MODULAR AND OFFSITE CONSTRUCTION SUMMIT
JULY 27-29, 2022 EDMONTON, CANADA

An Holistic Approach to Product Evaluation and Selection in Industrialised Building: Benchmarking of Long Span, Low Carbon Floor Systems

Ivana KUZMANOVSKA[1,2*], Victor BUNSTER[1,3], Angela SOLARTE[1,2] and
Duncan W. MAXWELL[1,4]

[1] *Building 4.0 CRC, Caulfield East, Victoria, Australia*
[2] *Postdoctoral Research Fellow, Future Building Initiative, Monash University*
[3] *Lecturer, Future Building Initiative, Monash University*
[4] *Senior Lecturer and Director, Future Building Initiative, Monash University*
[*] *Corresponding author's e-mail: ivana.kuzmanovska@monash.edu*

ABSTRACT

As the construction industry shifts towards more systematised methods of designing and delivering buildings, data-informed approaches towards product development, evaluation, and selection promise to enable improved performance (structural, acoustic, fire, environmental), material efficiencies, and ease of production while maintaining the highest quality end result. This paper presents the outcomes of an applied research project that takes the first steps towards the development of a framework to guide holistic evaluation of product performance and future design efforts. Key outcomes of the research include: a *systems matrix* approach to (1) map the current product landscape, (2) select representative systems for benchmarking, and (3) to communicate relative performance; and a *decision matrix* used to illustrate the effect of varying priorities when selecting products for use in a building project.

KEYWORDS

Data-informed design, benchmarking, future building, mass timber, MCDM, industrialised construction

INTRODUCTION

Buildings consist of materials, components/parts, and systems that come together in different ways to respond to different programmatic, contextual, and stakeholder/user needs. In practice, once conceptual design has been defined, decisions around which specific material options, components, and systems to use in any given building design tend to be guided by tacit previous experience, simplistic cost estimates, rules of thumb, and 'gut feel' about overall performance. This approach can largely be attributed to traditional construction's project-based working methods that consider each project as having a unique design, changing site conditions, and the creation of temporary design-build teams (Dubois & Gadde 2002, Vrijhoef & Koskela 2005). This working approach is compounded by the industry's lack of clear performance metrics, and simplistic approach to data collection when compared to other sectors (Construction Task Force 1998, Ahmad et al. 2015) and is further hampered by the absence of standard benchmarking methods and formal guidance in product evaluation and selection (Kärnä & Junnonen 2016). With the increasing industrialisation of construction, pre-designed product solutions are likely to become more prevalent in building delivery. This shift will have implications for future design professions and the roles that they play in the overall building project (Vibæk 2014).

Mass timber construction lends itself to industrialised modes of delivery because it unlocks prefabrication opportunities, encourages the use of digital design-to-production tools, emphasises early design freeze, and is well suited to a more productised approach to building design (Yazdi et al. 2021). Importantly, the carbon sequestration potential of CLT and glulam components, combined with their capacity for easy disassembly and re-use, position mass timber construction as a potential solution pathway towards more sustainable construction (Abed et al. 2022, Ahn et al. 2022). A range of products developed for mass timber construction have recently penetrated the market—for example: connection systems; panelised facade, wall, and floor systems; and modular solutions such as bathroom pods. However, there is a notable lack of systematic guidance to inform the selection of the appropriate products for a given design brief.

The research project discussed in this paper emerged out of a desire to understand the relative performance of existing product solutions on the market (specifically, long span, low carbon floor systems suitable for use within a mass timber building typology), as the first step in the development of a ‘new and improved’ solution. Throughout the research, the value of a systematic and synthetic performance evaluation and benchmarking process became apparent, and indeed foregrounded as a key industry need.

Benchmarking is a management process that aims to gauge relative performance and identify performance gaps (in aspects ranging from products, practices, and services, to organisational strategy) in order to increase competitive advantage (Meade 1998). Emerging from the manufacturing industries, many different benchmarking methods have been developed and published, typically aiming to measure, compare, and improve certain outcomes (Bi 2017). The concept of benchmarking has entered construction discourse as a way of addressing productivity and improving performance, however, very often benchmarking in construction focuses on project or organisational performance (Costa et al. 2006, Kärnä & Junnonen 2016). Where product-focused benchmarking is considered, current research tends to focus on workflows featuring the use of Building Information Models for product selection and specification (Adamus 2014). However, as BIM uptake is currently not consistent across the entire construction industry, these methods may struggle to offer widespread benefits in the immediate future (Dainty 2017).

This paper reports on CRC Project #18 (CRC#18) which was developed via the Building 4.0 Cooperative Research Centre—a multi-university, Australian Commonwealth supported consortium engaging in applied research projects with 30+ industry partners. CRC#18 was a study that was run as a collaboration between two universities and two industry partners within the consortium. Through the benchmarking of nine long span, low carbon floor systems, the project sought a framework for analysing existing product solutions and informing the brief for further design development and evaluation moving forward. While the project was specifically concerned with floor systems, the key findings and the resulting frameworks for the product mapping, visualisation of benchmarking analysis, and synthesis of benchmarking findings point towards a logic and workflow that could be applied to any productised building element.

METHOD

CRC#18 was an interdisciplinary, collaborative project between industry (Lendlease and Sumitomo Forestry) and academia (Monash University and University of Melbourne). Lendlease is developer/construction business with a digital platform arm, and Sumitomo Forestry is a timber processing company with a prefabricated housing arm. The research questions and many of the project's objectives were guided by current industry needs, as expressed by both industry partners. Weekly project meetings held between the research team and representatives of the industry partner companies were instrumental in providing insights to current state of play both within Australia, and internationally (both companies also operate outside of Australia). These conversations added industry context to the research activities and ensured that the implications of the findings could be considered from the perspective of their pragmatic consequences.

Market Review and System Selection

An extensive market search was conducted to identify the range of commercially available floor systems able to achieve spans of 8m or more. Of these, an early decision was made to exclude concrete-only, and steel-only systems, as they were not deemed to satisfy the low-carbon objective. The capacity for prefabrication was an important driver for both industry partners, so a decision was made to exclude highly componentised solutions that would require all of the assembly activities to occur on site (for example, beam and slab systems delivered to site as separate beams and slab panels). In order to make sense of the remaining 50+ systems, they were mapped according to two key characteristics deemed to be important to their performance, manufacture, and cost: their materiality (timber only, timber-concrete composite, timber-steel composite); and their elemental typology (flat slab, open and closed rib panels, integrated panel and beam elements). This type of market mapping, whereby existing products are plotted according to two key variables, is a fairly common business tool used to identify market gaps (Shawhan 2022). The systems matrix was used to identify nine systems for benchmarking that were representative of the market spread, and over the course of the project evolved to become a key outcome of the research (to be discussed shortly).

Benchmarking

The literature on benchmarking in construction suggests that successful benchmarking processes are interactive and dependant on developing a consensus view within the team (Garnett & Pickrell 2000). Important benchmarking considerations were gathered over several conversations with the industry partners. The resulting list of considerations reflect industry requirements and priorities, as they are informed by years of experience (from the perspective of developer, designer, head contractor, and part manufacturer). The considerations were categorised according to discipline:

- Structural (aim for minimum floor depth while achieving 8m span)
- Vibration (achieving acceptable floor vibration levels)
- Fire (meeting fire safety requirements for multi-storey residential buildings)
- Environmental (low carbon with a potential pathway to achieve zero carbon product)
- Design (services integration, design flexibility and high visual quality)
- Production, with a strong focus on prefabrication and Design for Manufacturing and Assembly (optimised handling and transportability, easy installation/assembly, capacity for automated manufacturing, and disassembly)

Interdisciplinary Research Team

The research team was necessarily large and interdisciplinary, to address the range of criteria listed above, in the most holistic way possible. The 20+ member research group was organised into discipline-specific teams to conduct the analysis. These teams investigated the systems' performance in terms of the key identified considerations. Each team defined unique criteria and metrics, as well as a methodology for analysis that was most relevant to their specific focus. The discipline-specific benchmarking metrics and methods are not the focus of this paper, and will therefore not be discussed in detail.

Scope and Limitations

The study focused on suspended floor systems with minimum 8m spans, deemed suitable for residential applications in Australia. The 8m minimum requirement was largely driven by the need to accommodate basement carparking (3 x 2.5m car spots) in many such buildings. It is important to note that CRC#18 was run as a 6-month scoping study. This short duration limited the scope of benchmarking considerations that could feasibly be included. The benchmarking analyses focused only on the floor systems themselves, and did not consider their performance as part of the broader building. An important factor that was excluded from the study was cost. While in practice, cost is highly influential in the determination of product viability, a conventional cost-driven analysis may have distracted from a deeper understanding and comparison of overall value (performance, quality, safety, and program benefits, etc.). It is intended that cost, and project-specific application, will be considered in the next phase of the project. This paper reports (a) the procedure that informed the selection of products that are representative of the market offering for long span, low carbon floor systems, and (b) the definition of a design-support matrix to synthesise performance findings. The evaluation of the selected flooring solutions under specific performance criteria is not included in this paper.

RESULTS AND DISCUSSION

The benchmarking analyses, when considered together, did not identify a best performing or 'optimal' system across all criteria, and thus trade-offs became apparent, highlighting the implications of prioritising one consideration over another in both the selection of existing products, and the development of new ones (Aitchison et al. 2017). For example, aiming to optimise structural efficiency is likely to lead down a different design path than one in which production efficiency is prioritised. The same can be said of a design and/or selection process driven by cost, which is very often a key consideration in practice. The hierarchy of priorities, whether explicit or not, impact the product understood to be best suited; it is therefore important to at least be aware of the nature of this hierarchy. While in an industry setting, decisions on which product pathway to pursue are often made based on previous experience, rules of thumb, or costing, this study explores the possibility of approaching such a problem systematically. Two outcomes of the project are foregrounded in this paper as important in the consideration of a systematic approach to holistic design evaluation: the *product matrix* (Figure 1); and the *decision matrix* (Figure 2).

Product Matrix

The proposed product matrix (see Figure 1) has two functions: market mapping; and performance visualisation. It was initially developed to make sense of the categories of products available on the market (by material type and elemental make-up), and to ensure that this market spread was

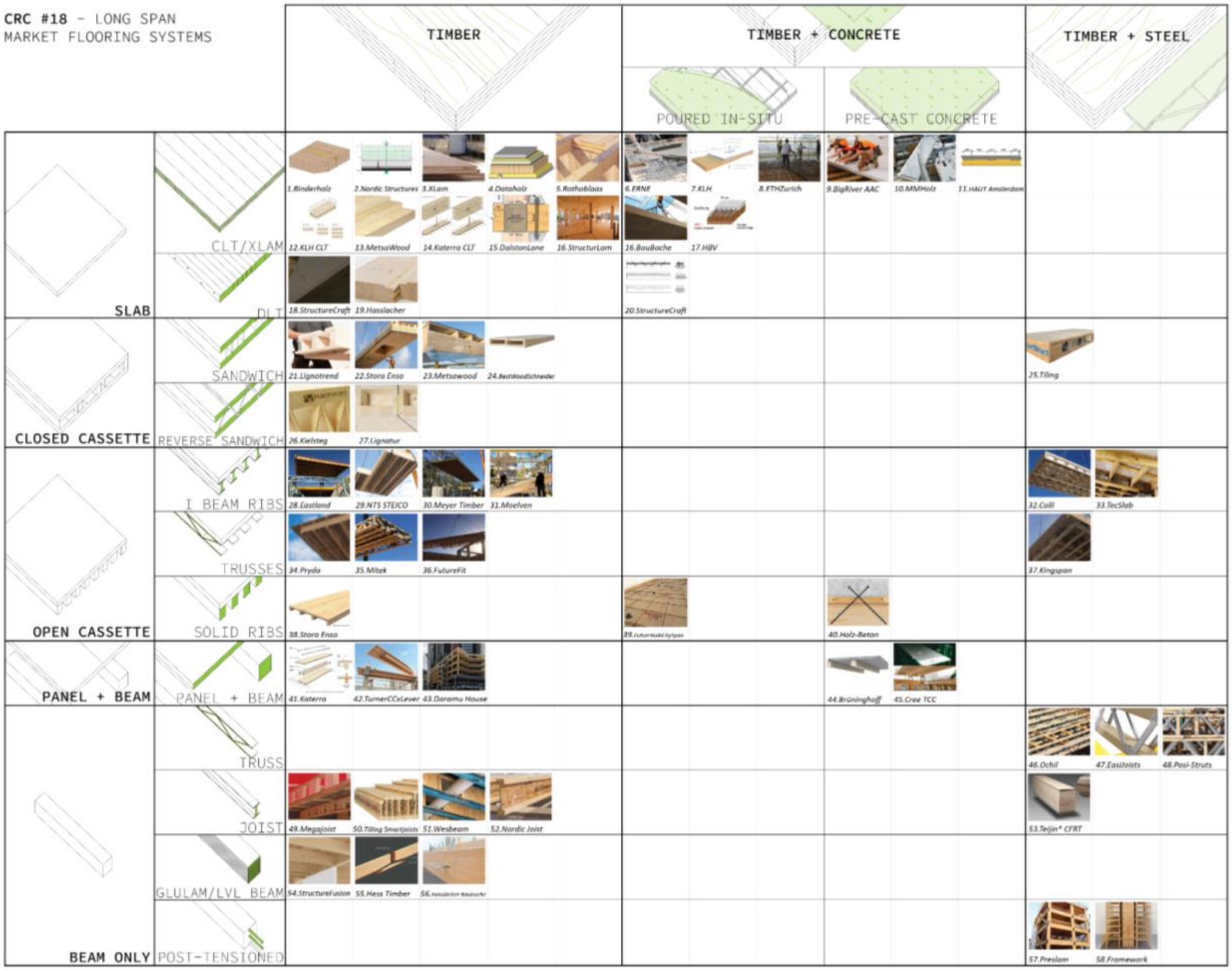


Figure 1. The product matrix: floor systems mapped according to material and elemental strategy.

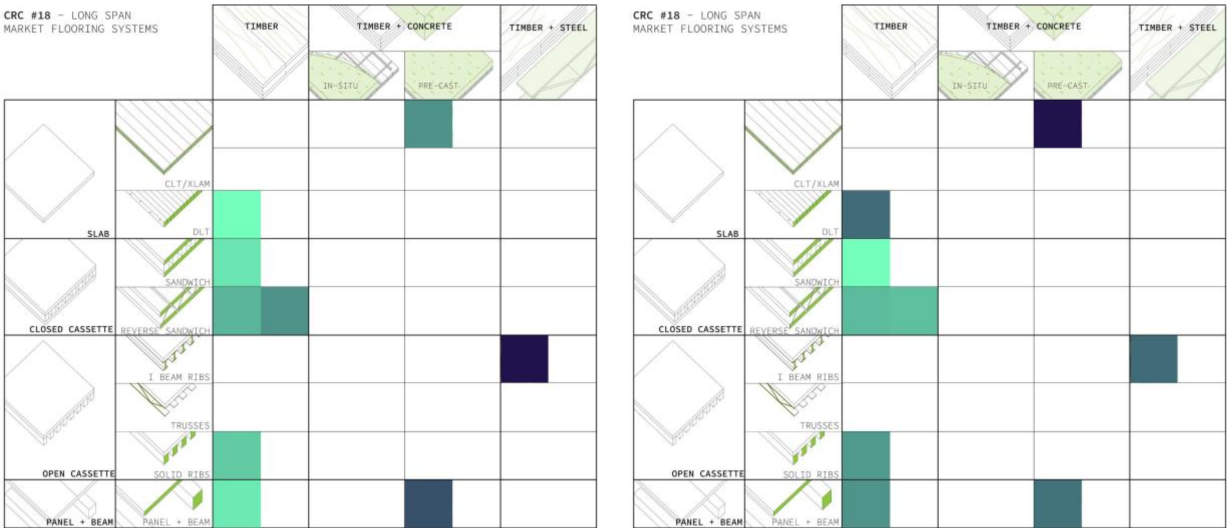
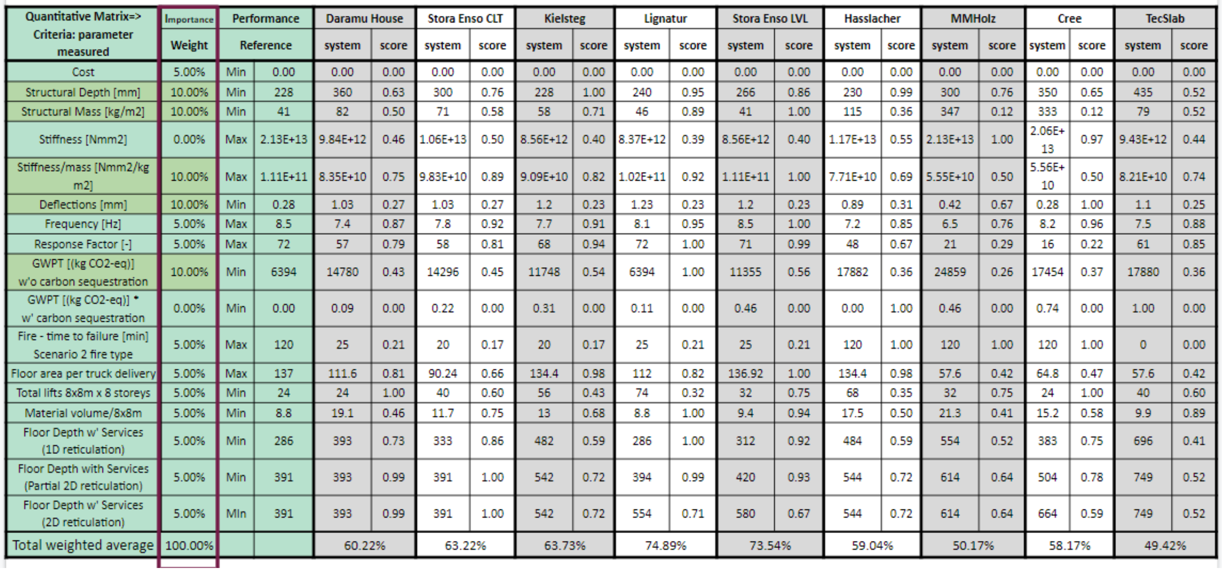


Figure 2. Relative performance of benchmarked systems according to Global Warming Potential with sequestration (left) and without sequestration (right). Light green indicates better, dark navy indicates worse.

represented in the nine floor systems selected for benchmarking. However, further to this, once the benchmarking analyses had been completed, the matrix became instrumental in communicating system performance in relation to their material and elemental characteristics (see Figure 2). A separate matrix was created for each benchmarking metric, capturing relative performance of each system according to a gradient spectrum of colour. Representing relative performance in this simple way enables better/worse judgements to be made quickly, offering potential in the explorative early phase of the design process, when project priorities are being established and high-level design decisions are being made. Take for example the CLT-concrete slab system depicted in the matrices in Figure 2. If carbon sequestration is not considered in the carbon accounting for whatever reason (for example, life cycle projection under 100 years), this system is the poorest performing of the nine benchmarked (as indicated by its navy colour in the matrix on the right). However, the volume of timber in the CLT slab increases the system's performance from a carbon accounting perspective if carbon sequestration is taken into consideration. In the matrix on the left, two other systems are worse performing than the CLT-concrete slab (those indicated in navy).

Decision Matrix

After the benchmarking process had been carried out by each discipline-specific team, a prototype multi-criteria decision analysis (MCDA) matrix was developed to synthesise the findings of each team, enabling transparent discussion of overall performance (see Figure 3) (Keeney and Riffa, 1993).



Quantitative Matrix=> Criteria: parameter measured	Importance	Performance		Daramu House		Stora Enso CLT		Kielsteg		Lignatur		Stora Enso LVL		Hasslacher		MMHolz		Cree		TecSlab	
	Weight	Reference		system	score	system	score	system	score	system	score	system	score	system	score	system	score	system	score	system	score
Cost	5.00%	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Structural Depth [mm]	10.00%	Min	228	360	0.63	300	0.76	228	1.00	240	0.95	266	0.86	230	0.99	300	0.76	350	0.65	435	0.52
Structural Mass [kg/m2]	10.00%	Min	41	82	0.50	71	0.58	58	0.71	46	0.89	41	1.00	115	0.36	347	0.12	333	0.12	79	0.52
Stiffness [Nmm2]	0.00%	Max	2.13E+13	9.84E+12	0.46	1.06E+13	0.50	8.56E+12	0.40	8.37E+12	0.39	8.56E+12	0.40	1.17E+13	0.55	2.13E+13	1.00	2.06E+13	0.97	9.43E+12	0.44
Stiffness/mass [Nmm2/kg m2]	10.00%	Max	1.11E+11	8.35E+10	0.75	9.83E+10	0.89	9.09E+10	0.82	1.02E+11	0.92	1.11E+11	1.00	7.71E+10	0.69	5.55E+10	0.50	5.56E+10	0.50	8.21E+10	0.74
Deflections [mm]	10.00%	Min	0.28	1.03	0.27	1.03	0.27	1.2	0.23	1.23	0.23	1.2	0.23	0.89	0.31	0.42	0.67	0.28	1.00	1.1	0.25
Frequency [Hz]	5.00%	Max	8.5	7.4	0.87	7.8	0.92	7.7	0.91	8.1	0.95	8.5	1.00	7.2	0.85	6.5	0.76	8.2	0.96	7.5	0.88
Response Factor [-]	5.00%	Max	72	57	0.79	58	0.81	68	0.94	72	1.00	71	0.99	48	0.67	21	0.29	16	0.22	61	0.85
GWPT [(kg CO2-eq)] w'o carbon sequestration	10.00%	Min	6394	14780	0.43	14296	0.45	11748	0.54	6394	1.00	11355	0.56	17882	0.36	24859	0.26	17454	0.37	17880	0.36
GWPT [(kg CO2-eq)] * w' carbon sequestration	0.00%	Min	0.00	0.09	0.00	0.22	0.00	0.31	0.00	0.11	0.00	0.46	0.00	0.00	1.00	0.46	0.00	0.74	0.00	1.00	0.00
Fire - time to failure [min] Scenario 2 fire type	5.00%	Max	120	25	0.21	20	0.17	20	0.17	25	0.21	25	0.21	120	1.00	120	1.00	120	1.00	0	0.00
Floor area per truck delivery	5.00%	Max	137	111.6	0.81	90.24	0.66	134.4	0.98	112	0.82	136.92	1.00	134.4	0.98	57.6	0.42	64.8	0.47	57.6	0.42
Total lifts 8x8m x 8 storeys	5.00%	Min	24	24	1.00	40	0.60	56	0.43	74	0.32	32	0.75	68	0.35	32	0.75	24	1.00	40	0.60
Material volume/8x8m	5.00%	Min	8.8	19.1	0.46	11.7	0.75	13	0.68	8.8	1.00	9.4	0.94	17.5	0.50	21.3	0.41	15.2	0.58	9.9	0.89
Floor Depth w' Services (1D reticulation)	5.00%	Min	286	393	0.73	333	0.86	482	0.59	286	1.00	312	0.92	484	0.59	554	0.52	383	0.75	696	0.41
Floor Depth with Services (Partial 2D reticulation)	5.00%	Min	391	393	0.99	391	1.00	542	0.72	394	0.99	420	0.93	544	0.72	614	0.64	504	0.78	749	0.52
Floor Depth w' Services (2D reticulation)	5.00%	MIn	391	393	0.99	391	1.00	542	0.72	554	0.71	580	0.67	544	0.72	614	0.64	664	0.59	749	0.52
Total weighted average	100.00%			60.22%		63.22%		63.73%		74.89%		73.54%		59.04%		50.17%		58.17%		49.42%	

Figure 3. Prototype decision matrix, developed to illustrate the impacts of prioritising certain parameters over others.

In the decision matrix, the y-axis contains the individual analysis parameters identified by each benchmarking team, and the x-axis contains the nine systems selected for study (each assigned an absolute performance value and a relative performance score for each benchmarking parameter). A weighting column (outlined in red in Figure 3) contains the percentage weighting assigned to each parameter in the overall analysis. The matrix illustrates the effect of adjusting the weighting of any of the identified performance parameters, thereby offering a way of exploring selection biases and explicitly communicating the hierarchy of priorities. Rather than aiming for definitive weighting metrics, this matrix is intended to serve as an interactive tool to guide the selection process. For the purposes of this project, the weighting values were assigned subjectively; however, future phases of the research could focus on better understanding how these weighting values might be informed by previous project performance data and contextual factors.

CONCLUSION

This paper outlines the first steps towards a systematic approach for holistic product evaluation in the building industry. The systems matrix and the decision matrix are two key outcomes of the research, facilitating:

- product mapping according to material and element type as an approach to categorising and making sense of market offering according to these two key variables.
- simple visualisation of high-level product benchmarking performance findings for easy comprehension in the early building design phase.
- synthesis of detailed benchmarking findings to highlight the effects of selection priorities, enabling transparent discussion of decisions and their impacts on overall performance.

These points come together in a framework that can be used to evaluate productised solutions developed for construction, regardless of type or scale (from connection systems to modular pods). The framework can be used as the basis for: (1) further product benchmarking; (2) evaluation and selection of products most suitable for any given building project according to an explicit set of selection priorities; and even (3) design development of improved products in the future. Such data-informed methods of evaluation are currently lacking, and reveal the promise of a future holistic approach to data-driven design and decision-making.

Future research

CRC#18 was conducted as a short scoping study, laying the groundwork for future research trajectories. The synthesis of benchmarking findings in the project raised some interesting questions which require further investigation:

1. How can real project data be used to inform parameter weighting for any given context?
2. In what ways are the evaluation parameters identified by each of the discipline-specific teams related to one another (in-so-far as altering one will impact performance of another)?

ACKNOWLEDGEMENTS

This research was supported by Building 4.0 CRC, an industry-led research initiative co-funded by the Australian Government. The authors would like to acknowledge the broader research team from both Monash University and the University of Melbourne, without whom this project would not have been possible. The authors would also like to thank our industry partner teams from Lendlease and Sumitomo Forestry. We are especially grateful for the contributions of Karl-Heinz Weiss, Steven Huang, and Mario Lara Ledermann from Lendlease, and Ryo Kaburagi from Sumitomo Forestry.

REFERENCES

Abed, J., S. Rayburg, J. Rodwell and M. Neave (2022). "A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures." *Sustainability* 14: 5570.

Adamus, L. (2014). “Environmentally friendly construction products selection based on building model data.” *Procedia Engineering* 85: 18-25.

Ahmad, S. B.S., F. Svalestuen, B. Andersen and O. Torp (2016). “A Review of Performance Measurement for Successful Concurrent Construction.” *Procedia - Social and Behavioral Sciences* 226: 447-454.

Ahn, N., A. Dodoo, M. Riggio, L. Muszynski, L. Schimleck, and M. Puettmann (2022). “Circular economy in mass timber construction: State-of-the-art, gaps and pressing research needs.” *Journal of Building Engineering* 53:104562.

Aitchison, M. (2017). *Prefab housing and the future of building: product to process*. Lund Humphries

Bi, H. H. (2017). “Multi-criterion and multi-period performance benchmarking of products and services: Discovering hidden performance gaps.” *Benchmarking: An International Journal* 24(4): 934-972.

Construction Task Force (1998). *Rethinking Construction*. Department of Trade and Industry, Crown Copyright.

Costa, D. B., C. T. Formoso, M. Kagioglou, L. F. Alarcón, and C. H. Caldas. (2006). “Benchmarking Initiatives in the Construction Industry: Lessons Learned and Improvement Opportunities.” *Journal of Management in Engineering* 22(4): 158-167.

Dainty, A. R. Leiringer, S. Fernie, and C. Harty (2017). “BIM and the small construction firm: a critical perspective.” *Building Research and Information* 45(6): 696-709.

Dubois, A. and L.-E. Gadde (2002). "The construction industry as a loosely coupled system: implications for productivity and innovation." *Construction Management and Economics* 20(7): 621-631.

Garnett, N. and S. Pickrell (2000). Benchmarking for construction: theory and practice. *Construction Management & Economics* 18(1), 55-63.

Kärnä, S. and J. Junnonen (2016). “Benchmarking construction industry, company and project performance by participants’ evaluation.” *Benchmarking: An International Journal* 23(7): 2092-2108.

Keeney, R. L., H. Raiffa and R. F. Meyer (1993). *Decisions with multiple objectives: preferences and value trade-offs.* Cambridge university press.

Meade, P. (1998). *A guide to benchmarking*. University of Otago.

Shawhan, G. (2022), “Market Mapping.” *Coatings World.* Rodman Media. Accessed on 15.06.2022. https://www.coatingsworld.com/issues/2022-04-01/view_business-corner /market-mapping/

Vibæk, K. S. (2014). *Architectural System Structures : Integrating Design Complexity in Industrialised Construction*. Taylor & Francis Ltd.

Vrijhoef, R. and L. Koskela (2005). “Revisiting the three peculiarities of production in construction.” *Proceedings of the 13th Conference of the International Group for Lean Construction*. Sydney, Aus.: 19-27.

Yazdi, A. J., A. Ahmadian, and P. Forsythe (2021). “Mass-customisation of cross-laminated timber wall systems at early design stages.” *Automation in Construction* 12: 103938.