Developing Construction 4.0 transformation of Aotearoa New Zealand's construction sector

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ABSTRACT

The construction industry in New Zealand exceeded $18.1 billion in 2022 and was the third largest workplace for the year ending in June 2022, making a significant contribution to the country's economy. However, it has long been criticised for low productivity, inefficiencies, and a significant contribution to carbon emissions. The primary challenge is that complex decisions with far-reaching consequences spanning generations are being made based on outdated "pre-digital age" practices. The decision-making process is traditionally carried out in linear silos with little interconnection or data-derived decision support. To solve these long-standing limitations and revolutionise conventional construction, this challenge requires a combination of complexity science and Construction 4.0 approaches, including design-led construction processes.

HERA, in cooperation with research and industry partners, has responded to this challenge and successfully secured MBIE Endeavour Funding to develop the Construction 4.0 transformation of Aotearoa New Zealand's construction sector. This research program will facilitate transformation in terms of construction productivity, quality, resilience, affordability, and sustainability. Additionally, it will provide opportunities for Māori enterprises, incorporate distinctive Māori relationships in the industry, create positive impacts on whānau, and meet Māori needs in innovation and technology. The increased adoption of Industry 4.0 technologies within the sector will also lead to new types of innovation based on data collection, management, and analysis, involving high-tech development. To achieve the research objectives, the research method used is a combination of complexity science, Industry 4.0 technologies, participatory approaches, and mixed-methods research techniques. This paper provides a high-level overview of the objectives and scope of this research to shed light on the benefits that will accrue from its successful implementation.

1 INTRODUCTION

Aotearoa's construction industry reached over $18.1 billion in 2022 and it was the third largest employer in the year ended June 2022. The sector's contribution to New Zealand's economy is summarised as follows (MBIE, 2022):

- 6.7% GDP in the year ended March 2022;
- 10.5% employment in the year ended June 2022; and
- 12.6% of business enterprises as of February 2022.

However, it is an industry that requiresrapid transformation and has long been criticised for its low productivity, inefficiency, and significant contribution to New Zealand's carbon emission. In May 2018, Thinkstep-anz published a report calculating that the built environment contributes up to 20% of New Zealand's GHG emissions (MBIE 2020). Further, the recently released Climate Change Commission Evidence Report states that buildings contributed 3% of long-lived greenhouse gas breakdown and 7% of fossil fuel composition for heat, industry, and power (CCC 2021).

Currently, there is a profound limitation in the way that buildings are built in New Zealand. The challenge is that complex decisions are being made based on limited data inputs. The decision points in the process are done in linear silos with little inter-connection or data-derived decision support. The process is entrenched and far from optimised. For example, designers do not have adequate tools to optimise designs for the ease of manufacture/fabrication, let alone the ability to resolve the conjoint considerations required to deliver design for sustainability, constructability, te ao Māori, resilience and affordability simultaneously. Construction data used to inform those decisions is typically considered in a linear fashion and does not accommodate the fact that it is a complex decision-making system that is greater than the sum of its parts.

To address the current construction issues and transform conventional construction, complexity science and construction 4.0 techniques (design lead construction process) are needed. Construction 4.0 requires three transformations: industrial production and construction, cyber-physical systems, and digital technologies (Sawhney, Riley & Irizarry, 2020). Past studies revealed significant knowledge gaps in construction 4.0 and highlighted a critical need for extensive future research to overcome the current construction issues (HERA R5-90, Forcael et al 2020).

There are many Small to Medium Enterprises (SMEs) in New Zealand that are unable to employ digital prod ucts effectively due to a lack of technical expertise (Allison & Hartley, 2020). If these problems are fixed, th e construction industry will be able to integrate technology more readily, which will facilitate a more seamles s transition to Construction 4.0. Adopting Construction 4.0 will enable the construction industry to contribute more to New Zealand's circular economy, boost productivity, produce highly skilled jobs, and reposition the industry as "technologically aware."

The implementation of Construction 4.0 presents several challenges, including:

Resistance to change: One of the biggest challenges confronting the implementation of Construction 4.0 is the resistance to change. Many stakeholders in the construction industry are used to traditional methods and may be reluctant to adopt new technologies and processes.

Lack of skills and training: Another challenge is the lack of skills and training required to implement Construction 4.0 technologies and processes. The construction industry may need to invest in training and education programs to ensure that workers have the necessary skills to adopt and use new technologies effectively.

Cybersecurity risks: Construction 4.0 technologies involve the use of interconnected systems and devices, which increases the risk of cybersecurity threats. Effective cybersecurity measures must be implemented to mitigate these risks.

Cost: Implementing Construction 4.0 technologies and processes may require significant investment, which could be a challenge for smaller companies or those with limited resources.

Regulatory barriers and drivers and development of appropriate strategies to regulate the transition toward Construction 4.0 in New Zealand.

To effectively handle these challenges, several possible solutions could be considered, including:

Communication and collaboration: It is essential to communicate the benefits of Construction 4.0 and collaborate with stakeholders to ensure their buy-in and involvement in the implementation process.

Training and education: The construction industry may need to invest in training and education programs to provide workers with the necessary skills to adopt and use new technologies effectively.

Cybersecurity measures: Effective cybersecurity measures must be implemented to mitigate the risk of cybersecurity threats. This can be achieved by working with cybersecurity experts and implementing best practices.

Strategic planning: Developing a strategic plan for implementing Construction 4.0 technologies and processes can help identify potential risks and challenges and develop effective mitigation risks.

Investment: The construction industry may need to invest in new technologies and processes to implement Construction 4.0 effectively. This investment could be offset by the long-term benefits of improved productivity, quality, and sustainability.

To successfully implement Construction 4.0, research is required in several areas. Here are a few examples:

Technology development and integration: Research is required to develop and integrate new technologies into the construction industry, such as Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), and automation systems. This research should focus on developing technologies that are specific to the needs of the construction industry and can be easily adopted by the industry.

Process optimisation and standardisation: Construction 4.0 requires the optimisation and standardisation of construction processes to improve productivity, quality, and sustainability. Research is required to develop new processes and standardisation frameworks that can be applied across the industry.

Data management and analysis: Construction 4.0 involves the use of data for decision-making and process optimisation. Research is required to develop effective data management and analysis systems, including data collection, storage, analysis, and visualisation.

Overall, research in these areas is critical to the successful implementation of Construction 4.0 and the transformation of the construction industry towards improved productivity, quality, and sustainability.

The Construction 4.0 research programme aims to transform New Zealand Construction sector from linear to circular systems to address sustainability, productivity, and technical issues. A combination of complexity science, participatory approaches, and mixed-methods research methodologies will be used. This research will improve industry tech-readiness and quality within the sector and unlock Māori knowledge in the short term. It will create a more productive and stable construction sector, balanced Māori employed, and the sector will meet the Building for Climate Change and carbon dioxide emission targets in the long term.

2 HIGH-LEVEL SCOPE AND OBJECTIVES OF THE RESEARCH

Addressing the current issues of New Zealand's construction industry requires better integrated decision-making tools, building upon the complex data analytical capabilities offered by Industry 4.0. New technologies of the 4th industrialisation age are required to transform construction from a linear to a circular system known as construction 4.0. Construction 4.0 promises the construction industry with a decentralized connection between the physical space and the cyberspace via ubiquitous connectivity. Therefore, the science problem is complex big data managing and connectivity.

It includes collection and analysis of complex data sets based on a complexity science and construction 4.0 approaches (design lead construction process) to solve these long-standing limitations and to revolutionise conventional construction.

This paper introduces a newly MBIE Endeavour Funded research programme for developing Construction 4.0 transformation of Aotearoa New Zealand's construction sector. The Construction 4.0 framework and guidelines developed in this programme will manage complexity and reduce uncertainty; and enhance information exchange and communication between construction project stakeholders to increase productivity and quality. It will create a step-change in construction sector transformation, create jobs and upskill the workforce through innovation and/or digital literacy.

A core research theme will focus on technology transfer and policy development and implementation. This will ensure that the research outcomes are both adoption-ready and readily adoptable. The outcomes will be widely disseminated through published literature but also in terms of industry adoption and practice improvements.

This research will develop a solution to source and use complex system and interactive data sets simultaneously to inform decisions made across the construction value chain that concurrently impact subsequent and preceding steps in that chain. That is, this research will develop a process that is currently limited by its sequential nature be transformed, through novel use of data collection and analysis, to consider the interactive complexities that cross those linear boundaries.

This research programme aims to deliver high quality research to create a transformation in terms of productivity, quality, affordability and sustainability. It will include key experts from the global research community and leverage international research. It will provide opportunities for Māori enterprises, incorporate distinctive Māori relationships in the industry and create positive impacts on the whenua, as well as meet Māori needs in innovation and technology. It will link into key emerging MBIE strategies and policies, such as the "Building for climate change" programme to transform the building and construction sector to become climate resilient. It also supports key aspects of the

Construction Sector Accord, which is a shared commitment between government and industry to transform the construction sector. It will grow knowledge-intensiveness in manufacturing/fabrication, which has NZ's highest business investment in R&D and will grow the requirement for highly skilled employees in the sector. This research programme will lead to reductions in carbon emissions in a major carbon emitting industry.

The research will be world-leading in an emerging area of international interest and create data-driven decision-making for the future of construction. It will also incorporate Mātauranga Māori interfaces, making it unique globally.

3 STRUCTURE OF THE RESEARCH PROGRAMME, AIMS AND TEAM

In order to address these questions, three overlapping research sub-programmes (RPs), four underpinning research themes (RT) and an over-arching protocol are envisaged. Figure 1 shows the structure of the research programme. In the following research aims are discussed briefly.

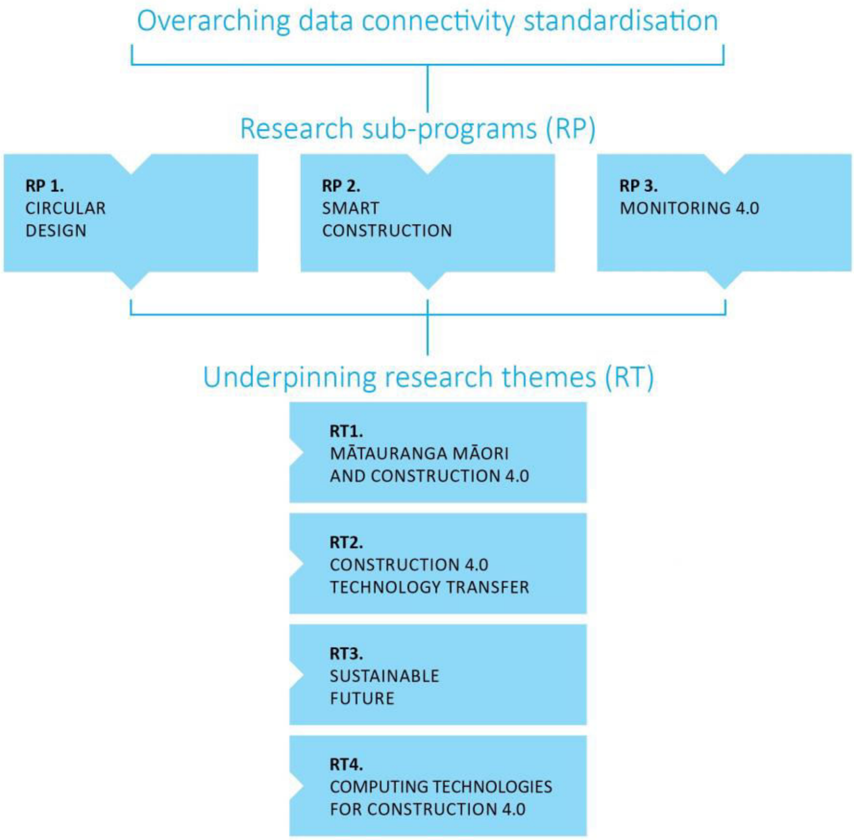

Figure 1: Structure of the Construction 4.0 research programme

3.1 Overarching Data Connectivity Standardisation

This research will develop New Zealand's first standardisation infrastructure for: 1) vertical integration of construction participants' systems; and 2) horizontal integration of the value chain and collaborative networks. Cyber-physical Construction Systems (CPCS) will be developed whereby digital twins that rely on field data are integrated with their physical counterparts to enable smart decision-making (Figure 2). Figure 2 shows a diagram of cyber-physical construction system (CPCS).

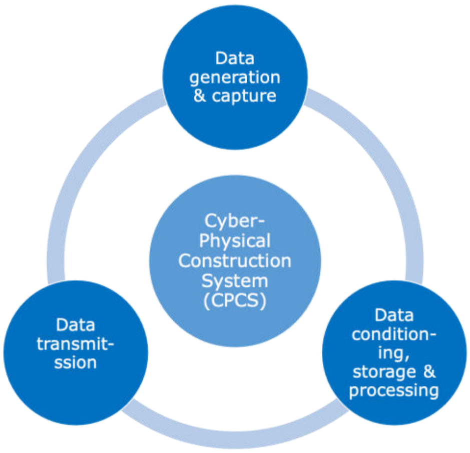

Figure 2: Cyber-physical system

3.2 RP 1. Circular Design

The research novelty is in using Construction 4.0 enabled data to create a better design. The hypothesis is that the optimisation requirements can be fulfilled by a structural synthesis system, in which a cost/environmental impact function is minimised considering constraints on design, manufacturability etc derived from the Construction 4.0 data. The Circular design objective will involve consultations between a number of stakeholders to the determine the design objectives and constraints; modification of the configuration based on the optimised design considering the design objectives and constraints (from which design is made at the push of a button). These considerations include material availability (new and used), sustainability (e.g. considering carbon footprint, resilience (including seismic), maintenance / durability, reusability of components), health and well-being, architectural/cultural significance, costing, and construction time). Modifications are then made to the structure by the stakeholders until they find an appropriate solution. The outputs include all information required for construction and consenting. At the push of another button, the process may be initiated with fund transfers, consents, procurement, fabrication, and full construction. Such an approach will take many years to develop, but the essential framework will be developed in this project.

3.3 RP 2. Smart Construction

This research will investigate the intrinsic properties and invariant signatures of construction objects, such as footings, slabs, beams etc, as well as their synergistic structural performance, to create a new end-to-end computational platform for design and manufacture. This opens the door to full automation of prefabrication and modularisation, which will significantly improve building performance, environmental profile and productivity in the sector.

3.4 RP 3. Monitoring 4.0

This research will develop a framework for 1) objective/improved monitoring and performance assessment of structural systems using in-situ data and numerical models, and 2) optimal instrumentation plans to maximise the information gain while limiting the monitoring and instrumentation cost. The resultant novel calibrated digital twin, as an integral part of CPCS (Figure 2, overarching standardisation program), will be used to compare the overall performance of structural systems to design expectations and identify modelling errors (thereby supporting the overarching data standardisation program, and RP1 and RP2). There are several structures that have a monitoring system installed on them. However, almost invariably the monitoring system only provides raw data, or at best, some basic data analyses. The aim of Monitoring 4.0 is to extract information from measured raw data and provide insights for stakeholders, including practitioners, owners, and decision makers. This information would include modal properties of the structure, and can provide feedback on design assumptions and potentially improve them.

3.5 RT1. Mātauranga Māori and Construction 4.0

This research aims to address the gap of knowledge that exists between Construction 4.0 and Mātauranga Māori by building a uniquely Māori framework to address the challenges of Construction 4.0. This will create new knowledge domestically and will sit internationally as an example of indigenous knowledge

3.6 RT2. Construction 4.0 Technology Transfer

This research will develop an alternative to traditional linear knowledge/technology transfer. It will investigate organisation- and sector-specific characteristics of technology transfer in New Zealand Construction. This new approach will draw on the principles of co-creating value and models for knowledge flows in innovation ecosystems, including the development and implementation of regulatory governance models and related policy by and for the sector.

3.7 RT3. Sustainable Future

Existing greenhouse gas emission datasets (e.g. ecoInvent, BRANZ CO2NSTRUCT) for building materials and products will be adapted and extended to represent the NZ construction situation. They will be used to calculate the carbon footprint of the alternative prefabrication and modularisation solutions developed in RP1/2/3, and then compared with existing approaches using a whole-of-life whole-of-building modelling

approach. Their performance will be calibrated against carbon budgets based on the 1.5°C global mean surface temperature target.

3.8 RT4. Computing Technologies for Construction 4.0

This research will investigate emerging artificial intelligence approaches (typically developed for domains outside of construction) applicable to our research programmes and adapt emerging computing techniques to the complex requirements of Construction 4.0 data.

The application of complexity science and Industry 4.0 in construction is an immature discipline globally with very few identified experts in Construction 4.0 research. Hence, a team of global experts in the component parts of Construction 4.0 (in terms of experience and skills mix) have been brought together and will use a complexity science approach. International linkages, industry linkages and linkages to existing research programs will ensure that the research program and project outcomes avoid redundancy and are international best practice. Experts in Mātauranga Māori and its interface with Engineering, as well as sustainability and resilience in the built environment are also key team members. Finally, we have also incorporated expertise in technology transfer in traditional industries, and public policy development to ensure that the project outcomes are ready for adoption and readily adoptable.

The programme includes international collaborations with ETH Zurich, Hong Kong Polytechnic, Tufts University, University of Hong Kong, University of Michigan, University of Miskolc, and University of New Hampshire, and potentially other universities if required, leveraging world-leading expertise.

4 IMPACTS AND ADVANTAGES OF CONSTRUCTION 4.0 ADOPTION IN NEW ZEALAND

Construction 4.0 will deliver research excellence to transform a high-value sector. This programme will introduce new thinking, technologies, processes, policies and business models to ensure that the sector transitions to Industry 4.0 approaches and delivers a step-change in productivity and technology adoption.

This programme will leverage knowledge and expertise from overseas, with a focus on overcoming barriers to adoption of Industry 4.0 and the newly emerging and existing knowledge about technology readiness of Construction 4.0 developed in New Zealand and will focus on:

- digitalisation for optimisation of information, design and interoperability;
- computation of workflows and optimisation;
- training and skills in Industry 4.0; and
- interoperability of product data and BIM models.

The results of this research will be widely applicable in the construction and building sector in New Zealand as well as internationally , and could ultimately lead to seamless and universal interoperability of data from a wide range of manufactured components; optimised specifications of material selections for prefabrication/modularisation in different structures (timber, steel, concrete, or hybrid); full automation of structural analysis, manufacturability assessment and manufacturing process optimisation; and flow-on benefits for improved structural health monitoring. The methods and results of this project will be integrated into university coursework to support research-informed teaching and wider vocational training and skills development.

This research programme will have at its core Whai Painga and the Te Takere framework. This will ensure the integrity of Mātauranga Māori is preserved. Opportunities will be provided to Māori/non-Māori enterprises and incorporate distinctive Māori relationships with the industry. It will consider the effects of the industry on Te Taiao and its impacts on tangata whenua. It will also consider Māori needs, innovations and opportunities. This will be achieved through our Mātauranga Māori research theme and Māori participation in our Industry Advisory Group.

The research programme links directly to key emerging MBIE strategies and policies, such as the "Building for climate change" program to transform the building and construction sector to reduce emissions and improve climate resilience. It also supports key aspects of the Construction Sector Accord, which is a shared commitment between government and industry to transform the construction sector. It will seek to understand where in the sector and at what phases it is adequate to rely on selfregulation, where external government policy and regulation are required and where forms of joined-up governance/collaboration between government and the sector are possible. Informed by complexity science, this programme will produce guidelines for policy and regulatory governance that will help to facilitate a transition to Construction 4.0 within the broader NZ-philosophy of Regulatory Stewardship.

This research programme will grow knowledge-intensiveness in manufacturing/fabrication of building materials and structures, which has NZ's highest business investment in R&D and will grow the requirement for highly skilled employees in the sector. It will also transform the sector overall to one better able to manage and use data and knowledge. In addition, structural optimisation can lead to innovative design and design processes, and materials solutions for specific structural components or materials.

A recent study conducted by BERL to model the economic consequences of construction 4.0 adoption in New Zealand (Hurrener et al. 2021) showed that widespread uptake of Construction 4.0 in Aotearoa could add up to just over $8 billion in GDP over the next five years. Wages across the economy could increase by almost $3.5 billion in the same period. This Endeavour programme will address the current construction issues and aim to deliver the projected GDP improvement.

A recent report published by MBIE concluded circular design approaches, new materials, and technologies emerged from industry 4.0 revolution offer considerable opportunity to boost sector productivity and safety while also assisting the government in meeting its climate change targets and ensuring that New Zealanders have safe, healthy, and long-lasting structures today and in the future (MBIE 2021).

The increased adoption of Industry 4.0 technologies within the sector will also lead to new types of work. This work will be based on data collection, management and analysis and involve high-tech. In March 2018, there were 247,000 employed in the construction industry and it was identified in the Government's Construction Skills Action Plan (launched October 2018) that "the construction workforce does not have the capacity to deliver New Zealand's growing pipeline of construction projects" (Construction Action Plan 2018). Specifically, this transformation will comprise new types of work in technology and data management required of Construction 4.0, which are also likely to be higher paid roles for the sector. It will also lead to increased participation of Māori (currently at 19,000 employees), particularly in skilled roles. According to the Māori in the Construction Sector Report, one in five Māori are employed as a labourer compared with one in 10

for non-Māori. The report also found that the impact of the higher skilled in the construction workforce is reflected in incomes, with the median income for Māori in the sector is $3,600 higher than Māori in employment generally.

The primary resultant national benefits are improved:

- economic performance(Refer Impact Section for details);
- improved productivity in the construction sector;
- buildings perform within environmental limit;
- building resilience;
- building and infrastructure affordability; and
- interfaces with indigenous knowledge.

The results of this research will be widely applicable in the construction and building sector internationally as well as in New Zealand, and could ultimately lead to seamless and universal interoperability of data from a wide range of manufactured components; optimised specifications of material selections for prefabrication/modularisation in different structures (timber, steel, concrete, or hybrid); full automation of structural analysis, manufacturability assessment and manufacturing process optimisation; and flow-on benefits for improved structural health monitoring. The methods and results of this research programme will be integrated into university coursework to support research-informed teaching and wider vocational training and skills development. It will also support the development of capabilities of our construction sector, as well as to augment the career pathways and reputation of team members, both nationwide and beyond. It will leverage knowledge from overseas, with a focus on overcoming barriers to adoption of Industry 4.0.

5 SHORT, MEDIUM, AND LONG-TERM HORIZON OF NEW ZEALAND CONSTRUCTION INDUSTRY POST RESEARCH PROGRAMME

To imagine changes in the New Zealand construction industry, the short (2-year), medium (5-year), and long-term (10-year) horizon of the sector after this research programme will be predicted in the following:

5.1 2-year horizon

1.Industry tech-readiness; this improvement can be measured by:

- reduced cost of investment in technology and its adoption at a company level;
- new Construction 4.0-related courses and qualifications added to the NZQA accredited list;
- increased number of construction companies adopting Construction 4.0 and associated increase in
- their labour productivity; and
- increased adoption of digitisation standards, (e.g. ISO:19650).

2. Improved quality within the sector; this improvement can be measured by:

- number of guidelines, standards and regulations using research outcomes.

3. unlocking of Maori knowledge, resources and people; this improvement can be measured by:

- increased number of Māori students enrolled in related training;
- increased number of Māori enterprises and employment in the sector; and
- greater integration of te ao Māori principles in Construction 4.0 through the weaving of knowledge.

5.2 5-year horizon

1. A more established construction practice using Construction 4.0; this improvement can be measured by:

- increased revenue and cost savings of manufacturers and fabricators.
- increased applications/use of New Zealand Venture Investment Fund and equivalents working on seed funding for early-stage technology start-ups;
- Increased average salaries;
- Increased Māori employed in the sector; and
- sector starting to adopt Industry 5.0 approaches.

2. Industry tech readiness; measured by:

- number of students enrolled in above new courses.

3. Achievement of MBIE carbon reduction targets.

5.3 10-year horizon

1. A more productive and stable construction sector; long-term these trends can be measured through business confidence surveys, construction industry benchmark measures, reduced indemnity and liability insurance claims in the sector, lowered sector employment turnover and reduced enterprise failures.

2. Balanced Māori employed in the sector and increased income levels.

3. Sector meets the Building for Climate Change carbon dioxide emission targets.

6 CONCLUSIONS

Construction 4.0 is an evolving concept based on the complexity science and advances in digital and related technologies. It has the potential to transform several areas of the construction industry in a number of positive ways, including saving time and money, raising productivity standards, improving sustainability, and reducing risks and environmental impacts.

To successfully implement Construction 4.0, research is required in several areas such as Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), and automation systems. Construction manufacturing increasingly relies on sensors, robots, and drones to see jobs through to completion, along with digital twinning and monitoring that integrate product life management linked to circular design principles. A critical pillar of Construction 4.0 is Monitoring 4.0, which aims to convert measured sensory data into information to support structural health diagnostics and prognostics, structural performance before, during, and after extreme events, construction quality, and more.

To achieve the research objectives, the research method used is a combination of complexity science, Industry 4.0 technologies, participatory approaches, and mixed-methods research techniques.

HERA's Endeavour-funded Construction 4.0 Research Programme will contribute to the transformation of New Zealand's construction sector.

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