustainability agenda in construction that has largely focused on the environmental issues through the reduction of energy consumption and carbon emissions, reduced wastage of building materials, reduced use of non-sustainable materials and so on. These reductions are mainly achieved through the application of metrics to evaluate and score performance; that is to achieve credit points needed for obtaining certain certifications and credentials, such as the Building Research Establishment Environmental Assessment Method (BREEAM) and the Leadership in Energy and Environmental Design (LEED). These two views (LC & SC) are conceptually quite different, but it is a common mistake in construction literature and practice to attempt to integrate the lean and sustainable construction initiatives merely through tool-focused frameworks, rather than altered perceptions, relationships, and understandings (Figure 1). They need integrating in the overall process.

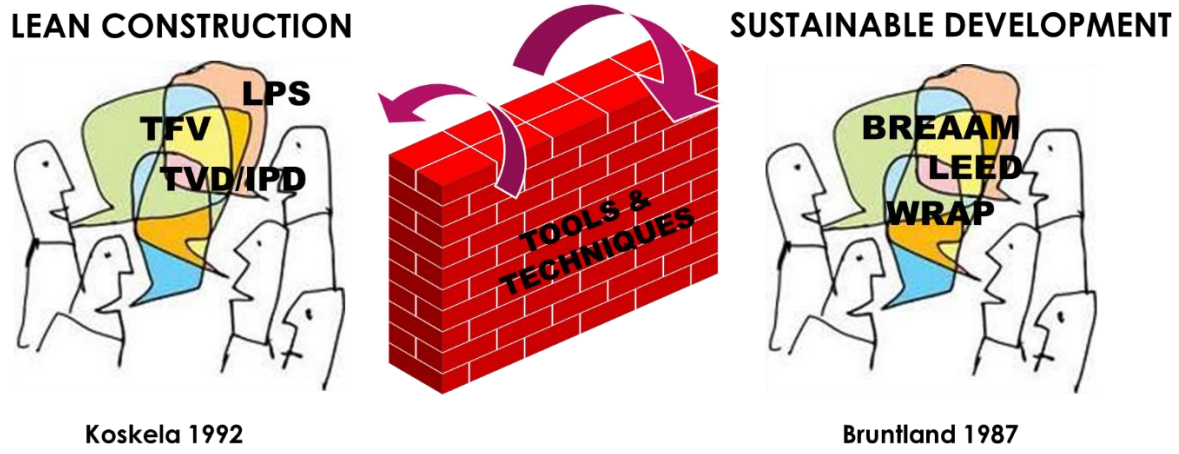

Figure 1: Research problem being addressed in this special issue (adapted from Sarhan, et al., 2019; courtesy: Christine Pasquire)

There seems to be a crucial need for overcoming the limitations of each of the two initiatives when used separately. For example, in studies and approaches to SC, the main focus is often on optimising the design and operational stages of projects, but much less attention is given to the production delivery stage. When comparing the sustainability impacts of designs or materials in buildings, the means and management of production delivery is often overlooked or assumed to be constant between the alternative options. Likewise, SC studies and efforts mainly focus on the health, comfort and wellbeing of occupants and the community, but much less attention is given

to accident-reduction and the safety of workers during the on-site production stage. There seems to be three main limitations in approaches to LC research and practice as identified in a comprehensive review study by Sarhan, et al. (2019). The first limitation is associated with the predominance of a limited customer-focused perspective of 'value'. It is argued that in LC, the main focus is on customer satisfaction and not necessarily the wider society and environmental performance, so value delivery in LC tends to be generally limited to a 'project' rather than a 'global' perspective. This has led some researchers to re-define and expand the concept of the 'customer' to include 'all' stakeholders including the wider environment. Secondly, most LC studies and efforts tend to focus on the production stage (i.e. design and delivery) with less attention given to the project life cycle requirements (e.g. facilities, operations and maintenance); thus limiting the opportunity to take a whole project-life cycle perspective. Thirdly, it is argued that the prevailing conceptualisation of 'waste' in LC is mainly focussed on the elimination of both process and material wastes on-site, but there is scope for taking a wider account for environmental and social impacts. This special issue, therefore, considers the challenges that need to be addressed. It also presents the latest advancements and emerging trends in lean and sustainable construction topics, to stimulate interdisciplinary research and encourage both academics and practitioners to discuss future collaboration.

Overview of this Special Issue

This special issue covers both 'lean' and 'sustainability' topics in the construction field. The guest editors invited researchers from practice and academia to submit original papers that include empirical, analytical or case study approaches. Topics of interest of the call for abstracts included but were not limited to the following:

- Strategies and guiding frameworks for integrating lean and sustainability in construction
- Waste minimisation and the sustainable use of resources
- The role of information and communication technologies (e.g. BIM, Internet of Things and Big data) in supporting lean and/or sustainability improvements in construction
- Technological developments (e.g. the science of materials and Artificial Intelligence) and how they influence lean and/or sustainability in construction
- Challenges and incentives for implementing lean and/or sustainability in different countries and contexts
- Carbon emissions and energy usage in the built environment
- Innovated concepts, tools and techniques in lean and sustainable construction
- Circular Economy in construction
- The changing roles and responsibilities of project stakeholders in lean and sustainable construction projects
- Health, safety and well-being of construction workers and end users
- Evaluations of Just in Time and pre-fabrication techniques from a holistic perspective
- Synergies and inconsistencies between Lean Design and Sustainable Design
- Innovated concepts, tools and techniques in lean and sustainable construction
- Sustainable supply chain management and procurement strategies in construction

Most submitted papers were focussed on innovative methods for integrating lean and sustainable principles and practices. Authors of studies focussed mainly on sustainable construction (e.g. assessing energy performance of buildings) were requested, for example, to reflect on how production processes and methods may influence energy usage and carbon emissions. Likewise, authors of studies largely based on lean construction methodologies (e.g. investigation the role of

LPS on improving production effectiveness) were recommended to reflect on the wider economic, societal and environmental benefits of its use). Thus, it is hoped that this special issue could help to breakdown silos that exist between promoters of each of the two initiatives. It is also expected to encourage interdisciplinary research and future collaboration between academics and practitioners on the topic of lean and sustainable construction (Figure 2).

Overall, the special issue received 46 abstracts from contributing authors based in almost every continent in the World: Europe (Denmark, Poland UK, Turkey, Germany, France, and Ireland); Africa (Nigeria and South Africa); Asia (Malaysia, Sri Lanka, Jordan, UAE, Pakistan, Iran and India); North America (USA); South America (Peru and Brazil) and the Oceania (Australia). Of these, 7 abstracts were excluded due to their irrelevance or poor quality. Consequently, 27 full papers were submitted to the special issue and were subject to a rigorous peer review procedure, which included more than 50 reviewers from all over the world, who are known to be experts in this field of knowledge. Most papers were subject to two rounds of review resulting in the acceptance of 13 high-quality papers out of a total of 27 submitted papers. This represents an acceptance rate of about 48%. The 13 papers that have been selected for publication are clustered in this editorial paper into five main themes as shown and critically discussed below:

- The efficient use of ***energy*** and related management strategies
- Project-life cycle approaches to ***waste-minimisation*** in construction
- Innovative approaches to improving ***productivity*** in construction
- ***Integrated Models*** for improving sustainability in construction
- ***Drivers and barriers*** to SC in developing countries.

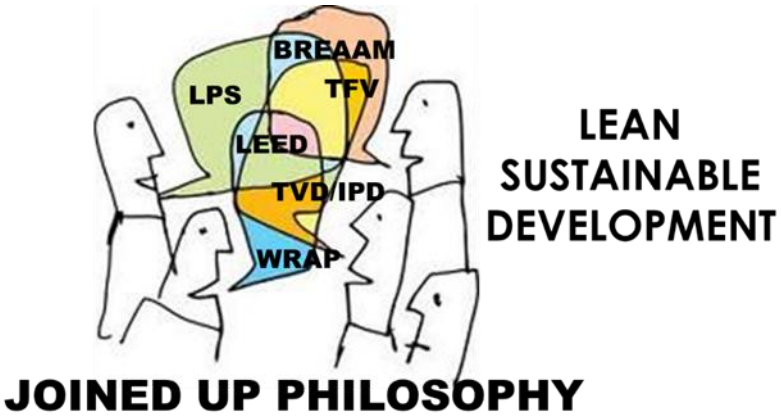

Figure 2: Towards a joint up philosophy for integrating lean and sustainable construction (adapted from Sarhan, et al., 2019; courtesy: Christine Pasquire)

The efficient use of energy and related management strategies

Both sustainable and lean construction initiatives aim for the reduction of energy use. In SC, efforts are focussed on optimising energy performance of buildings, during maintenance and operational stages, to lessen the impact of climate change and global warming, whilst LC focusses on minimising energy usage during the production stage. Both consider the design stage as essential in achieving their targets. Integrating both initiatives could lead to more efficient usage of energy throughout the construction project life cycle. In this special issue, **Ahmed, Saboor, Almarzooqi, Alshamsi, Alketbi and Almarei** adopt semi-structured interviews and surveys to compare the energy performance of three different types of educational buildings within Higher Education

establishments in the UAE**.** Their study identifies the type of building which has the best energy performance, but it also looks at the topic of energy from a 'lean' perspective by recognising that there is an amount of energy that is 'wasted', which implies that none of the buildings are fully and effectively consuming the energy. This finding could have a significant implication on the UAE government's policies and approach to providing a sustainable environmental infrastructure. It also indicates the importance of raising the awareness of the end users and occupants of the buildings about the value of embracing lean and sustainable thinking.

Within this same topic of minimising energy use and emissions, **Wandahl, Pérez, Salling, Neve, Lerche and Petersen** conduct an exploratory case study in four domestic housing renovation projects in Denmark, to investigate the means and the extent to which an efficient and highly productive construction process can contribute to the European Green Deal's Renovation Wave efforts in achieving carbon dioxide savings. Traditionally, efforts to reduce carbon emissions tend to focus on the operational energy of the building (i.e. the final product). However, this study sheds some empirical light on the role and importance of considering the embodied energy of the building's construction process, especially in renovation projects. This study is novel because it establishes the link between construction process improvements, using LC tools and techniques, and reduced energy consumption and emissions, which is becoming a focal point worldwide. The original findings of this study have the potential to support politicians and infrastructural developers in decision-making for a more sustainable built environment.

Project life-cycle approaches to waste-minimisation in construction

The concepts of waste-minimisation and value-maximisation are arguably the most obvious connections between the LC and SC initiatives. However, each initiative focusses on addressing different types of 'waste' and dimensions of 'value'. LC focusses on eliminating or minimising both material and process wastes, and it aims for maximising 'value' at a project level; while SC pays more attention to reducing material and environmental wastes, and it considers the concept of value from a global perspective. The papers accepted for publication in this special issue contribute to existing knowledge in this domain by exploring and developing novel approaches to waste minimisation in construction. For example, **Zighan, and Abualqumboz** investigate the causes and sources of physical waste in construction projects, through interviewing thirty professionals in the Jordanian construction. Their findings show the significance of proactively contemplating the various sources of waste as early as the concept phase of the construction project. Their study also informs practitioners and academics about the mitigating actions that can be designed to tackle the waste before it emerges. The study then concludes by providing a holistic and proactive waste management framework for practitioners to adopt in the early stages of the construction project.

On the same topic of waste-minimisation, ecological modernisation is introduced as a concept that seeks to delink sector growth from environmental damage It is, however, a concept that is underexplored in construction literature. To help fill this gap in knowledge, **Al-Hamadani, Egbelakin, Sher and Von Meding** adopt a research survey to investigate the drivers of applying ecological modernisation, to reduce construction and demolition wastes currently plaguing the construction sector of New South Wales. Their study reveals five important drivers for ecological modernisation application to construction waste-minimisation. The critical measures for each of these five drivers, within the context of the NSW construction sector, are also identified. The findings of this study could be used as a stepping-stone to inform construction waste-minimisation (CWM) policymaking and future CWM-related studies.

Innovative approaches to improving productivity in construction

Construction projects are subject to substantial inefficiencies and rework stemming from a proliferation of non-value-adding activities and institutionalised wastes embedded within the traditional approach to project delivery (Sarhan, Pasquire and King, 2017). This prevailing approach works against the construction sector's economic and environmental sustainability. In contrast, digital fabrication and prefabrication are production approaches that have the potential to lead to significant productivity and sustainability improvements in the sector. The rapid advances in both the science of materials and digital technologies have prompted architects and structural engineers to modify their design optimisation methodologies. In digital fabrication, designers face the challenge of adjusting the manufacturing technologies and the types or properties of materials used, to meet the desired aesthetic requirements. This is also possible through the design optimisation of structural elements. Building on a comprehensive review of interdisciplinary design trends in the application of timber and wood-based materials, and a comparative analysis of contemporary fabrication techniques, **Stefańska, Cygan and Kinga Batte** use a case study to present new tools and methods for the optimisation of structural elements. The findings of their case study indicate the need for multivariate optimisation, especially free-form structures, favours the use of structural forms based on the paraboloid arches, and recommends the use of Computerized Numerical Control (CNC) tooling to achieve precision while saving time and material. These findings are significant in terms of providing suggestions for an effective research-based design that can help to maximise the sustainable and productivity benefits of digital fabrication in construction.

On a similar topic, **Mossman and Sarhan** explore how offsite fabrication can be synchronised with production and assembly on-site. The study draws on two case-studies and the authors' experiences in the context of a critical review of literature on Flow, Capacity, Buffers, Critical Path Method (CPM), the Last Planner® System (LPS) and Just-in-Time (JIT). The aim of their study is to propose ways for improving production predictability and the coordination between off-site fabricators and their customers on-site in prefabricated construction projects. The findings of their study suggest that failing to fully implement JIT across an entire production system can reduce both productivity and profitability and lead to client dissatisfaction. Their study also criticises CPM for its inadequacies in controlling work and managing flow in construction projects. Instead, they recommend the use of the LPS and other lean systems, as an effective way to create a steady predictable flow on-site. Their study concludes by offering three propositions for future empirical investigation, and by generating new questions and ideas for further research.

As an elaboration, the LPS for production planning and control is a key tool of LC that prioritises flow efficiency in construction projects by addressing workflow variability and waste elimination. Introducing LPS on a project can influence social dynamics; thus, enabling a complete LPS implementation to achieve its full potential, arguably, requires a precise set of skills and competencies for dealing with the softer side of human interaction. For this reason, **Power, Sinnott, and Lynch** adopt a mixed-methods approach utilising case study design to evaluate how the presence of a dedicated knowledgeable and competent LPS Facilitator contributes to improved construction flow, efficiency, and productivity. This paper contributes to academic and practitioner communities by presenting case study evidence, from a live construction project, that the presence of the LPS Facilitator can substantially improve project performance and success.

Construction is labour-intensive. The performance of construction projects depends on the construction employees' productivity and their value-adding activities. Thus, in order to maximise

value, it is important that employees feel psychologically safe at work. LC practices (e.g. LPS and visual management) have been shown to be effective in terms of improving health and safety in construction projects. There are few studies, however, that have sought to study the link between LC and psychological safety in construction. To address this gap in knowledge, **Demirkesen, Sadikoglu and Jayamanne** conduct semi-structured interviews and a survey with employees working in U.S. construction companies, to assess the level of psychological safety in both Lean and non-Lean (traditional) construction projects. Their study presents empirical evidence that psychological safety is problematic within teams in the construction sector. However, the findings of their study suggest that companies adopting the Lean philosophy are more successful in managing psychological safety in construction projects. The study contributes to theory by developing a conceptual framework that considers the interactions that may exist among lean principles, psychological safety, and occupational health and safety in construction. Practically, this study provides construction companies with insights on how to measure psychological safety and manage its impacts accordingly.

Integrated models for improving sustainability in construction

The construction sector faces sustainability challenges due to low productivity, waste, safety, and environmental hazards attributed to existing construction management practices. LC has been widely accepted as a robust philosophy to enable SC practices. However, more of the existing academic literature and sector efforts are inclined towards defining the integration between LC and sustainability through the use of certain tools and techniques. Few studies have been undertaken to tackle the challenges of achieving sustainable goals in construction projects within the current practices. For this reason, **Aslam, Gao, and Smith** conduct a meta-analysis to identify the challenges for implementing SC by the construction sector and to present a strategy for overcoming the main challenges of SC in the traditional construction management practice using LC methodologies. The study contributes to theory by helping academics and practitioners to understand the concepts and rationale for integrating LC and SC based on their principles and drivers. Practically, it provides construction companies with a Lean Approaching Sustainability Tools (LAST) matrix that is developed in this study to provide guidelines to the construction stakeholders for the selection of LC practices/tools/techniques in overcoming the top 15 most important SC challenges identified in this study. Interestingly, the authors of this study shed light on and recommend future studies to focus on evaluating the role of LC facilitators in supporting the implementation of their LAST strategy – a topic that is also explored, but in more detail, in this special issue by **Power, Sinnott, and Lynch.**

Under this same theme, Circular Economy (CE) is introduced as a new approach to sustainable development. It aims at restoring any damage done in resource acquisition, while minimising waste throughout the production process and in the life history of the product (Murray, Skene and Haynes, 2017). Seeing that the construction sector is responsible for the extraction of raw materials and the generation of waste in large quantities, it is regarded as an opportune sector for transition to a circular economy. The existing literature of CE in construction is focused on raising awareness on CE and its applicability to various phases of a construction project. A consolidated picture of CE strategies for different stages of the building is missing. Thus, **Smitha and Thomas** attempt to address this gap in knowledge by developing an integrated model of CE that comprehensively identifies the strategies applicable to the various stages in the Indian construction sector. Their study used a multi-criteria decision-making method to develop an index for measuring the circularity potential in construction materials, based on attributes developed from literature review and the analysis of a questionnaire survey. The Circular Economy Potential Index (CEPI)

developed in this study could be used to support decision-making in the initial stage of construction projects and help to compare the circularity of materials.

Similarly, eco-innovation (EI) is presented as a concept that integrates eco-consciousness within innovation development. Although EI has been widely applied in manufacturing, its adoption in construction remains patchy. To address this gap in knowledge, **Isa and Abidin** explore the level of adoption of eco-innovation and investigate its drivers in contractor firms, through the use of a questionnaire survey that targets the largest contractor firms in Malaysia. Their study reveals that the level of EI adoption in large contractor firms is still only moderate. It also identifies the EI components and driving factors that can help contractor firms to adopt EI practices effectively. The findings of their study provide future studies with the fundamental knowledge needed for developing a framework on strategies to increase the rate of adoption of EI amongst contracting firms in Malaysia.

Drivers and barriers to SC in developing countries

Sustainability has been receiving significant attention in construction sectors in developed countries; however, this seems to be less true for developing countries. Therefore, **Khalil, Rathnasinghe and Kulatunga** conduct a mixed-methods research approach consisting of a questionnaire survey and expert interviews to investigate the challenges of implementing SC practices in Libya. In their study, three main challenges were identified: steering and knowledge challenges; technological and cost challenges; and organisational and technical challenges. Under those three categories, seven sub-challenges were identified as highly significant for the successful implementation of SC in Libya. This study contributes to knowledge by providing readers with an in-depth understanding of the complexities related to integrating sustainability in the Libyan construction sector. It contributes to practice by proposing strategies to avoid or minimise the identified challenges and their consequences.

On a similar topic, it has been adjudged that the construction sector is a slow adopter of new digital technologies, such as big data analytics (BDA), that are needed to improve its service delivery. The implication of this slow adoption is the lack, or relatively limited level, of innovation and unsustainable project delivery that has characterised the sector in most countries, particularly in developing ones. For this reason, **Aghimien, Ikuabe, Aigbavboa, Oke and Shirinda** use a quantitative survey to investigate the factors influencing the intention of construction organisations in South Africa to adopt BDA, using the unified theory of technology adoption and use of technology (UTAUT) model. The findings of their study could benefit South African construction organisations to better understand the factors that they need to consider, if they are to derive the positive outcomes of adopting BDA in their organisation. In addition, their study provides an excellent theoretical background for future research on construction digitalisation, in particular BDA adoption.

Concluding Discussion and Recommendations

A growing body of knowledge is emerging from the construction research communities, in relation to assessing the synergies and inconsistencies between lean and sustainable construction. Some studies and practitioner efforts have been conducted to develop frameworks for integrating the two initiatives. There is little doubt that this integration can lead to better results than what each can achieve on its own. Most of those few studies that have been conducted have merely utilised tool-oriented approaches for implementation, without considering the mind-set barriers and the

lack of shared understanding that exist between promoters of each of the two initiatives (Figure 1).

What we need now is more empirical research on the topic. This special issue was designed to kickstart this work, and to encourage a shift in the mindset and perceptions needed for enabling a joint-up philosophy of lean sustainable development (Figure 2). The five themes that emerged out of the papers published in this special issue (energy; waste-minimisation; productivity, integrated models, and drivers and barriers to SC in developing countries) represent the state of the art on the topic of lean and sustainable construction. Thus, construction academics are encouraged to collaborate with their practitioner colleagues in conducting interdisciplinary research to explore the topics within these themes in more depth and detail.

The papers published in this special issue provide novel contributions to knowledge, with the potential of leading to serious implications for practice and policy. Under the theme of 'Energy', there are some important contributions that include, for example, the provision of some empirical evidence on the importance of considering the embedded energy of the building's construction process when attempting to assess and reduce energy consumption and emissions of buildings. Another important contribution is that of shedding empirical light on the significance of considering the amount of 'wasted' energy when comparing between the energy performance of different buildings.

Then, under the theme of 'Waste-Minimisation', the importance of proactively contemplating the various sources of waste as early as the concept phase of both design and construction is highlighted. Furthermore, the idea of adopting the concept of ecological modernisation for waste-minimisation in construction is relatively new and worth further empirical investigation. While, under the theme of 'productivity', an innovative and effective research-based design has been provided that can help to advance digital fabrication practice in construction. Additionally, some important propositions for improving production predictability and the coordination between off-site fabricators and their customers on-site in prefabricated construction projects. Furthermore, a novel framework has been developed and presented to reveal the relations and anticipated interactions between LC principles, psychological safety, and occupational health and safety in construction. Finally, the competencies and importance of the role of the LPS facilitator has been highlighted to support construction companies with improving their value delivery.

Under the 'Integrated Models' theme, an innovative matrix is developed to present guidelines to construction companies and stakeholders on the selection of appropriate LC practices/tools/techniques for overcoming SC implementation challenges. In addition, a novel index for measuring the circularity potential in construction materials is developed and presented. Similarly, the concept of eco-innovation, which is an underexplored topic in construction, is presented, including an identification of its main components and driving factors to help contractor firms to adopt EI practices effectively. Finally, under the 'Drivers and Barriers' theme, an examination of the challenges to sustainable construction in a developing country is provided. This also included proposing strategies for avoiding or minimising the impacts of the identified challenges. The identification of drivers to the adoption of BDA also represents an important contribution to knowledge in the field of construction digitalisation, which plays an important role in supporting lean and sustainable construction practice. Although most of the studies included in this special issue are country specific, it is believed that many of the findings may be carefully generalized, in an attempt to promote the 'Lean Sustainable Development' of our built environments.

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