A Proposed Conceptual Framework for Computational Design Sustainability in Industrialized Building

Sahar SOLTANI[1&2*], Victor BUNSTER[1], and Duncan MAXWELL[1]

[1] *Future Building Initiative, Monash University, Melbourne, Australia*
[2] *Australian Research Center for Interactive and Virtual Environments, University of South Australia, Adelaide, Australia*
[*] *Corresponding author's e-mail: sahar.soltani@monash.edu*

ABSTRACT

The construction industry has benefited from the recent methodological advancements in Computational Design (CD) and its associated technological developments. However, the multifaceted challenges faced by the construction industry have limited its capacity to achieve global sustainability goals. In this context, Industrialized Building (IB) has opened new avenues to take advantage of technology while promoting the incorporation of sustainability principles to mainstream construction problems. Despite its great potential, the literature in this area is fragmented, and the relationship between various aspects of these topics is not fully understood. This paper aims to bring awareness to the potential integration of IB and CD in promoting sustainability, thereby advancing the understanding of the topic by proposing this integration for future investigations and unraveling their relationships and underpinning ideas. The critical discussion presented in this paper proposes a common ground on which to build new knowledge in seeking to disclose conceptual patterns and links instead of specific causal mechanisms. We propose that this integration paves the way for creating a trade-off structure to manage these multifaceted and complex factors through "satisficing" – finding the satisfactory solutions rather than the optimized ones – the design, operation and delivery of a building project (and its construction value chain) in a more sustainable way.

KEYWORDS

Computational Design Sustainability; Computational design; Sustainable construction; Industrialized Building, Offsite construction

INTRODUCTION

Globally, buildings and the construction sector are responsible for 35% of the final energy use and 38% of the energy and process-related CO2 emissions, 30% of the waste and 32% of the use of natural resources (Purchase et al., 2022, UNE, 2020). On average, in Australia, about one ton of solid waste is generated per person per year, which goes to landfills (AGO 2002d). Construction and demolition of buildings contribute 30-40% of this waste. With the rapid urbanization and densification of the cities, the detrimental impact of building and construction continues to surge as the population grows. Sustainable construction is a trending concept that aims to mitigate some of these adverse impacts during the whole life cycle by promoting the principles of sustainability in its three main pillars; environmental, social, and economic. One of the effective methods of delivering greener construction is the Industrialized Building (IB) (Yunus and Yang, 2012). IB promotes sustainability from a controlled production environment, minimization of waste generation, extensive usage of energy-efficient building materials, practical logistics, and long-term economic stability, contributing to better investment in environmental technologies. IB, thereby, presents viable opportunities for integrated systems and automation in construction while allowing more flexible approaches to construction using advanced methodologies.

However, the complexity of the grand challenges in the rather fragmented construction sector bound with the multifaceted factors, such as dealing with massive networks of stakeholders and organizations, has made it difficult to fully embrace sustainability goals across all the pillars of sustainability. Although the construction sector has started to involve more sustainable-oriented approaches through technological advancements in the contemporary methods of IB, the adaptation does not seem to be happening at the same rate as in other sectors and industries (Gallo et al. 2021). It is an underestimation to limit the role of technology to the mere application of tools within ICT, but it can be employed to empower many advanced methodologies and processes. In this regard, Computational Design (CD) is one of the robust methodologies that explore the design problems through computation with flexible methods and techniques. CD brings forth devices for developing adaptable solutions and methodologies suitable for solving a problem, which can be rescaled and adjusted to solve another problem across different industries (Soltani et al., 2020). Such advancements are beyond the limitations of a particular technological tool or instrument but rather are about generating innovative methodologies and integrated processes. Despite this potential, the integration between CD and IB to endorse sustainability has not been very well understood, and the current applied approaches do not represent a coherent synthesis. This will lead to massive missed opportunities that could have been otherwise provided through a broadly used integrated framework.

This article, as a position paper, takes a theoretical approach to investigate these concepts in order to propose an argument and set the scene for a critical conceptualization and mapping. This leads to the core argument aimed at encouraging a more integrated approach, bringing awareness to the essential role of sustainability to reflect in the whole life cycle as facilitated by technology and CD methodologies.

Sustainable Construction through Industrialized Building

The Conseil International du Batiment (CIB) defines sustainable construction according to its dependency on resources and ecological principles in order to build and operate a healthy environment. CIB also introduces seven elements through which the whole life cycle of a building can be considered in various stages of construction sustainability. These elements include: reducing resource consumption, reusing resources, using recyclable resources, protecting nature, eliminating toxins, applying life-cycle costing, and emphasizing quality. According to Sassi (2006), the main goals of sustainable construction are to decrease the effects of building on the environment from birth to death and focus on people's psychological and physical well-being through socially responsible and sustainable design. Sustainable development can be enhanced through modularization and industrialization (Jelodar et al., 2013). Recently, new approaches and concepts such as Industry 4.0 (i.e., Construction 4.0) and Circular Economy have gained momentum in the field of industrialized construction, promising to enhance the benefits of offsite construction.

IB represents an opportunity to introduce sustainable features to the construction process and enhance its sustainability. IB is a broad term referring to a wide variety of methods and strategies including prefabrication, modularization, offsite fabrication, or modern methods of construction (MMC) (Kedir and Hall, 2019). According to Lessing, J. (2006), Industrialized Housing Systems are characterized by nine elements that need to be integrated and reinforced by continuous improvements. These characteristics include: structured and systematized planning and control of processes; technical solutions that are developed and structured into systems; building parts that are manufactured in facilities offsite; long-term relationships of the participants; logistics and the flow of materials and related information that is integrated with design; production and building processes; use of ICT tools and systems support structuring and managing information throughout all processes and technical systems; reuse of experience and measurements about process performance to reinforce best practice; and thorough knowledge about different customer segments' needs, priorities and expectations (Lessing and Stehn, 2019). In this context, sustainability can be achieved in IB through streamlined design, controlled production environment, minimization of waste generation, extensive usage of energy-efficient building material, effective logistics, long term economic stability, safer operation and higher stakeholder engagement, and greater opportunities for integrated systems and automation in construction.

Computational Design Leveraging Sustainability

The Design Method Movements in the 1960s initiated a revolutionary effort, triggering innovative integrations of methods in design research. The movement started a series of formal and collective investigations to understand design processes. It aimed to enable collaborative design for complex design problems and employ computers to facilitate the process, amongst other goals. Computational design (CD) is a product of such efforts. CD refers to a set of processes through which design problems are explored with computational capabilities. Common approaches to CD include parametric design, generative design, performance-based design, and algorithmic design (Caetano et al., 2020).

Computational Design Sustainability (Soltani et al., 2020), as an interdisciplinary and collaborative field, aims to advance knowledge in both computational design and sustainability by developing integrated computational approaches while balancing sustainability pillars. The key argument is that computation and sustainability move each other forward by adapting methods developed to solve one problem in a discipline to tackle another problem in the same or other disciplines. An example of a CDS approach is the work of Haidar et al. (2019), studying and employing parametric design in empowering sustainable processes and recycling. Figure 1 shows the conceptual framework of CDS.

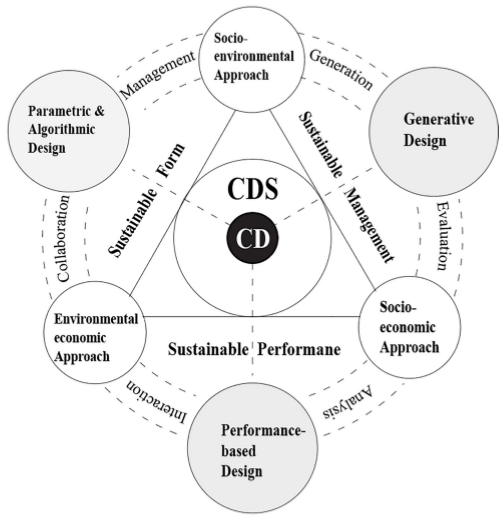

Figure 1. Computational Design Framework (Soltani et al., 2020)

METHODS

This paper takes a theoretical approach to lay the groundwork for the topic's conceptual investigation (Jaakkola, 2020). This investigation builds on the theories in CD, sustainability, and IB, focusing on the concepts of complementary value in conceptualizing and mapping them into one unified framework. This leads to a theory synthesis to enhance understanding and unravel the rather multifaceted relationships in these areas, introducing CDS in IB. In doing so, a number of fundamental theories have been selected for CD and its categories from Caetano et al. (2020), CDS from Soltani et al. (2020), and IB from Lessing (2015). Figure 2 illustrates a primary synthesis of these three concepts to initiate a deeper investigation.

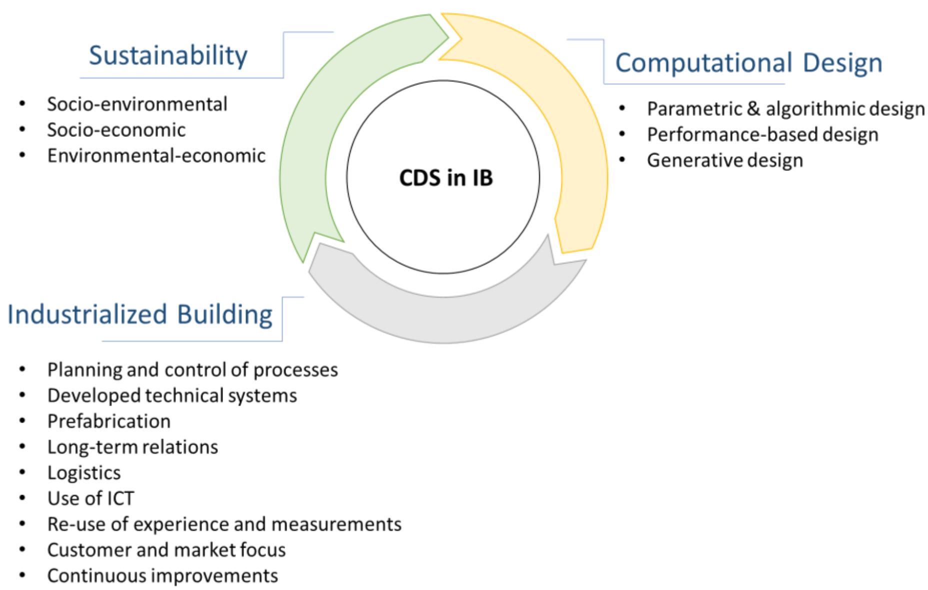

Figure 2. The proposed conceptual framework of CDS in IB

In order to enable a discussion on this emerging topic as a proposed concept, evidence from the current literature has been sought through a systematic search. The search was conducted through Scopus, focusing on scholarly publications in the past ten years. The literature search does not aim to present a thorough review of the current state, rather it intends to support the paper's argument that the integration of IB and CDS has not been well established, and that the combination entails great potential and value. The employed keywords include variations from the main three terms of sustainability, computational design (also design computation, computation, generative design, parametric design, algorithmic design, and performance-based design as variants), and industrialized building (and variants including, manufacturing, building, industriali*, fabrication, modulari*, MMC, and prefab). This search resulted in a total number of 63 articles, out of which 10 papers have been selected after reviewing the title and abstracts, with one paper being a review article. To enhance the findings, the query has been performed through the industry firms and companies in the construction sector.

RESULTS AND DISCUSSION

Table 1 summarizes the results of the literature review. Most of the publications found focus on environmental sustainability and performance assessment. Parametric design is the most utilized technique individually (Chen and Lu, 2018) and in combination with other methods and technologies (Agustí-Juan and Habert, 2017). Within the IB realm, these methods have been mostly used for material fabrication (Agustí-Juan and Habert, 2017, Mayencourt and Mueller, 2020, Yazici and Tanacan, 2020) and DFMA (Chen and Lu, 2018). The limited number papers within IB suggests that the opportunities within CD to promote sustainability are currently under studied. This aligns with the recent studies pointing to the great potential of platforms in tackling complex design problems. In a study of integrated industrial building design (IIBD) through parametric design methods in optimizing the automated structural design, Reisinger et al. (2021) highlight the efficiency of such methodologies in leveraging multidisciplinary design optimization and emphasize its wider application in future research.

Table 1. Summary of the papers employing CD methods to endorse sustainability in the context of IB

Author	**Industrialized Building**	**Computational Design Sustainability**	
		Computational design approach	**Sustainability**
Reisinger et al. (2021)	Integrated industrial building design (IIBD)	Parametric design	Environmental sustainability
Djokikj and Jovanova (2021)	Structural design	Generative and parametric design	Sustainable manufacturing

Gernay and Khorasani (2020)	Structural design and fire safety	Performance-based design	Environmental-economic sustainability
Mayencourt and Mueller (2020)	Material-efficient: mass timber beams	Computational optimization	Efficient use of materials
Yazici and Tanacan (2020)	Material Fabrication	Material-based Computational Design (MCD)	Sustainable manufacturing
Chen and Lu (2018)	DFMA	Parametric design	Environmental sustainability
Agustí-Juan and Habert (2017)	Material fabrication	Combination of CD and robotics	LCA: Environmental assessment
Siani (2015)	Digital product manufacturing	Parametric design	Environmental sustainability
Spiegelhalter (2012)	Manufacturing	Parametric design	Environmental sustainability

While the literature review outlines a significant academic research gap, industry dynamics are trending towards the integration of CDS and IB. Skanska USA Building, e.g., utilizes an Embodied Carbon in Construction Calculator (EC3) – in partnership with Microsoft and Autodesk – to assess the impact of their choices of materials and procurement processes to reduce carbon emission in the life cycle of a construction project (Skanska 2019). Similar approaches have been put forward by Laing O'Rourke, a construction and engineering company, in their digital carbon calculator platform (O’Rourke 2022). The tool allows real time data synchronization and creates a carbon heatmap, establishing a log of all the changes in the model and carbon measurement.

Lendlease’s Podium is another industry initiative with sustainability ambitions in digital building. Rather than aiming for digitizing one part of the value chain, the platform establishes a unified project data system, using a range of technologies and methods, such as AI and Digital Twin. Podium Twin, e.g., has been utilized in testing the possibility of building a multi-storey complex from sustainable timber in Melbourne, Australia (WEF 2021). The platform is being expanded towards supply chain automation for more integration across all project stages. Such initiatives are exploring the use of project data beyond the simple model integration as currently allowed by mainstream BIM platforms, which often lack a holistic approach to linking not only the data but also the stakeholders for a more informed decision making.

CONCLUSION

This study explores the potential of formalizing an integrated approach to the relationship between CD and IB. This is shown to be a significant gap in the current literature while a trend of growing momentum in the industry. One advantage of defining this integrated approach is to better understand the trade-offs that need to be addressed towards outcomes capable of satisficing the multiple factors involved in a construction project rather than optimizing a single factor. In this context, integrative design platforms are being developed to focus on various methods, tools, and technologies to tackle the fragmentation resulting from the complexity of current construction projects. The proposed integrated approach makes use of CD principles as a means to enable a shift from common technology-focused strategies towards leveraging the underlying processes, methods, and systems capable of driving innovation. This opens opportunities for adaptation by enabling thoughtful planning, development, and more informed decision making.

Within the scope of this study, a holistic conceptualization has been presented. Future research will address in depth specific relationships between CD categories and related elements of IB in all sustainability dimensions. This also includes emerging ideas such as computational construction, digital platforms, and decision-support systems towards facilitating integrated and collaborative approaches. Further work should extend the outcomes of this study to enable empirical investigation and more thorough case study explorations.

REFERENCES

AGUSTÍ-JUAN, I. & HABERT, G. 2017. Environmental design guidelines for digital fabrication. *Journal of Cleaner Production,* 142**,** 2780-2791.

CAETANO, I., SANTOS, L. & LEITÃO, A. 2020. Computational design in architecture: Defining parametric, generative, and algorithmic design. *Frontiers of Architectural Research,* 9**,** 287-300.

CHEN, K. & LU, W. 2018. Design for manufacture and assembly oriented design approach to a curtain wall system: A case study of a commercial building in Wuhan, China. *Sustainability (Switzerland),* 10.

DJOKIKJ, J. & JOVANOVA, J. Generative design of a large-scale nonhomogeneous structures. 17th IFAC Symposium on Information Control Problems in Manufacturing INCOM 2021, 2021. Elsevier B.V., 773-779.

GERNAY, T. & KHORASANI, N. E. 2020. Recommendations for performance-based fire design of composite steel buildings using computational analysis. *Journal of Constructional Steel Research,* 166.

HAIDAR, A., UNDERWOOD, J. & COATES, P. 2019. Smart processes for smart buildings: ‘sustainable processes’, ‘recyclable processes’ and ‘building seeds’ in parametric design. *Architectural Engineering and Design Management,* 15**,** 402-429.

JAAKKOLA, E. 2020. Designing conceptual articles: four approaches. *AMS Review,* 10**,** 18-26.

JELODAR, M. B., JAAFAR, M. S. & YIU, T. W. 2013. In Search of Sustainability: Constructability Application and Contract Management in Malaysian Industrialized

Building Systems. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction,* 5**,** 196-204.

KEDIR, F. & HALL, D. 2019. *Assessing the Environmental Implications of Industrialized Housing: a Systematic Literature Review*. Modular and Offsite Construction Summit. Banff, Canada.

LESSING, J. 2015 . Industrialised H ouse-B uilding. PhD Thesis, Lund University.

MAYENCOURT, P. & MUELLER, C. 2020. Hybrid analytical and computational optimization methodology for structural shaping: Material-efficient mass timber beams. *Engineering Structures,* 215.

O'ROURKE, LAING. 2022. Laing O'Rourke's new carbon calculator reduces carbon in project designs, viewed 30 May 2022. <https://www.laingorourke.com/company/press-releases/2022/laing-o-rourke-s-new-carbon-calculator-reduces-carbon-in-project-designs/>

PURCHASE, C. K., AL ZULAYQ, D. M., O'BRIEN, B. T., KOWALEWSKI, M. J., BERENJIAN, A., TARIGHALESLAMI, A. H. & SEIFAN, M. 2022. Circular Economy of Construction and Demolition Waste: A Literature Review on Lessons, Challenges, and Benefits. *Materials,* 15**,** 76.

REISINGER, J., KNOLL, M. & KOVACIC, I. 2021. Design space exploration for flexibility assessment and decision making support in integrated industrial building design. *Optimization and Engineering,* 22**,** 1693-1725.

SASSI, P. 2006. *Strategies for sustainable architecture / Paola Sassi,* Oxford, Taylor & Francis.

SIANI, R. 2015. The sustainable potential of digital fabrication process and de-standardisation of architectural products. *Progress in Clean Energy, Volume 2: Novel Systems and Applications.* Springer International Publishing.

SKANSKA. 2019. Skanska Conceives Solution for Calculating Embodied Carbon in Construction Materials, Announces Transition to Open-Source Tool, viewed 30 May 2022. <https://www.usa.skanska.com/who-we-are/media/press-releases/238250/ Skanska-Conceives-Solution-for-Calculating-Embodied-Carbon-in-Construction-Materials%2C-Announces-Transition-to-OpenSource-Tool>

SOLTANI, S., GUIMARÃES, G., LIAO, P., CALIXTO, V. & GU, N. 2020. *Computational Design Sustainability: A Conceptual Framework for Built Environment Research*.

SPIEGELHALTER, T. 2012. Designing and manufacturing zero fossil energy buildings with 3D/4D parametric performance tools. *International Journal of Architectonic, Spatial, and Environmental Design,* 6**,** 27-41.

UNE, U. N. E. P. 2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary.

WEF. 2021. How digital twins will troubleshoot – and even help design – the buildings of the future, viewed 30 May 2022. <https://www.weforum.org/agenda/2021/03/digital-twin-building-construction/>

YAZICI, S. & TANACAN, L. 2020. Material-based computational design (MCD) in sustainable architecture. *Journal of Building Engineering,* 32.

YUNUS, R. & YANG, J. 2012. Critical sustainability factors in industrialised building systems. *Construction Innovation,* 12**,** 447-463.