building 4.0 crc

#17: THE IMPLICATIONS OF INDUSTRY 4.0 FOR THE BUILDING INDUSTRY

TOWARDS A ROADMAP

THE UNIVERSITY OF MELBOURNE
MONASH University
QUT
Australian Government
Department of Industry, Science and Resources
AusIndustry
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First and foremost, this report was commissioned by the Advanced Manufacturing Growth Centre, whose foresight enabled us to gather concrete data for the first time on how participants in the building industry value chain perceive Industry 4.0 and new technologies.

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This report ultimately targets a range of actors in the building industry, providing pertinent recommendations to policymakers, educational institutions, and practitioners.

Disclaimer:

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Authors and Contributors

CONFIDENTIAL:	☐ Yes ☒ No
Lead Organisation:	Building 4.0 CRC
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Industry Partners:	Bentley Homes, BlueScope, Exergenics, Fleetwood Australia, Hyne Timber, Lendlease Digital, prefabAUS, Space Platform, XLam Australia, Ynomia
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Project Duration:	28 months
Research Organisations:	The University of Melbourne (UoM), Monash University, Queensland University of Technology (QUT)
Working Group Members:	Dr Philip Christopher – Project Lead (UoM), Dr Duncan Maxwell (Monash), Dr Sahar Soltani (Monash), Dr Siddhesh Godbole (UoM), Dr Ali Rashidi (Monash), Dr Aravinda Rao (UoM), Dr Tendai Makasi (QUT), Dr Francisca Leonard (QUT), Dr Priyadarshini Das (Monash)
Steering Committee:	Professor Mathew Aitchison – CEO, Building 4.0 CRC Professor Chris Knapp – Research Director, Building 4.0 CRC Professor Tuan Ngo – Program Leader, Building, 4.0 CRC (UoM) Dr Duncan Maxwell – Director, Future Building Initiative, and, Program Leader, Building 4.0 CRC (Monash Univeristy) Dr Tanja Tyvimaa – Program Leader - 2022, Building 4.0 CRC (QUT)
Review Committee:	Professor Chris Knapp – Research Director, Building 4.0 CRC Dr Chris Landorf – Project Milestone and Reporting Manager, Building 4.0 CRC Associate Professor Dane Miller – Lighthouse Project Manager, Building 4.0 CRC Dr Sara Omrani – Program Leader, Building 4.0 CRC (QUT) Daniel Rex – Partnerships Director, Building 4.0 CRC
PhD Contributors:	Brandon Johns (Monash), Marko Radanovic (UoM), Sajjad Eini-Zinab (UoM)
Copy Editor:	Jenny Flynn – Communications Manager, Building 4.0 CRC
Project Sponsor:	Advanced Manufacturing Growth Centre Ltd (AMGC)

EXECUTIVE SUMMARY

Industry 4.0, characterised by the integration of advanced technologies and digitalisation, is reshaping the global business landscape across many industries. To date the building industry has lagged behind manufacturing industries and has failed to realise the key benefits of Industry 4.0. This executive summary provides an overview of the key insights and recommendations presented in the report.

The report aims to highlight the transformative implications of Industry 4.0 for the Australian building industry. Implementation of key principles and technologies are summarised along with an action plan and roadmap for the building industry. Industry 4.0 involves integrating advanced technologies like the Internet of Things (IoT), cloud computing, artificial intelligence (AI), robotics, and automation.

These technologies promise to improve sustainability, efficiency, productivity, and project timelines. They can also help enhance safety practices and risk management through real-time monitoring and data analysis.

In contrast to the traditional industry's data paucity, Industry 4.0 enables data-driven insights, predictive analytics, and collaborative ecosystems that connect stakeholders in the building process. By adopting Industry 4.0 technologies, techniques and processes, the Australian building industry can drive substantial enhancements, empowering both industry professionals, customers, and end-users alike.

In leveraging data and advanced analytics, building companies can gain valuable insights that will help customise products for individual customers, offering premium 'customised' products without added overheads that result from traditional bespoke manufacturing Connecting machines and enabling seamless communication between people and technology enables enhanced collaboration and efficiency in industrial processes.

Real-time, data-driven decision-making empowers organisations to make informed choices by integrating disparate systems such as Building Information Modelling (BIM), Digital Twins and IoT.

KEY BENEFITS

Increased efficiency: Processes are accelerated by enabling automated tasks, reducing human error, and enhancing data collection and collaboration, thus driving efficiency and speeding up project timelines.

Enhanced productivity: Automation of repeated tasks enhances resource optimisation and productivity by reducing manual labour, accelerating activities, and minimising accidents, thereby enabling workers to focus on skilled, complex tasks.

Improved accuracy and quality: The use of advanced design and modelling software results in higher quality outputs by facilitating precise designs, ensuring adherence to specifications, reducing errors, and often surpassing industry standards.

Cost savings: Increased efficiency, enhanced productivity, and improved accuracy and quality ultimately fosters cost savings.

Safety and risk mitigation: Automation and digitisation enhance worker safety by mitigating risks, reducing accidents, and fostering proactive risk management through improved monitoring and analysis of safety data.

Data-driven decision-making: Leveraging data analytics enables informed decision-making that enhances project performance, optimises resource allocation, and improves overall project management, thus leading to better outcomes.

KEY BARRIERS

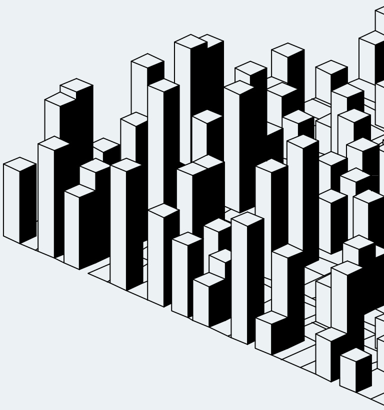
Complexity: The complexity of building projects, marked by numerous interconnected processes, diverse participants, and varied locations, poses a significant challenge.

Uncertainty: The unique, time-limited, and site-specific nature of each building project creates unpredictability due to incomplete process specifications and a lack of uniformity in design, materials, work, and teams.

Fragmented Supply Chain: The highly fragmented supply chain, characterised by numerous small and medium enterprises (SMEs) providing undifferentiated products and services with limited capacities for technology investment, is a key challenge.

Short-term thinking: The building industry's loosely connected permanent networks yet tightly coupled project structures promote short-term thinking and inhibit long-term learning and innovation.

Culture: The building industry has a strong aversion to change and is usually the third or fourth adopter.



THIS REPORT HIGHLIGHTS THE NEED FOR **POLICY MAKERS** TO AID IN THE ACCELERATED ADOPTION OF INDUSTRY 4.0 IN THE BUILDING INDUSTRY ACROSS SIX KEY AREAS:

Skills Development and Education Policies:
This research identified the need for upskilling digital capabilities whilst increasing capabilities of those new to the workforce.

Developing a National Strategy:
A National Strategy is crucial for successful technology implementation whereby construction companies are encouraged to adopt new technologies

Financial Support:
The constraints associated with investing in new technologies is readily apparent in an already challenging sector. Policymakers can assist by providing financial support, such as grants, subsidies, or tax incentives, to encourage construction to invest in the latest technologies.

Collaboration and Knowledge Sharing:
Promoting collaboration and knowledge sharing among industry stakeholders can foster innovation and adoption of Industry 4.0 technologies.

Regulatory Frameworks:
Policymakers should establish supportive regulatory frameworks that promote the adoption of Industry 4.0 technologies in the construction industry. This includes addressing data privacy and security concerns, standardizing digital processes, and ensuring interoperability among different technologies and systems.

Research and Development:
Investing in research and development initiatives focused on Industry 4.0 technologies specific to the construction industry can drive innovation and provide practical solutions to industry challenges. Policymakers should encourage collaboration between academia, research institutions, and industry players to accelerate technological advancements such as the case in The Building 4.0 CRC.

THE REPORT ALSO HIGHLIGHTS RECOMMENDATIONS FOR THE **INDUSTRY** FOR THE ADOPTION OF INDUSTRY 4.0:

Collaborative Efforts:
Transitioning to Industry 4.0 requires collective efforts from industry, government, and research institutions. Education, communication, and regulatory support should be prioritised to incentivise and realise the potential benefits of Industry 4.0 in construction.

Whole Asset Life Approach:
Construction organisations should embrace future operating models that consider the entire lifecycle of assets, similar to Product Lifecycle Management in manufacturing. This approach ensures long-term sustainability and optimisation throughout the asset's lifespan.

Integration of Design, Manufacturing, and Assembly:
Digitisation and automation of the design, manufacturing, and assembly stages are crucial for achieving Industry 4.0 principles in construction. Seamless integration of these stages enables greater efficiency, quality control, and information exchange.

Construction-specific Industry 4.0 Processes:
The unique challenges of the construction environment require tailored Industry 4.0 processes. These specialized approaches address the dynamic nature of construction and offer solutions specific to the industry's needs.

Embrace Relevant Technologies:
In addition to traditional Industry 4.0 technologies, construction should embrace relevant technologies such as smart cities, cloud computing, AI, machine learning, and GIS-enabled mapping. Leveraging these technologies enhances productivity, sustainability, and decision-making processes in construction.

Leveraging Digitisation:
Digitization offers unique opportunities for the construction industry. Adopting digital tools and platforms enables faster and more accurate predictive building modelling, facilitating comprehensive assessments of life cycle, energy efficiency, compliance, and structural performance.

Data Integration:
The construction industry generates vast amounts of data. Prioritising data integration allows for effective utilization of this data. Integrated data provides valuable insights, supports informed decision-making, and drives improvements across the industry.

Ten Year Roadmap to Industrialised Construction in Australia by 2033

KEY ACTIONS AND MILESTONES

	2023	10 YEARS	
GOVERNMENT LED INITIATIVES	Local, State and Federal Government Pilots	Public/Private Ecosystem Programs	Creation of industry cluster hubs
INDUSTRY LED R&D	Building 4.0 Research and Lighthouse Projects	Showcase strategic projects	Scali into l
DIGITAL ECOSYSTEM	Digitally Connected Platform Supply Chain	Modern governance policies	Platf form
ADVANCED CAPABILITIES	Robotic and automated construction capabilities	Digitalisation, and data-driven construction capabilities	Auto and i envir
MODERNISED POLICY	Regulatory body establishment	Certification records and compliance	Robust data privacy laws
SKILLS & TRAINING	Skilled workforce trained in Industry 4.0	Digital training programs and grants	Modernise apprenticeship programs
CULTURE CHANGE	Industry leader recognition	Socially aware practices and processes	Trans buildi

2033

Australia 4.0

Implement a National Strategy

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Supportive regulatory frameworks

Industry driven education curriculum

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KEY TERMS AND DEFINITIONS

AI: Artificial Intelligence refers to the development of intelligent machines capable of performing tasks that typically require human intelligence. It encompasses techniques such as machine learning, natural language processing, and robotics to enable systems to analyse data, reason, learn, and make decisions.

AR: Augmented Reality is an interactive experience that combines the real world and computer-generated content. It allows users to experience virtual objects superimposed on top of physical objects or places.

BIM: Building Information Modelling is a set of technologies, processes, and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. It allows for collaboration, integration, visualisation, and simulation throughout the construction project lifecycle.

Cloud Software: Software applications and services that are hosted and accessed over the internet. In the construction industry, cloud software allows for seamless collaboration, document sharing, and real-time access to project data from various devices.

CNC: Computer Numerical Control is a manufacturing process that utilises computerised systems and software to control the movement and operation of machine tools. CNC machines are capable of executing precise and complex machining operations with high accuracy and repeatability.

DfMA: Design for Manufacturing and Assembly is an approach that focuses on optimising the design of a product or system to simplify manufacturing and assembly processes.

Digital twin: A digital twin is a virtual replica of a physical object or system that provides real-time data and simulations for analysis, monitoring, and optimisation purposes.

Industry 4.0: A term referring to the fourth industrial revolution, characterised by the integration of digital technologies, automation, and data exchange in various industries, including construction.

IoT: Internet of Things refers to the network of physical objects or 'things' embedded with sensors, software, and connectivity capabilities that enable them to collect and exchange data over the internet.

ML: Machine Learning is a branch of artificial intelligence that enables computers to learn from data and make predictions or decisions without explicit programming.

Prefabrication and Modular Construction: Construction methods that involve manufacturing and assembling building components or modules off site, which are then transported and installed on site.

SCMP: Supply Chain Management Platforms are software systems that streamline and optimise the end-to-end processes of planning, sourcing, manufacturing, logistics, and distribution in a supply chain network.

SME: Small and medium-sized enterprises

VR: Virtual Reality is an Immersive Environment where users experience simulated places, objects, and processes. As opposed to Augmented Reality Simulation, VR may require full 'immersion' within multi-projection rooms (CAVE) and/or through stereoscopic goggles and other specialised gear.

XR: Extended Reality is an umbrella term that encompasses virtual reality (VR), augmented reality (AR), and mixed reality (MR). XR refers to the blending of real and virtual worlds to create immersive experiences that can be perceived through digital devices, such as headsets, smartphones, or tablets.

1. REPORT OVERVIEW

1.1 RATIONALE FOR THE RESEARCH

Despite the fervour surrounding Industry 4.0, there remains a noticeable lack of comprehension surrounding its full meaning and the unique value it can provide, especially for the construction industry. This deficiency is further compounded within a disjointed industry where the responsible party for orchestrating efforts to implement Industry 4.0 is not universally agreed.

Moreover, significant skills training is required to leverage its maximum potential, emphasising the pressing need for broader understanding and enhanced workforce preparedness. This project brought together leading companies and research organisations to develop a roadmap towards adopting Industry 4.0 in the broader Australian building industry.

The overarching aims of this research were to shed light on the nuanced meaning and value of Industry 4.0, elucidate the need for clear coordination of efforts, and underscore the importance of skill training and development.

1.2 OBJECTIVES

The key objectives of the research were to:

1. understand the implications of Industry 4.0 for the construction industry by evaluating how it has impacted other sectors and industries
2. examine emergent technologies that facilitate industrialisation and encourage a transition towards off-site manufacturing, after considering their cost-effectiveness, drivers, barriers, and maturity
3. propose practical recommendations for the government based on international best practices and conclusions derived from the rigorous investigation.

1.3 METHODS

The research adopted a triangulation approach:

- a review of academic and industry literature on the implications of Industry 4.0 including existing global benchmarks and white papers
- case studies that embody principles of Industry 4.0 relevant to the construction industry, the technology innovation they exhibit, and their outcomes
- a series of industry workshops to gain insights on the overall industry readiness and awareness of Industry 4.0 in an Australian context
- a series of academic workshops to understand the academic's perception of Industry 4.0, its benefits and challenges, and the areas in the Australian context that need immediate attention
- concept development for an implementation roadmap to synthesise the findings of the above streams of research.

1.4 STRUCTURE OF THE REPORT

This report details the methods and findings of each research stream and can be summarised as follows:

Overview of Industry 4.0: This section elaborates on several key aspects of this transformative industrial paradigm. First, it outlines the general environment of Industry 4.0, illuminating the essential dynamics and significant factors that shape this landscape. Next, it focuses on the recent developments within Industry 4.0, providing a comprehensive update on the progressions and breakthroughs in this area. The report then transitions to explore the role and impact of Industry 4.0 within the sphere of modern manufacturing, analysing its influence on contemporary manufacturing practices and strategies. Finally, the report delves into the digital transformation aspect, elucidating how Industry 4.0 fosters operational efficiency and yields substantial benefits for industries willing to embrace this digital shift. This overview aims to provide a well-rounded comprehension of Industry 4.0, addressing environmental factors, recent advancements, role in manufacturing, and contribution to digital transformation.

International best practice: This section assesses international Industry 4.0 best practice and offers insights into emerging trends, innovative approaches, and successful strategies employed by companies and country policies globally. By understanding and learning from these practices, the Australian building sector can leverage international knowledge to inform their own strategies, improve their competitiveness, and drive positive change in the industry.

Global benchmarking: This section provides an overview of prevailing policies, scholarly articles, and strategic plans published worldwide, thereby encapsulating the current global landscape. It facilitates comprehension of the most contemporary developments in the building sector, spurred by the advent of Industry 4.0. Subsequently, this will facilitate the application and contextualisation of these insights within the Australian context.

Industrialisation in building: This section presents an analysis of the current state of industrialisation in the building industry. It commences by discussing industry platforms, providing relevant background information, elucidating the aims, and detailing the outcomes, before proposing future directions. It then discusses the Product Lifecycle Management (PLM) approach in the context of these platforms.

The report progresses to explore digitalisation in building, enumerating the challenges encountered, identifying key themes and outcomes, and suggesting potential future directions. It considers integration of artificial intelligence (AI), machine learning (ML), and data analytics in building, highlighting their current state, potential applications, and associated challenges. The report further expands on the role of robotics and automation, also known as mechanisation, within this sector. It then delves into the concept of digital twins and BIM, expounding on their importance in modern building. Finally, it examines the utility of extended reality (XR) technologies in the building industry. This comprehensive analysis aims to provide an all-encompassing understanding of the ongoing industrialisation in the building sector, influenced by the integration of modern technologies and innovative practices.

Drivers and challenges of Industry 4.0 adoption: This section summarises the drivers and challenges the Australian building sector faces adopting Industry 4.0.

Case studies, industry and academic workshops: The case studies illustrate the practical applications of Industry 4.0 principles and methods in the real world. Next, the report presents findings from industry and academic workshops, designed to garner insights on the preparedness and understanding of Industry 4.0 in the Australian context, as well as to comprehend academic perspectives regarding its advantages, challenges, and areas of immediate concern.

Pathways to an Industry 4.0 roadmap: The final section articulates key recommendations that pave the way for a successful transition into Industry 4.0. It shares critical technological insights which are instrumental for adopting and integrating Industry 4.0. The report expands on the general understanding of Industry 4.0 and the lessons that can be learned from sectors already immersed in this paradigm. Lastly, the report explores the crucial element of people, focusing on the need for upskilling, education, and training to enable the workforce to thrive in the era of Industry 4.0. This section aims to provide a comprehensive guide for industries navigating the journey towards Industry 4.0.

2. INTRODUCTION TO INDUSTRY 4.0

The combined Australian construction and property sectors together generate AUD371 billion in revenue (or 9% of gross domestic product in 2022)[1] but face major challenges including a fragmented supply chain, cost overruns, material price escalations, skills shortages, and relatively low productivity. In today's rapidly evolving digital landscape, Industry 4.0 has the potential to address many of these challenges and transform the building sector. Australia finds itself in a global race with countries that recognise the significant changes taking place in the sector. The digital transformation of manufacturing through Industry 4.0 is reshaping traditional production methods and business models, presenting both challenges and opportunities for the Australian building industry.

Despite the rapid approach of the next wave of industrial change, the majority of Australian building businesses are still grappling with what Industry 4.0 means much less adopting relevant technologies and practices. Scepticism about return on investment and uncertainty about where and how to embark on the Industry 4.0 journey persist among many of the industry actors. Further, there is a misconception, particularly among small and medium-sized enterprises (SMEs), that these new technologies are expensive, complicated, and out of reach.

This report aims to address these challenges and provide insights into the adoption of Industry 4.0 in the Australian building landscape. By engaging with both industry and academia, this report sheds light on the specific issues hindering progress. Additionally, the report delves into the limited understanding of Industry 4.0, the low buy-in from top management, the lack of solutions tailored to the needs of SMEs, and the critical aspect of data security.

Through a comprehensive analysis of these challenges and their implications, this report equips Australian policymakers and actors in the building sector with the necessary knowledge and strategies to adopt many of the Industry 4.0 principles and technologies. By providing practical recommendations and highlighting global success stories, we aim to inspire and empower businesses to embrace digital transformation, overcome obstacles, and unlock the full potential of Industry 4.0.

This report provides a roadmap to support Australian building companies and stakeholders in the building sector as they embark on their Industry 4.0 transformation. It aims to enhance their competitiveness and efficiency, while also improving building quality and safety.

1 Australian Bureau of Statistics (March 2023)

3. INTERNATIONAL BEST PRACTICE

Penetration of Industry 4.0 into the building sector varies around the world. However, we can learn key strategies and initiatives from global leaders of Industry 4.0. Although these strategies do not necessarily directly focus on construction, they can be applied in a way that considers the complexity and diversity of construction, as we will discuss. A summary of international best practice examples is presented below, with more specific case studies detailed in Section 4 (Global benchmarking).

National Strategies and Initiatives:
Example: Germany's "Industrie 4.0" initiative is a national strategic plan that aims to strengthen Germany's position as a leader in advanced manufacturing which includes funding for research and development, support for SMEs, and collaboration between government, academia, and industry.

Collaboration and Public-Private Partnerships:
Example: Singapore's Advanced Remanufacturing and Technology Centre (ARTC) is a public-private partnership that brings together government agencies, research institutions, and industry partners to develop advanced manufacturing technologies and drive adoption in the manufacturing sector.

Digital Infrastructure:
Example: South Korea has made significant investments in its digital infrastructure, including widespread availability of high-speed internet and the development of 5G networks. This infrastructure supports the implementation of technologies like IoT and enables the integration of smart factories.

Skill Development and Education:
Example: Switzerland has a dual education system that combines classroom learning with practical training. The Swiss Vocational and Professional Education and Training (VPET) system prepares students with the necessary technical skills for Industry 4.0 by offering apprenticeships and specialized vocational training programs.

Innovation and Research:
Example: The United States has established innovation hubs and technology parks, such as Silicon Valley and Research Triangle Park, which serve as ecosystems for collaboration, entrepreneurship, and technological advancements. These hubs attract startups, research institutions, and venture capitalists, fostering innovation in various sectors.

Regulatory Frameworks and Standards:
Example: The European Union's General Data Protection Regulation (GDPR) sets standards for data privacy and protection. It establishes rules for the collection, storage, and processing of personal data, ensuring that businesses adopting Industry 4.0 technologies comply with stringent data privacy regulations.

Testbeds and Demonstrators:
Example: The Netherlands' Smart Industry Field Labs are physical environments where companies can experiment with Industry 4.0 technologies and solutions. These field labs provide a collaborative space for businesses, research institutions, and technology providers to test and validate innovations before scaling up.

International Cooperation:
Example: The Japan-Germany Industrial Cooperation Initiative promotes collaboration between Japanese and German companies in areas such as robotics, automation, and digitalisation. Through this initiative, companies from both countries share knowledge, expertise, and technologies to drive advancements in Industry 4.0.

4. GLOBAL BENCHMARKING

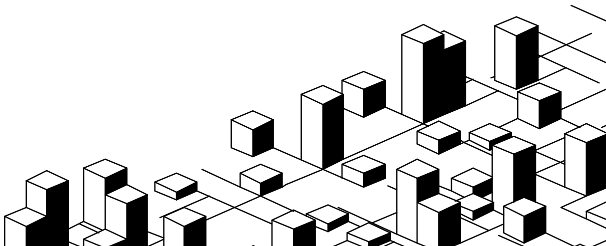
A global benchmarking exercise provided insights and knowledge from best practices and successful strategies implemented in different countries and organisations worldwide. This allowed us to compare policies and approaches as well as outcomes between industry leaders and top-performing countries. It also helped us identify areas for improvement, set performance targets, and implement effective strategies to enhance competitiveness, efficiency, and productivity.

We have documented the insights gained from the global benchmarking into the emergent trends and successful strategies that have the potential to foster growth and enhance the performance of the building sector.

EMERGING TRENDS

- A significant trend is integrating Industry 4.0 technologies to achieve smart operations. This involves utilising data-driven decision-making, reducing budget and schedule variances, and implementing dynamic scheduling to enhance operational efficiency.
- Prefabrication and modular construction methods are also gaining traction. These off-site production approaches are consistently identified as solutions that improve quality control and shorten project schedules. By embracing these methods, building companies can optimise productivity and minimise budget overruns.
- Using data and advanced analytics is another key trend. Companies are leveraging advanced analytics and AI to move from reactive to predictive decision-making. By harnessing the power of data-driven insights and AI technologies, building businesses can optimise processes, enhance productivity, and improve overall performance.
- As technology continues to evolve, the future of work in the building industry is also evolving. Organisations need to consider how roles and jobs may change to align with emerging technologies. This trend highlights the importance of workforce adaptation and skill development to meet Industry 4.0 demands.
- Further, strategic sourcing is gaining prominence as companies shift from traditional budget-focused approaches. Strategic sourcing aims to reduce complexity and create ecosystems of key partners, enhancing responsiveness to future disruptions while optimising costs and project delivery.

These emerging trends reflect the growing influence of Industry 4.0 and digital transformation in the building industry. By embracing innovative technologies, data-driven decision-making, modular construction methods, and strategic approaches, building companies can enhance their competitiveness and overall performance in the evolving landscape of the industry.



SUCCESSFUL STRATEGIES

We identified a number of successful strategies. First and foremost was embracing digital transformation, where successful companies integrate digital technologies and Industry 4.0 principles into their operations. This includes implementing smart operations, utilising data and advanced analytics, and adopting emerging technologies like AI, robotics, and automation to improve productivity and efficiency.

Collaboration and connected construction are also emphasised as best practices. Companies recognise the value of collaboration among stakeholders and the benefits of using connected building platforms. Bringing all relevant parties onto a single platform streamlines building projects, optimises processes, and enhances communication, leading to improved project outcomes.

Lean and modular construction methods are widely regarded as best practices. Embracing lean principles helps eliminate waste, improve efficiency, and maximise value throughout the construction process. Modular construction, including prefabrication, enables greater standardisation, better quality control, and shorter project schedules.

Prioritising talent development and workforce adaptation is another best practice. Companies that invest in upskilling their workforce and providing training in emerging technologies are better prepared to navigate the challenges of Industry 4.0. It involves fostering a culture of innovation, adapting job roles to align with digital construction, and staying abreast of technological advancements.

Data-driven decision-making is essential, and best practices include establishing robust data collection and management systems, leveraging data analytics tools, and utilising predictive modeling to optimise project planning, scheduling, and resource allocation.

Finally, a culture of continuous improvement and learning is emphasised. Companies that embrace a mindset of innovation, encourage feedback and collaboration, and actively seek opportunities to learn from successes and failures are more likely to thrive in the era of Industry 4.0. By adopting these best practices, building companies can position themselves for success in the changing landscape of the industry. Embracing technology, fostering collaboration, and prioritising efficiency enable better project outcomes and help maintain a competitive edge.

5. DECONSTRUCTING INDUSTRY 4.0

The manufacturing industry has undergone several foundational changes since the beginning of the first industrial revolution[1]. The First Industrial Revolution (the 1780s) introduced manufacturing plants powered by hydro and steam; the Second Industrial Revolution (the 1870s) introduced shared mass production with electricity; the Third Industrial Revolution (the 1970s) began automating manufacturing systems through information technology and the Fourth Industrial Revolution[2] (the 2000s, now) is driven by seamless connectivity, cloud services, advanced materials and processing, collaborative manufacturing networks, collaborative robots, cyber-physical systems (devices and networked controlled automatically), mass customisation, and product-as-a-service[3]. The Fourth Industrial Revolution includes changes to the entire value chain from raw materials to end-use, influencing the entire supply chain networks, processes, and stakeholders (suppliers, manufacturers, logistics, etc.).

5.1 INDUSTRY 4.0 ENVIRONMENT

The digital transformation of manufacturing/production and allied industries, as well as value creation processes, is known as Industry 4.0. It is sometimes associated with the fourth industrial revolution, and it refers to a new stage in the organisation and management of the industrial value chain. Products and production methods become networked and can 'communicate' in this fashion, enabling new production methods, value creation, and real-time optimisation[1]. The following are some of the advantages of Industry 4.0:

- Increased digitisation and automation of the manufacturing environment
- creation of a digital value chain to enable communication between products, their environment, and business partners
- product and production process planning leading to improved product quality, reduced time to market, and improved enterprise performance.

5.2 INDUSTRY 4.0 DEVELOPMENTS

The term 'Industry 4.0' can be divided into two development paths[4]: (i) strong application pull resulting in a significant demand for adjustments when the operating framework evolves and (ii) an exceptional technological drive-in industrial practice. Some of these developments are influenced by social, economic, and political developments, such as:

Shortened development and innovation timeframes: For many businesses, high innovation capability is becoming a critical success factor ('speed to market').

Individualisation on demand: For decades, a shift from a seller's to a buyer's market has been evident, implying buyers can set the terms of the sale. This trend leads to increased product individualisation, and in certain situations, individual products ('batch size one').

Flexibility: Meeting new and varied project requirements requires more flexibility in product development, particularly in production.

Decentralisation: Dealing with the given circumstances requires quicker decision-making procedures. Hierarchies inside organisations must be reduced to achieve this.

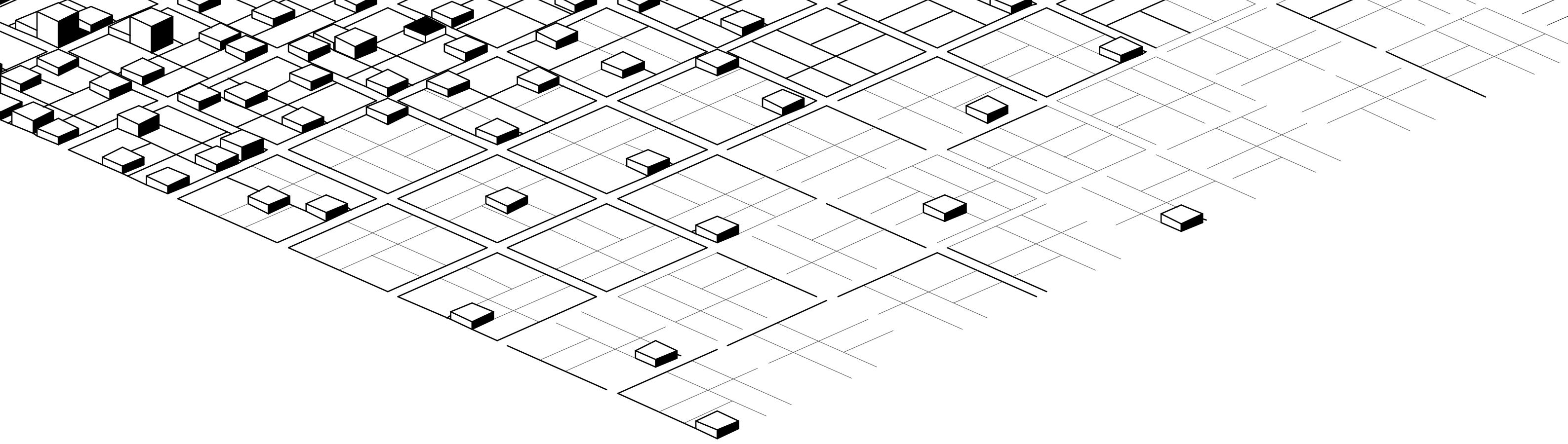
Resource efficiency: Increasing scarcity and the resulting rise in resource prices, as well as social change in the context of environmental issues, necessitate a more focused attention on sustainability in industrial settings. The goal is to boost efficiency in a way that is both economical and environmentally friendly.

1 Advanced Manufacturing Growth Centre (2018)

2 Cheng et al. (2020)

3 van Thienen et al. (2015)

4 Lasi et al. (2014)



5.3 INDUSTRY 4.0 IN MODERN MANUFACTURING

Industry 4.0 is increasingly adopted in modern manufacturing with the following key benefits:

- New design principles[1] with increased interoperability among manufacturing networks, virtual plants and simulation models
- Virtualisation of manufacturing processes linked by sensor data (physical sensors), decentralised decision-making, real-time analysis and monitoring, adapt to real-time changes to cater for manufacturing and services
- New materials and manufacturing technologies are enabling efficient manufacturing while increasing the customisability and scaling
- Collaborative networked systems (machines, sensors, processes, people and robots) working together to provide greater operational efficiency
- Extract knowledge from sensor data and AI to optimise operations, planning schedule, predictive maintenance to reduce downtime

5.4 DIGITAL TRANSFORMATION: INDUSTRY 4.0 FOR OPERATIONAL EFFICIENCY AND BENEFITS

There are three levels of digital transformation: strategy, execution, and technology[2]. Having at least two of the three levels is recommended to achieve the digital transformation. Enabling technologies are the foundation for this transformation, but technology alone cannot transform the business. In the middle, we have execution; this is where Industry 4.0 plays a major role in optimising the operations, operating model within the company, and product customer value proposition.

At the top of the pyramid is a business strategy that defines the path forward. It is not enough to have any one of the three levels, but an organisation should have an integrated view of the entire business that is enabled digitally.

1 Thienen et al. (2015)

2 Turchi (2018)

6. INDUSTRIALISATION IN BUILDING

6.1 OVERVIEW

Industrialisation in building refers to the adoption of manufacturing-like processes and technologies to improve efficiency, productivity, and quality. It involves shifting from traditional on-site construction methods to more off-site and prefabrication approaches.

This section presents five key technologies and concepts leveraging existing Building 4.0 CRC projects where appropriate to provide greater and specific insight for the Australian building industry.

6.2 SUPPLY CHAINS IN BUILDING

The building supply chain is one of the critical enablers for the building industry. It poses challenges and risks mainly due to the typical make-to-order nature of the building supply chain, which is often unstable, highly fragmented, and geographically dispersed. The ability to track and trace, or traceability, is becoming increasingly important as it contributes to and associates with building compliance, safety, project efficiency, sustainability, and performance.

Through one if its projects the Building 4.0 CRC aims to understand the state-of-the-art traceability in the building industry and key stakeholders' perspectives and recommend future research. The longer-term objective of Building 4.0 CRC's work in this area is to demonstrate how sensor networks can provide live-streamed data to improve project management and validate building compliance through measures used to guarantee the provenance of the supply chain.

For example, food safety and quality drive traceability in the food industry, which are the primary concerns of any food business. Other benefits of traceability include optimising process efficiency, improving sustainability performance, and increasing consumer confidence. Also, there are comprehensive legislation, regulations, and international standards mandating traceability in the food industry. Although the legislative requirements demand minimal information and can be fulfilled with a paper-pencil approach, some sectors (e.g., red meat) take an extra step and rely on complete digitalisation and a centralised database. For example, the company GS1 plays a pivotal role in traceability, providing standards for identifying, capturing, sharing, and using information related to a product. The GS1 12 Identification Keys contains information describing the critical tracking events, including the who, what, where, when, and why.

Transporting materials is critical in building processes, accounting for a sizeable portion of total project expenditure. In traditional material management methods, the logistics of building materials are manually tracked and updated from the factories to the building sites. This manual method causes excessive procedures (e.g., counting and inspections) and extra labour costs that are avoidable with the aid of sensing technologies. However, unlike other venues along the supply chain (e.g., factories, ports, and distribution centres), the building site is highly complex and dynamic and requires flexible and specifically tailored solutions.

Supply chains in building projects differ from other industries. The main differences are: (i) the complexity and inter-related nature of building projects and their legal context, generally undertaken by a temporary consortium of firms; (ii) unique activities such as excavation, where the 'supply activity' is a removal activity; (iii) the active role of the demand chain participants in checking and approving the results of supply chain activities; (iv) the heavy use by all of a flexible mix of 'supply only', 'service only', and 'supply and service' subcontracts; and (v) the role of the lead contractor (construction systems integrator) in creating and managing a production facility which can change dramatically throughout the single contract.

A building project often involves a complicated and dispersed supply chain. Accountability is required to ensure the exchange of accurate data on quality, safety, progress, costs, resources, and payments, and collaboration is necessary to manage such a fragmented supply chain.

Although some modern supply chain management platforms (SCMPs) have long been committed to eradicating fragmentation in the industry, there is still a lack of accountability or collaboration, which results in disputes, cost overruns, decreased productivity, and accidents. For instance, di erent suppliers may use different supply chain management systems and tracking methods to track their building materials in one project. Integrating these data from di erent systems and providing accurate and timely information is still a problem to be solved. Blockchain technology can address the current building industry's issues by making the building supply chain more transparent, traceable, and accountable for all project participants.

In general, technologies with common standards can be integrated into a suite for material tracking and construction processes. Although most technologies have standards, a few proprietary technologies could be integrated with mainstream technologies for easy integration and interoperability of data flow and tracking. The available technologies are relatively advanced, and the commercial solutions would easily cater to most construction processes. In addition, the commercial solutions are flexible and have options to integrate into existing technology platforms as needed.

The benefits of enhanced supply chain collaboration and greater transparency will become more evident when the entire supply chain engages in traceability. Some barriers/challenges (e.g., short-term relationships and unbalanced risk across the supply chain) may be inherent to how the building supply chain is designed and, hence, more challenging to overcome. Early adopters of traceability will see the benefits more quickly than late adopters. Traceability technology offers the opportunity for building companies to semi-automate select processes that have been traditionally manual and improve access to real-time information (of improved quality) to inform project decision-making.

6.3 DIGITALISATION IN BUILDING

Digitisation and automation play a crucial role in the building industry by revolutionising traditional processes and bringing about significant improvements in efficiency, productivity, and overall project outcomes. The effects of enhanced digitisation and automation in building are summarised below:

Increased efficiency: Digitisation and automation streamline building processes, improving efficiency. Tasks that were previously manual and time consuming can now be automated, reducing human error and speeding up project timelines. Digital tools and technologies enable faster data collection, analysis, and sharing, facilitating better coordination and collaboration among project stakeholders.

Enhanced productivity: By automating repetitive tasks, building companies can optimise their resources and boost productivity. Automation of construction machinery and equipment reduces manual labour requirements, accelerates construction activities, and minimises the risk of accidents. Workers focus on more skilled and complex tasks, ultimately increasing overall productivity.

Improved accuracy and quality: Digitisation enables the use of advanced design and modelling software, resulting in more accurate and precise building plans. Automated machinery ensures consistency and adherence to design specifications, reducing errors and rework. By minimising human intervention, digitisation and automation contribute to higher quality construction, meeting or exceeding industry standards.

Cost savings: Digitisation and automation can lead to cost savings in various ways. Automation reduces labour costs by minimising the need for extensive manual workforce and optimising resource utilisation. Accurate data and real-time insights enable better project planning, reducing material waste and optimising procurement. Additionally, improved efficiency and productivity translate into faster project completion.

Safety and risk mitigation: Automation helps mitigate safety risks and improve worker safety. Replacing human workers with automated machinery for hazardous tasks significantly reduces the risk of accidents and injuries. Digitisation allows for better monitoring and analysis of safety data, enabling proactive risk management and adherence to safety regulations.

Data-driven decision-making: Digitisation generates a wealth of data throughout the construction lifecycle. By leveraging data analytics, construction companies can gain valuable insights into project performance, identify bottlenecks, and make informed decisions. Data-driven decision-making improves project planning, resource allocation, and overall project management, leading to better outcomes.

This section investigates and categorises the role core technologies contribute in the construction sector which have been assigned into the following categories:

- IoT and Sensors: A bridge between digital systems and the physical world
- Artificial intelligence, Machine Learning and Data Analytics: Methods to gain insight from large amounts of data
- Robotics and Automation: A means for digital systems to interact with the physical world
- Digital twin and Building Information Modelling: Digital representations of building plans and built objects
- Extended reality (XR) technologies: A means to visually communicate digital information

Together, these technologies enable the digitisation of building, in digital planning, data collection, processing, visualisation, and automated interaction.

6.3.1 IoT and Sensors

IoT describes physical objects (things) that are embedded with sensors, software, and other technologies that can connect and exchange data. IoT and advancements in sensor technology enable real-time monitoring and information dissemination in building activities. Handheld tablets and smartphone apps provide direct access to data entry, distribution, retrieval, and analysis. The digital and connected nature of IoT enables seamless integration between stakeholder systems. In this way, sensors and IoT are the backbone of Industry 4.0 technologies and the key to their effective and efficient integration.

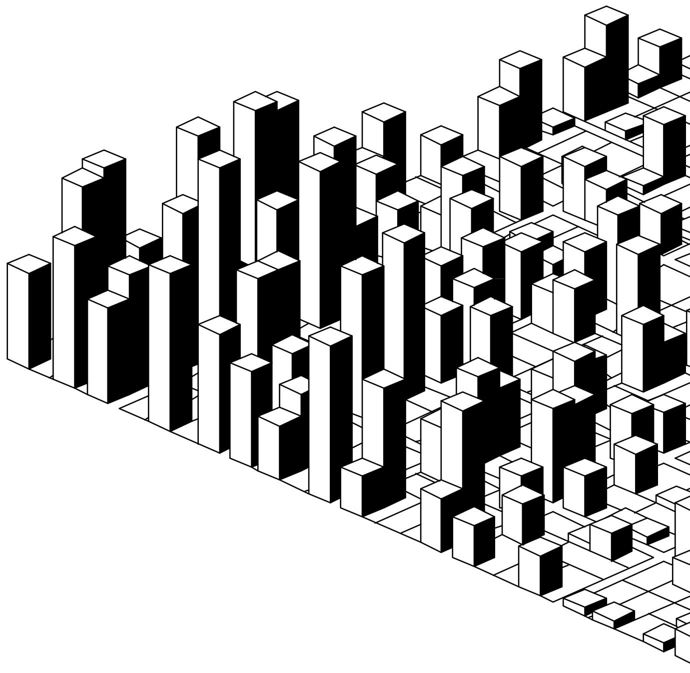
Sensor based monitoring within IoT networks can enhance communication between off-site and on-site activities. On-site robots and sensors can relay sensor data into systems for progress monitoring, safety monitoring, early fault detection, resource management, and change management. These systems can then give workers immediate alerts and instruction. The following are key challenges associated with sensors and monitoring onsite:

- An infeasible number of sensors are required to collect all information that can be collected.
- With increasing numbers of sensors, data processing becomes very difficult.
- This presents the question of what sensors should be used, and where, considering that building sites are constantly changing, causing data to become quickly outdated.
- Sensors are easily rendered ineffective (e.g., obscuring a camera view).
- Significant computational cost is incurred to extract actionable information from raw sensor data.
- Many sensor technologies require manual initialisation.
- Data privacy and security in IoT is crucial. Sensors gather information on materials, equipment locations, worker locations, and worker health status. Data is frequently exchanged with third-party applications, creating potential for data leakage and privacy violation.

Adopting the discussed technologies involves focusing on getting subcontractors onboard. Incentives could be considered to make it worthwhile to use the technology, while not affecting their productivity and the job they want to focus on (and get paid for).

Consideration must be given to not just generational issues, but how technology assists in execution/delivery tasks. Further, building is home to predominantly small businesses making up 62.1 % of persons employed in the building industry in Australia1. As such technology must be appropriate for implementation by sole traders and smaller contractors. User interface design is especially important for ease of use, ready interpretation, and perhaps providing a solution to future workforce training that is a major concern. There is a common perception that technology must not 'take over' from good work practices and understanding or be seen to be a silver bullet. Any future technological solutions must assist existing work practices.

It is clear that project scale limits opportunities for project-specific technological solutions. Project-to-project tests are common, and even large projects do not receive support from technology companies in appropriate ways. The technologies proposed and the system trialled in projects should have clear and communicated pathways for their future use.



1 ABS 2012

IOT AND SENSORS

Adoption

- Real-time Monitoring
- Equipment Tracking and Management
- Smart Asset Management
- Re-scalable platforms
- Connectivity and Network Infrastructure

Considerations

- Increasing R&D investments
- Smart Asset Management
- Compliance with data protection, safety, and environmental regulations
- Data privacy, ownership, and ethics

Benefits

- Enhancing communication between off-site and on-site activities
- Early detection of hazardous conditions
- Reducing equipment downtime
- Ensuring adherence to quality standards and minimising errors/defects
- Data-driven Insights and decision-making

Challenges

- Data Security and Privacy
- Integration Complexity and compatibility
- Cost and Return on Investment (ROI)
- Interoperability and Standardisation
- Change Management and Adoption Culture
- High processing requirements

Application

- Monitoring and safety
- Smart site management
- Quality Assurance and Defect Management
- Energy and resource efficiency

Maturity level

Basic Connectivity

- Connecting devices to the Internet and collecting data
- Enable data transmission and remote access

Data capture

- Capturing structured data from IoT devices and sensors
- Deployed data capturing and monitoring

Analytics & insights

- Derive value from captured data
- Establish systems to real-time monitoring and alerting

Advanced Automation

- Integration with other techs (AI and ML)
- Automate decision-making processes, optimise operations
- Enable predictive maintenance
- Interconnected software and hardware

6.3.2 Artificial Intelligence, Machine Learning and Data Analytics

AI and machine learning (ML) enable drawing insights from various types of data collected across different building activities. The building industry generates and records large quantities of data. There is potential to enhance productivity by optimising the use of data collected via AI/ML approaches[1]. Building data quality issues, including inaccuracies due to manual data entry processes and data untimeliness due to delayed data collection, can be addressed by automating data capturing tasks using AI technologies. In addition, ML offers enhanced data analysis capabilities that integrate the data collected across different stages to uncover key insights about building processes. AI/ML affords industry an opportunity to leverage past data (e.g., previously completed structures), current data (e.g., models), and other external data sources that influence operations in real time[2]. Building firms can experience significant advantages particularly around automating management processes to enhance data-driven decision-making.

Current state AI/ML

In Australia, building firms tend to take a cautious approach towards adopting AI/ ML technologies. Activities that can be facilitated by AI and ML are largely being handled either manually or through legacy technology systems. For instance, building site supervisors perform physical inspections to evaluate work progress and reassess scheduling plans accordingly. The complexity of visually matching a space to the specifications can result in errors due to such manual exercises. Notably, the Australian building industry is starting to have more conversations around the potential benefits of AI and its predictive capabilities to facilitate streamlined on-site operations[3].

Applications

Some of the benefits of AI and ML are improved project planning and designing. AI and ML can be used to explore multiple versions of project designs. In particular, ML approaches can be used to investigate the durability and compatibility of different building materials throughout the different construction stages. For example, engineers can use prediction tools based on ML models to design optimal foamed concrete mixtures[4]. In addition, AI-driven automation for repetitive tasks can improve planning efficiency. Modern building designs are leveraging AI-driven models to map the routing of plumbing and electrical systems[5].

AI is being used to design safety systems for worksites. Tracking of real-time interactions of workers, machinery, and objects on the worksite offers early intervention opportunities to minimise potential safety risks (e.g., worksite injuries). Manual construction tasks often require abnormal postures that can cause injuries. The conventional methods of worksite injury risk assessment which involve posture data collection through questionnaires and site observations, are inefficient and prone to subjective bias. ML models can analyse data from wearable sensors and monitoring devices (e.g., on-site cameras) to detect tiredness or fatigue in construction workers, which poses a safety risk.

1 Rampini et al. (2022)

2 Abioye et al. (2021)

3 Akinosho et al. (2020)

4 Salami et al. (2022)

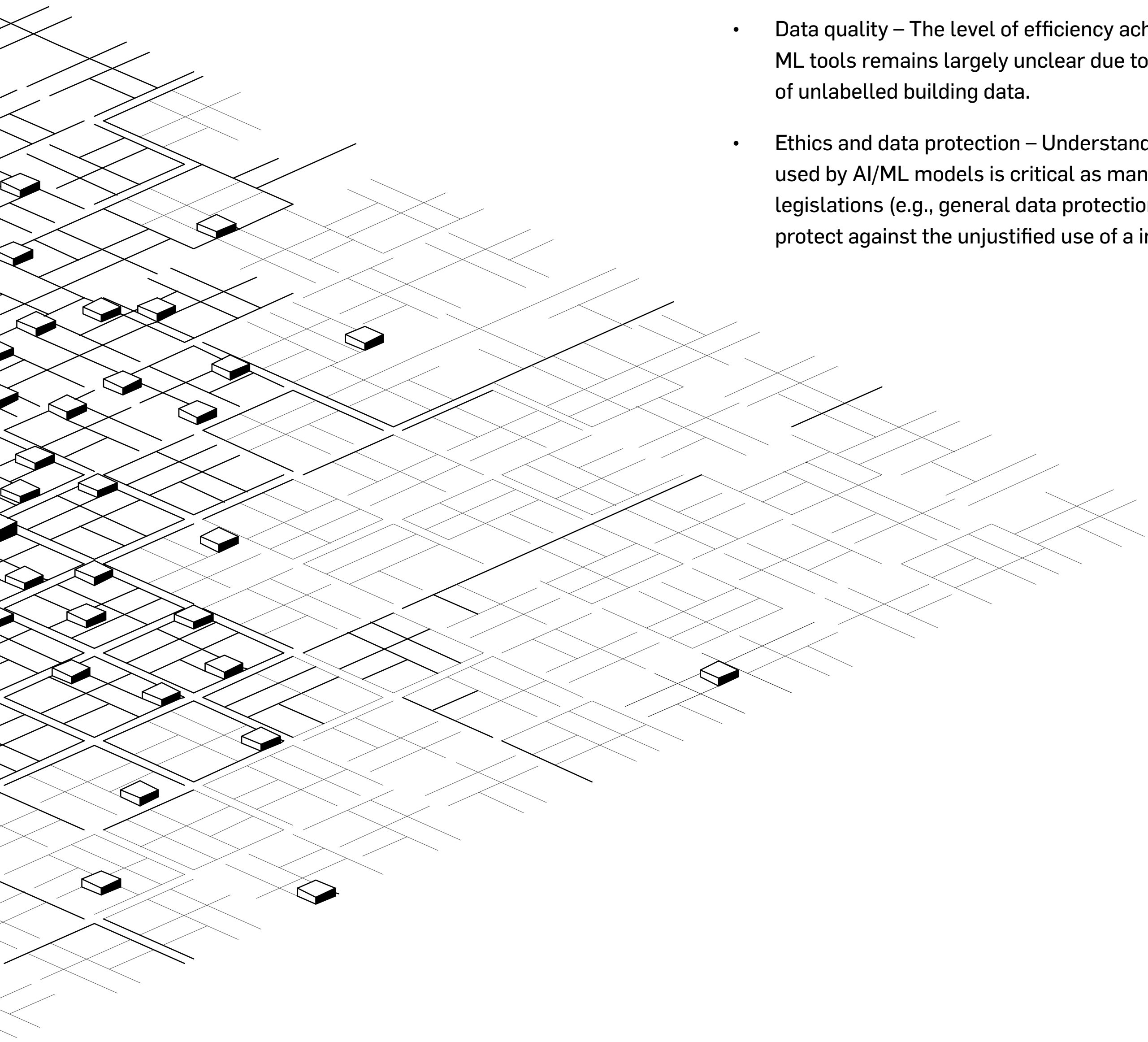
5 Nguyen et al. (2019)

Predicting building costs is frequently driven by factors such as construction type, building period, equipment, and labour requirements. Building costs, building period, and many other variables all depend on building design. Compared with reconstruction initiatives, remodelling building designs in the early project stages offers many benefits including low waste generation, shorter time periods, and significant resource savings. ML modelling tools can incorporate external environment variables such as economic indexes, time dependant variables, and other seasonal changes to improve cost predictions in the early stages of building projects[1].

Challenges

The main challenges to implementing AI/ML models in building industry include the following:

- Inhouse capability for AI/ML – While engineers best understand building problems and optimal solutions, knowledge of AI/ML remains scarce.
- Resistance to change – The construction workforce is accustomed to hands-on and practical ways of working, making it less interested in AI/ML tools, particularly when learning to use these tools is perceived as resource and time intensive.
- Data quality – The level of efficiency achievable through AI/ML tools remains largely unclear due to the vast amounts of unlabelled building data.
- Ethics and data protection – Understanding the exact data used by AI/ML models is critical as many data privacy legislations (e.g., general data protection regulation) protect against the unjustified use of a individuals' data.



1 Akinosho et al. (2020)

AI/ML AND DATA ANALYTICS

Adoption

- Early adoption
- Data Availability and Quality
- Data Governance and Infrastructure
- Integration with Existing Systems

Considerations

- Ethical considerations and responsible utilisation
- Data privacy and security
- Regulatory and legal compliance
- Scalability and interoperability of solutions
- Change management and organisational readiness

Benefits

- Improved decision-making based on data insights.
- Enhanced operational efficiency and productivity.
- Automation of repetitive tasks and processes.
- Personalization and improved customer experiences.

Challenges

- Data quality and availability for training ML models
- Lack of skilled professionals
- Integration with existing systems and processes
- Balancing cost and return on investment
- High processing requirements

Application

- Predictive Analytics for Project Planning
- Quality Control and Defect Detection
- Autonomous and Intelligent Equipment
- Energy Optimisation and Sustainability
- Safety Monitoring and Risk Management

Maturity level

Basic Awareness

- Understand AI/ML concepts and potential applications

Piloting

- Conduct small-scale pilots and proofs-of-concept
- Gain practical experience and validate concepts

Integration

- Integrate AI/ML into operational processes
- Optimised operations through AI/ML capabilities

Advanced AI-Driven Transformation

- Embrace AI/ML as strategic assets for transformation and innovation
- Leverage advanced techniques like deep learning or natural language processing

6.3.3 Robotics and Automation

Construction robotics is a paradigm of machinery design with the goal to create machines that, when given a task, can determine how to complete the task by themselves. Making a 'robot' is not necessary to robotic design. Robotic machinery does not need to be sophisticated or fully autonomous. An example of robotic design is a self-levelling line laser – it autonomously completes the task of levelling its laser. In this way, robotic design is a means to enhance current machinery and methods. The present and future of construction robotics is summarised as[1]:

- alteration of conventional processes and components to introduce robotic subsystems or interfaces
- off-site component prefabrication in factory environments
- on-site material handling, component installation, and inspection with single-task robots
- the subtle integration of robotic technologies ubiquitously into tools, building components, and our daily lives.

The recommended progression towards the robotic industrialisation of the building industry is to address each building task in isolation. For each task, first, replace manual labour with manually driven machinery. Then, progressively augment this machinery with computer assistance systems, where each progression allows the machine to complete more complex tasks with less operator input. As the system is made more capable, its purpose should be made more specialised. This results in the 'single-task robot'[2].

Application of single-task robots facilitates modularity in business decision-making towards both the gradual, targeted introduction of robots into building and also the long-term technological upgrade path. A single robot may be introduced, replaced, or upgraded without significantly impacting any other process. Hence the business impact is measurable as the increase in performance in that single task. To fully realise the benefits of construction robotics, all robots should be designed with standardised hardware and software interfaces. Open and manufacturer agnostic interfaces are imperative to modularity.

Advantages of modular robotic interfaces:

- As a component passes from manufacturer to contractor, the hardware interface is shared.
- Tooling need not be frequently changed.
- Robotic systems moving between projects are compatible with site-specific systems.
- Systems of collaborative robots can be composed and customised per the needs of the application.

This approach enables integration between robotics and the other Industry 4.0 technologies.

1 Bock (2015)

2 Brosque & Fischer (2022)

ROBOTICS AND AUTOMATION

Adoption

- Cost
- Compatibility
- Company's scale and scope
- Investment in devices and machineries
- Location and size

Considerations

- Measure business impact by task performance
- Long-term upgrade path: Machinery
- Long-term maintenance: Built object
- Interface compatibility: Between teams within a project
- Interface compatibility: Between projects

Benefits

- Increased task performance (economic efficiency, speed, safety)
- Expands worker demographic by reduced manual labour requirement
- Provides a medium for IoT, enabling other I4.0 technologies

Challenges

- High upfront cost
- Requires user training
- Potential for vendor lock-in by non-standard interfaces
- Interfacing between multiple robotic systems

Application

- Integrated into conventional tooling
- Prefabrication
- Material handling
- Component installation
- Inspection

Maturity level

Manual labour

- Digging with shovels

Mechanisation

- Humans piloting dumb machines

Analytics & insights

- Computers controlling machines to repeat specific instructions
- Little or no adaptability

Collaborative networked machinery

- Humans piloting or managing intelligent machines
- Adaptive to broader information

6.3.4 Digital twin and Building Information Modelling

Digital twin refers to a virtual or digital representation of a system or object that includes information across its whole lifecycle. Digital twins create a comprehensive database of the project by tracking the state of an asset through sensor networks; then mirroring this information onto a digital representation of the asset. The concept of collecting the accurate data about real-world conditions is called reality capture.

Many data capture devices and technologies exist, such as mapping sensors (e.g., laser scanners, cameras) and positioning sensors (e.g., global satellite navigation systems, inertial sensors) mounted on different platforms (e.g., equipment, unmanned vehicles). This data is used to generate, track, and improve a digital twin. Further, this real-time data of the asset and its environment can be combined with historical data and used to make maintenance predictions through machine learning techniques, or automated adjustments of building systems through the IoT network.

In the context of the building industry, digital twins can be used for building maintenance and operation, while its closest counterpart, BIM, creates a digital replica of a building mostly used in design and construction phases. BIM integrates representation of the physical and functional characteristics of buildings into a complete plan. BIM layers the work of every discipline (structural, mechanical, electrical, plumbing, etc.) to enhance the collaborative design process. It also enhances design validation, change management, scheduling, costing, and data management. BIM's core strength is in sharing the model between all stakeholders to support decision-making and the built object's lifecycle management.

Digital twins are ideal for lifecycle management because they can be used throughout all phases, from planning and design through to construction, maintenance, and operation. Some of the benefits of digital twins include the following:

- centralises project information within a single collaborative environment, improving information flow and providing instant communication
- integrates with MR technologies, bridging off-site and on-site processes and facilitating progress monitoring and building inspection
- enables lean construction, because although digital twin applications are extremely varied, most are steps towards lean construction
- promotes improved overall performance and lower building costs through a higher degree of automation, which enables better planning and control while reducing the time and lowering the margin of human error
- improves waste management and reuse
- improves transparency and offers guaranteed immutability of supply chains through blockchain integration.

Digital twins can be useful across a wide range of applications in the building industry:

Asset lifecycle management: Digital twins can be used to improve the building performance and energy efficiency through automated monitoring, control, and optimisation of different building subsystems such as temperature, humidity, or electricity. Continuous analysis of historical and live data is used for maintenance prediction using machine learning. AR integration allows overlay of integrated underlying digital content on top of reality for facility management. In emergency responses, live information streams can be used to calculate shortest and safest evacuation paths or assist the response teams in finding the victims in need of help.

Supply chain management: A digital twin can serve as an information flow integrator for the building supply chain. It also can be integrated with GIS for its geographic and other information to assist with supplier selection based on different criteria, such as waste management to help reuse and reduce waste. The lifecycle impact in terms of economic, social, and environmental impacts of chosen materials can be assessed through integration with different auxiliary databases that hold information such as material or fuel carbon data.

Automated planning: Construction schedules, construction tasks, sequencing rules, and activity durations from production rates are automatically created from digital twin information. Concrete pouring starting points, directions, and maximum daily volumes can be created and scheduled. The impact of construction change orders on physical conditions, schedules, and costs can be immediately assessed. Automated material logistics planning and managers can help reduce the impact of often haphazard site layouts amid various uncertainties and modifications to the construction schedule.

Health and safety management: Live IoT data on people and equipment can be combined with building or construction site information such as connectedness or closeness. Information streams can detect potential risks or identify unsafe behaviour.

Blockchain integration: Moving a digital twin to a blockchain is a natural direction because the relationships between stakeholders in building are natively peer-to-peer rather than hierarchical. Blockchains can bring transparency and immutability to digital twins, as well as the ability to trace the history of changes.

Building site monitoring: Digital twins can be superimposed on top of the site during construction to enhance the inspection process. Quick and accurate inspection process enables inspectors to make timely adjustments which minimises time and cost of adjustments to the schedule. Continuous laser scanning of building sites can be matched to the digital twin to detect discrepancies between the as-designed and as-built model and its building elements, such as pipes or ductwork. Real-time pose of heavy equipment, such as cranes, can be integrated into a digital twin using sensing technologies and be used to assist operators or to detect unsafe situations.

Monitoring worker behaviour: Real-time tracking of workers can be integrated with the digital twin to detect unsafe behaviours and significantly reduce the number of worker injuries. Distance to hazards is used to sound the alarm and notify workers of a potential threat, such as a piece of heavy equipment integrated in a digital twin.

Prefabrication: BIMs are of paramount importance in prefabrication processes because modular building elements assembled in a model during the design phase are used to construct site components. Point clouds of the constructed components can be compared with BIM elements to check for inconsistencies and update the BIM if necessary.

While digital twins are in use in several application areas, they are not as readily available as BIMs because a move from BIM to digital twin is not straightforward. The applications of both BIMs and digital twins still face numerous challenges:

- There is a lack of means to generate meaningful knowledge with high semantic richness from raw sensor data.
- Real-time monitoring of building sites is challenging due to their everchanging and dynamic nature.
- Decision-making processes are not yet fully automated and require human input, mainly because the level of the inherent difficulties in computer 3D scene understanding.
- Training and upskilling may be complex, especially if moving from paper-based processes.
- Algorithms for comparing as-built and as-planned models are constantly improving but there is still a lack of trust.
- Blockchain integration is challenging because the requirements of different industrial applications usually differ. Multiple blockchains can address this issue, but increase complexity.
- BIMs can blur the level of responsibility between stakeholders on a project.
- Setting up a connected and capable IT infrastructure is a challenge and of paramount importance for an effective digital twin.
- Interoperability and data integration are one of the biggest challenges in the wider adoption of digital twins, which must be addressed with standardised modelling and frameworks.

DIGITAL TWIN (AND BIM)

Adoption

- Scale and scope
- Internet and reality capture devices
- Accuracy
- Cost
- Skills

Considerations

- Stakeholders, technologies, and workers
- Methodology
- User's needs and usability
- Dynamic variability
- Investment in reality capture technology

Benefits

- Centralised project information within a collaborative environment.
- Improved information flow and instant communication
- Improved overall performance and lower construction costs
- Improved waste management and reuse
- Improved transparency and guaranteed immutability of supply chains

Challenges

- High upfront cost
- Requires user training
- Setting up a connected and capable IT infrastructure
- Generating meaningful knowledge with high semantic richness from raw sensor data
- Interoperability and data integration
- High processing requirements

Application

- Asset life-cycle management
- Supply chain management
- Automated planning
- Health and safety management
- Construction site monitoring

Maturity level

Static

- Initiating reality capture
- Project by project BIM models developed and verified partially by data

Reality Capture

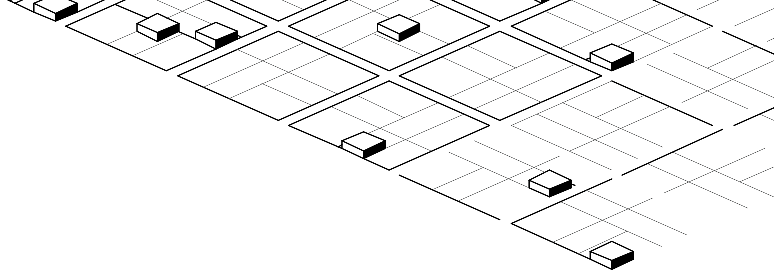
- Establishment of reality capture team
- Initiating reality capture in design phase

Analytics-Driven

- Reality capture used in enhancing data and shared
- Scanned data used in Quality Assurance processes

Autonomous

- Data used across multiple stages of the project in an integrated manner
- Record model development is fully automated
- AI is integrated to learn from the historic and real-time data



6.3.5 Extended Reality (XR) technologies

Extended reality (XR) refers to the combination of real and virtual environments and human–machine interactions powered by computer technology, including a range of areas such as mixed reality (MR), augmented reality (AR), and virtual reality (VR). VR is a technological tool in which a three-dimensional, computer-generated environment can be explored and interacted with. AR uses the same concept, but instead of interacting in a non-existing environment (digital fact), it uses the existing environment while incorporating virtual elements to make it appear as if both are present at the same time. The concept of AR combines real and computer-based scenes and images to create a unified but enhanced view of the world. Mixed Reality (MR) is a recent development of reality technologies which not only overlays the virtual contents on the real world, but also allows interaction between them.

The Vocational Education and Training (VET) sector plays a crucial role in equipping current and future employees with the necessary job-related skills in the Australian building industry. VET qualifications ensure tradespeople and workers have the knowledge and competencies required for effective, sustainable, and safe work practices. These requirements imply significant pressures to update the training delivery approaches in the construction VET system. Besides a growing demand for skilled workers, the building industry is experiencing significant digital disruption, altering how workers interact and operate[1].

This roadmap explores the potential of incorporating immersive learning environments into VET training to enhance job-related skills in line with 21st-century conditions (Building 4.0 CRC Project #12, 2022).Currently, AR/VR is used in the pre-construction phase to optimise design alternatives, cost estimation, and visualisation. AR/VR technologies can be also used in construction phases for scheduling, progress monitoring and controlling time and cost issues, safety management, quality and defect management, and construction workforce training[2].

XR technology has several benefits throughout a building project lifecycle, from the planning stage to the construction completion stage:

- ensuring safety by providing hazards identification tools, and safety education and training
- avoiding rework by improving communication and collaboration
- lowering building costs by improving the productivity
- identifying design flaws by improving project understanding
- ensuring project completion on time; adoption of XR in architecture, engineering and construction improves the delivery of building projects.

1 Noghabaei et al. (2020)

2 Gruber et al. (2010); Changyoon Kim et al. (2013); Syamimi et al. (2020)

EXTENDED REALITY (XR)

Adoption

- Investment in hardware and software
- Scale and scope
- Problem identification
- Accuracy
- Re-scalable platforms

Considerations

- Increasing R&D investments
- Workforce up-skilling
- Developing their client's vision regarding the new technology
- Updating standards and regulations considering new technology
- Integration of industry and resistance to fragmentation
- Data privacy, ownership, and ethics

Benefits

- Ensuring accuracy and safety
- Avoiding rework
- Lowering construction costs
- Ensuring project completion on time
- Design flaw identification

Challenges

- High upfront cost
- Requires user training
- Predominance of SMEs in the sector
- Lack of standard for information exchange
- High processing requirements

Application

- Design, planning, and visualisation
- Real-time project information and Progress monitoring
- Team communication, collaboration, and coordination
- Quality Assurance and Defect Management
- Workforce training

Maturity level

Explore

- Benefits of tech in solving company's problem explored
- Deployment discussed and options explored

Deploy

- Relevant tech platforms to solve the business problem developed
- KPIs and workflows established

Connect & Scale

- Platform connected to broader enterprise IT ecosystem
- Deploy across multiple departments with training and up-skilling in progress

Lead

- Platform available across organisation
- Interconnected software and hardware
- ROI maximised, KPI driven

7. ADOPTION OF INDUSTRY 4.0 IN BUILDING

This section summarises key challenges the Australian building sector faces adopting Industry 4.0 technologies.

Complexity: Building projects are complicated because they involve a large number of interconnected processes and sub-processes, as well as a large number of project participants at various phases and locations.

Uncertainty: Because each building project is a time-limited, site-specific enterprise, there is a lack of complete specifications for processes and sub-processes, as well as uniformity of materials, work, and teams, resulting in an unpredictable environment.

Fragmented supply chain: Another industry-specific feature is the supply chain's high fragmentation, as seen by a large number of SMEs offering undifferentiated products and services and limited investment capacities in new technologies.

Short-term thinking: The building industry is a loosely connected system with tight couplings in specific projects and loose couplings in the permanent network, which encourages short-term thinking but inhibits long-term learning and innovation. As a result, the decentralised organisation of building enterprises and the transient nature of building projects are hurdles to innovation.

Culture: The building sector has a strong aversion to change and its robust and strict culture.

In building, the hurdles tend to not be with the technology availability but with its implementation in the manufactured buildings and prefabricated building sector. The building sector is dominated by SMEs. It is not sufficient to modernise just one aspect of the building industry, because the modernised entity often finds itself in the queue behind the next bottleneck that is yet to be resolved. The solution that prefabricated construction proposes is that of decreasing the dependence on multiple independent slow-moving gears and bringing them together under one roof.

The extent to which this can be implemented is governed by various factors, one of which is the extent of standardisation that can be achieved in a building project. Robotic hardware and software architecture is getting better every day and there are always newer technologies available for companies to start with. This poses a challenge of standardisation even among those who have adopted a modern manufacturing technology. Cost and economies of scale is another barrier in the prefabricated building sector for decades.

7.1 POLITICAL AND LEGISLATIVE

Legislative changes are the direct consequences of political will for a paradigm shift in building, a sector that is one of the slowest to adapt. Building provided direct employment to 1.18 million Australians and contributed AUD360 billion in revenue accounting for 9% of Australia's GDP in 2023[1]. The sector is largely seen as change and risk-averse and hence any legislative change that can disrupt the status quo finds itself difficult to manifest. The political agenda would need to set courses for prefab friendly legislation that could then act as sources of accreditation and process certifications for prefab industry partners.

The National Construction Code (NCC) (produced by the Australian Building Codes Board (ABCB)) is a standard compliance document that regulates design and construction activities. Integrating of streamlined compliance pathways for manufactured homes and prefab building products in the NCC would assist in ensuring better quality and compliance outcomes. Australian Standards would need to be extended to provide structural compliance requirements to various prefabricated buildings and products. Various state-level government bodies such as planning departments and home warranty and insurance schemes would need to account for the rising prefabricated building market and suitably amend existing provisions to include them.

Government organisations, non-government organisations, industry, and academia would need to collaborate closely, and the collaboration would need to increase significantly to drive the change forward with respect to design for manufacturing and design for assembly in the prefab construction industry through innovation hubs, Testlabs and growth centres[2].

1 Australian Bureau of Statistics (2023)

2 DISER (2020)

7.2 ECONOMIC

The government plays an important role not only as a political driver but also as an economic driver. Government can motivate the industry players to move to modern methods of construction derived from Industry 4.0 and DfMA. The permanent modular school buildings program by the Victorian School Building Authority (VSBA), public housing through movable units by Housing Victoria, and the prefabricated quarantine accommodation tender are examples of the Victorian Government's direct investment push to prefabrication in recent times.

The larger portion of invested capital comes through private investments by direct consumers, banks, and large financial institutions. The manufactured building sector finds itself struggling to attract investor confidence in the current Australian building investment sector. Reasons range from end-product quality, business viability, design flexibility, regulatory compliances and provisions, and general risk aversion of traditional banking institutions[1]. Consumer perception of the product quality and design coupled with price competitiveness helps strengthen the demand pipeline. Current DfMA techniques in manufactured housing would need to be tailored to attend to this aspect for it to be more desirable.

7.3 SOCIAL AND CULTURAL

The collaboration between academia and industry could be strengthened to provide ease of access in uncharted technological territories. Robotics and automation are largely perceived as a threat by the established labour unions associated with large-scale job losses and substantive retraining requirements. The absence of easily available skills and training programs for advanced manufacturing technologies creates further roadblocks to those who are aware and are willing to retrain themselves.

The cultural acceptance of OSM buildings is yet another hurdle in the large-scale uptake of OSM methodology. Despite a range of benefits claimed by OSM, not many are accepted by the larger consumer market. Even though OSM building technology is not new, the older versions of prefabricated houses resembled those built as rehabilitation shelters for returning soldiers after World War II. The stigma attached to the box type temporary houses propagates through decades and is still a challenge today. Architects and engineers must understand the socioeconomic and cultural barriers that exist in adopting OSM houses and tailor the DfMA protocols accordingly.

7.4 TECHNOLOGICAL

The construction sector is one of the slowest adopters of new technology and digitisation as pointed out by McKinsey and Co2. Although it is evident that manufacturing has advanced further in digitisation in Australia, it too lags behind knowledge intensive industries such as finance and insurance across assets, usage and labour. This highlights the immense opportunity that digitisation offers the construction industry and that there is still so much ground to cover. BIM, robotics, and automation in the assembly line is proposed to facilitate the rapid production of prefabricated housing products. Advances in sensors, computing software and hardware, machine learning and AI, cloud computing, blockchain, and so on have significantly increased the production methodologies across manufacturing sectors. These technologies are being introduced to prefabricated construction through DfMA principles. Implementing these technologies is capital intensive and requires personnel with in-depth technical understanding. Since a large portion of the building industry is essentially dominated by SMEs, adapting high-end technology poses significant financial and technical challenges.

By contrast, technology changes are rapidly leaving behind those who do not have sufficient resources to upgrade hardware and software. The suite of Industry 4.0 technologies encapsulates required technologies for advanced manufacturing. Adopting Industry 4.0 techniques would enable SMEs and large firms to implement DfMA with greater success. The Australia–Germany Advisory Group was formed in 2014 to investigate how the Australian manufacturing sector could benefit from German Industry 4.0 software architecture and hardware advancements. State government initiatives such as the Victorian Digital Asset Strategy (VDAS) aims to move towards digital twin models for infrastructure assets. Digital twin technology can be harnessed to optimise OSM through DfMA effectively if a large number of industry players adapt to its usage. Concerns about data interoperability must be addressed through technological standardisation and benchmarking facilities[3].

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1 Lin et al. (2021)

2 Blackburn et al (2021)

3 Australia–Germany Advisory Group (2015)

Figure 1: Construction sector placement in readiness for technology adoption[1]

1 McKinsey & Company (2017)

8. INDUSTRY CASE STUDIES

This section presents case studies that embody Industry 4.0 principles relevant for building. Key learnings are highlighted and form part of the recommendations for the final roadmap. These have been selected to showcase the implementation one of more industry 4.0 principles or technologies that is of relevance to the building industry.

8.1 KiwiBuild PROGRAM

Location: New Zealand (NZ)

Priority Area: Affordable housing

Technologies: Off-site modular[1 2]

1 Smart (2019)

2 Scoop News (2020)

Figure 2: KiwiBuild off-site modular home building program

Context[1]: The KiwiBuild program was established in 2012 as part of a government response to the affordable housing crisis. It included an increase in public and emergency housing, tied to improved standards for rentals and modernised tenancy laws in New Zealand. The KiwiBuild business model considered a public–private partnership (PPP) to build 100,000 new affordable homes to be sold to first home buyers.

Technology innovation: One of the key characteristics of the project was delivering large scale projects, that is, integrating affordable housing into major urban regenerations. For this purpose, government agencies (i.e., Housing New Zealand and Homes, Land Community) engaged with off-site manufacturing suppliers to decrease the time for construction. An open call to pitch for offsite manufacturers.

Outcomes: Although the program has some initial issues about expected housing provision, it generated several opportunities to increase technology adoption and strengthen the ecosystem. For instance, sales for first home buyers were five times higher for KiwiBuild developments than those observed for similar purchases in the same period. The program also incentivised revision of regulatory aspects for sustainable growth in New Zealand, helped establish a methodology for quantifying the benefits of off-site construction, and strengthened the smart prefab ecosystem through the collaboration of manufacturing firms and construction companies using off-site methods.

1 Moir (2019)

8.2 Blockchain with BIM[1]

Client: Autodesk Forge, Ethereum Foundation

Outcome: Comments made on 3D BIM model in web browser were recorded and timestamped on Ethereum blockchain as ledger transactions

1 Doermann et al. (2020); van Vuuren & Middleton (2020); Prefab NZ (2018); Autodesk Forge (2019); Ethereum Foundation (2018).

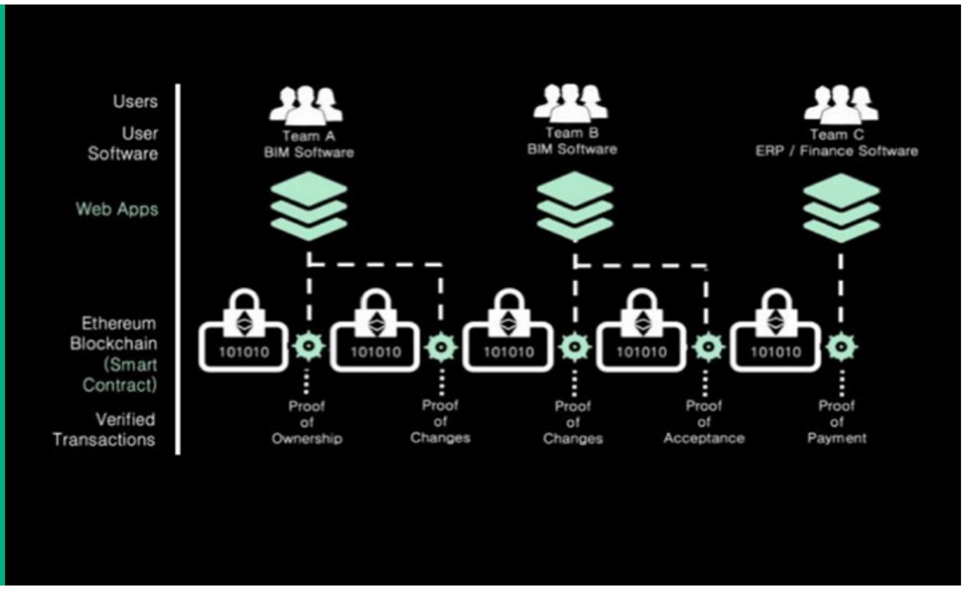


Figure 3: Autodesk Forge and Ethereum Foundation integration proposal

Project motivation: There is not any robust system to manage a central ledger of changes in cross-platform federated BIM models. A construction project conceived through BIM is divided on multiple bases such as stage of development and design, and engineering disciplines (structural, architectural, mechanical, etc.). Coordination must be continuous to advance the model development. Without robust recordkeeping of the time sequence of design changes, accountability assignment, chain of responsibility, and arbitration becomes tedious. Time keeping design changes in real time is crucial to ensure stakeholders use the up-to-date version of the project.

Technology innovation: Blockchain is a public time stamped decentralised ledger of transactions that cannot be altered once the record has been verified. The BIM software (Autodesk Forge) was integrated with the Ethereum blockchain ledger (MetaMask – web browser integration) so that any new changes made to the design were broadcasted and recorded on that ledger. This approach helped identify design-based constructability issues and project delays. The integration was done using open source JavaScript libraries.

Outcomes: The project successfully demonstrated changes made in the 3D model were recorded on Ethereum blockchain as ledger transactions. These transactions recorded who made the change, the details of the change, and the time the changes were made. The history of recorded transactions could be exported in a readable and accountable format.

8.3 Renault with Industry 4.0[1]

1 MetaMask (2019); Smith (2020); Scherer (2020); Coulmann (2018)

Context: Renault wanted to understand the implications of digital transformation on its business and operations. Analysis of design and manufacturing activities showed they could achieve €300 million worth of cost savings and optimisation each year. The digital transformation would provide better and faster decisions, and increase productivity for around 2000 legacy applications. Having real-time information from their production equipment and providing the related data to unit managers was essential to monetise data. They also found they could generate €300 million each year because becoming more digital would also help them to manage customer relationship lifecycle and personalisation needs. They went ahead with end-to-end pilot to test the assumptions.

Technology innovation: Renault Group created Renault Digital on 1 January 2017 (independent, fully-owned subsidiary) to help achieve digital transformation objectives. Renault Digital is a centre of excellence with more than 350 employees with Agile methodologies, UX Design, DevOps and Data Science. For each project, they set up a team (agile) with business experts and specialists. Renault Digital functions as a start-up and an incubator.

The CHUET project: Plant managers faced challenges managing a team of 10–12 employees. Managers had to run back and forth to their office computer to obtain the latest updates on production tuning and adjustments. By including Wi-Fi and developing a bespoke mobile office solution, saved plant managers 45 minutes every day. Managers now use mobile tablets around the plants and work units with real-time data and updates.

Predictive maintenance is another area where manufacturing companies need to reduce downtime. Renault has installed more than 2000 LoRa sensors to collect data from their equipment.

Outcomes: Adopting digital technologies (including sensors, data, robots, and humans), Renault Digital estimates the impact to be around €1 billion each year since inception (12 months).

8.4 Prefabricated building validation by VR

Company: Gilbane Building Company

Country: Rhode Island, USA

Figure 4: AR / VR in Construction

Project: Wentworth Institute of Technology building

Client: Wentworth Institute of Technology

Technology innovation[1]: This project used VR to validate the prefab building and faster project delivery. The 3D model is visualised with more dimensional and operational certainty via VR. The company uses the technology to facilitate better communication between different stakeholders. As well as improving communication between clients, owners, and architects, subcontractors and suppliers can better understand building assemblies and the associated risks ahead of time in the warehouse and during transportation.

Outcomes: VR saved time on project delivery by replacing many time-consuming methods of quality assurance and quantity con trol. Further, using VR across project stages enhanced stakeholder communication through more realistic visualisation.

1 Gilbane Building Company (2023)

8.5 Robots On-Site for Safety and Efficiency

Company: Verton Technologies Australia

Location: Australia[1]

1 Verton (2021)

Figure 5: Installation of prefabricated wall modules with Verton's remote load control system and RBD/HALE Steel's Tilt Table

Context: Industrialising on-site processes is much more difficult than industrialising prefabrication processes in factories. Yet, prefabricated components are large and heavy, and require cranes for on-site installation. Cranes are imprecise and do not facilitate payload orientation control. Many prefabricated components must be installed at a height; where manual manipulation by workers with tag-lines is difficult, unsafe, and inefficient.

Technology innovation: A below-the-hook-lifting device remotely controls crane payload orientation via a handheld remote. The device controls the payload orientation with gyroscopic fly wheels.

Outcomes: Safety is improved by positioning workers further from the crane payload, and by reducing sudden movements due to wind gusts. Operational efficiency and speed are increased because fewer workers are required to control the payload, and the payload may be correctly oriented while enroute to the installation location. Reduced lift times also generate cost savings.

Insights: Industrialising on-site processes is difficult. Yet, on-site robotics should not be ignored. Using both workers and robotic machinery can improve worker safety and efficiency.

9. INDUSTRY WORKSHOPS

This section summarises the outcomes of industry workshop sessions used to gain insight from industry leaders about how they perceived Industry 4.0 in relation to their businesses. Workshops were explorative rather than prescriptive; that is, the research team did not constrain the outcomes and recommendations given by industry. Attendees were also asked about barriers to Industry 4.0 adoption they faced as well as immediate prospects for future technologies.

The workshops highlighted important factors such as the need for a workforce skilled in Industry 4.0 technologies, the importance of decision makers driving adoption, and the challenges posed by complexity and dynamic regulations. Transitioning to Industry 4.0 requires collaborative efforts from industry stakeholders, government support, and education to integrate design, manufacturing, and assembly processes. Additionally, leveraging smart city development, cloud computing, AI, machine learning, and GIS mapping can contribute to the future of building. Prioritising data integration across construction processes was noted as a key task to unlock the vast potential of data-driven insights and decision-making in the industry.

Further, the discussions revealed five key themes.

Standardisation of processes, approaches and data interfaces:

The workshops emphasised the importance of standardising processes, approaches, and data interfaces in the building industry. Currently, there is a lack of compatibility across platforms and processes due to market segmentation. Automation of data, data standards, and integration across multiple platforms can significantly benefit the entire building lifecycle. Standardisation is crucial for enabling machine-to-machine communication and ensuring consistent and repeatable data transfer among different systems.

Industry readiness and awareness:

A challenge is highlighting and communicating Industry 4.0's value to the broader industry and workers. Industry professionals and ordinary people need to grasp the relevance and importance of Industry 4.0 for it to gain traction. Currently, there are smaller and isolated applications of Industry 4.0, but the full benefits can be realised only when data is easily accessible, and people are aware of the advantages of using such data in design, operation, maintenance, and recycling of buildings. Adapting Industry 4.0 technologies to the Australian context is also necessary for successful adoption.

Expertise and drive:

The workshops emphasised the need for training people in data collection and ensuring the quality of collected data. Operating new and existing systems and timely documentation of activities through digitisation are essential aspects. Conflict of priorities and the lack of standardisation inhibit Industry 4.0. Large-scale adoption requires interoperability of systems across the value chain and a collective eagerness to embrace Industry 4.0 technologies for their potential benefits.

Supply chain and digitisation:

New systems and software can be seen as expensive and risky. The adversarial procurement approach in the commercial sector discourages investment in technology when business-as-usual practices yield safe results. Supply chain disruptions have two effects: disruption to production, which incurs costs and causes customer dissatisfaction, and increased supply costs. Overcoming these challenges and embracing digitisation can lead to more efficient workflows and enhanced supply chain management.

AI for design and automation:

Automating design and construction processes can introduce new challenges. Conflicts may arise when responsibilities and boundaries between different components are not clearly defined. In such cases, fabricators may be forced to take on the role of consultants or coordinators to resolve conflicts and protect themselves. Additionally, current platforms used in residential construction often lack the necessary level of detail required for accurate automation. While automation can help limit the rate of cost increase in the short term, it is crucial to ensure that these platforms meet the building industry requirements.

10. ACADEMIC WORKSHOPS

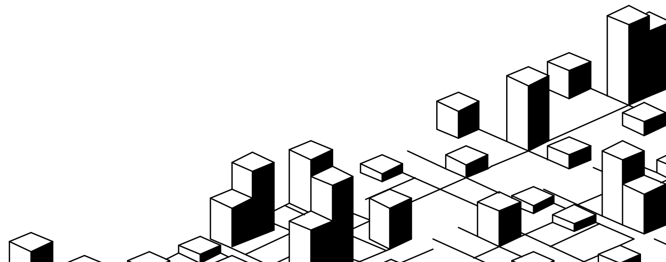
This section summarises the outcomes of academic workshop sessions designed to explore academics' perception of Industry 4.0, benefits and challenges, and the areas within the Australian context that need immediate attention.

Benefits:

- **Social awareness:** Industry 4.0 brings opportunities for increased social awareness, including equity and gender awareness. Integrating diverse stakeholders and using technology can help address social inequalities within the building industry.
- **Integrated processes, technologies, and approaches:** Industry 4.0 enables the integration of various processes, technologies, and approaches within the building sector. This integration enhances collaboration, communication, and efficiency among stakeholders, improving project outcomes.
- **Automation and data-driven construction:** Industry 4.0 technologies facilitate automation and data-driven decision- making. Real-time access to data allows for quicker and more informed decision-making, increasing productivity and reducing costs.
- **Bigger impacts of building**: Industry 4.0 has the potential to significantly impact the building industry in terms of its social and environmental footprint. Leveraging advanced technologies can optimise construction practices to minimise negative impacts on society and the environment.
- **Building regulations:** Industry 4.0 requires updated building regulations. These regulations should address the assignment of rights, responsibilities, and obligations concerning emerging technologies and their application.

Challenges:

- **Workforce transition:** Industry 4.0 technologies require a skilled and adaptable workforce. Upgrading the skills of existing workers and ensuring proper training for new technologies are a challenge.
- **Technological complexity:** Industry 4.0 introduces a wide range of advanced technologies and tools. Navigating this complexity can be challenging for building professionals, particularly in terms of selecting the most suitable technologies for specific projects.
- **Data management and security:** The increased reliance on data-driven decision-making raises concerns about data management and security. Safeguarding sensitive project data and protecting privacy become crucial challenges.
- **Cost implications:** While Industry 4.0 presents numerous benefits, the initial costs associated with implementing advanced technologies can be significant. Balancing the upfront investment with long-term benefits is a challenge.
- **Regulatory adaptation:** The rapid pace of technological advancements may outpace regulatory frameworks. Adapting existing regulations to accommodate emerging technologies poses challenges in ensuring adequate oversight, safety, and ethical considerations.



Socio-Environmental Sustainability in Building 4.0:

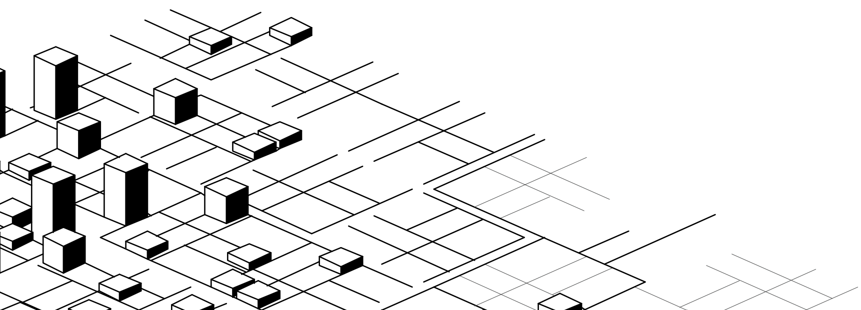
- Current government databases lack access to important cultural data such as gender and racial information, limiting comprehensive studies.
- The rapid advancement of technologies creates knowledge and skill gaps, making it overwhelming for industry professionals.
- Early initiation of upskilling programs in educational institutions can facilitate better adoption of new technologies.
- Emphasise teaching principles, skills, and thinking methods rather than focusing solely on specific software.

Data-driven construction in the Australian context

- The absence of regulations increases costs and hampers the progress of data-driven construction.
- While data-driven approaches impact people, processes, and products, the environmental and social implications are often overlooked.
- Employ a 'co-design' and bottom-up design approach to foster collaborative understanding of decision support systems.
- Gain a comprehensive understanding of users' needs and requirements before implementing new systems.

Final lessons for the roadmap

- Recognise the essential role of the client, involving them early in the project and ensuring their awareness of technology's potential.
- Legislation and regulations play a crucial role in procurement processes, and their importance should not be underestimated.
- Users' involvement in building maintenance presents an opportunity for a novel business model and should be prioritised.
- Consider regulatory perspectives when adopting new technologies, considering the diverse 'culture of building' and industries involved.
- Address ethical implications, data privacy, and ownership issues associated with new technologies and innovation.
- Learn from past practices by adopting an historical perspective to inform decision-making.



11. PATHWAYS TO INDUSTRY 4.0 ROADMAP

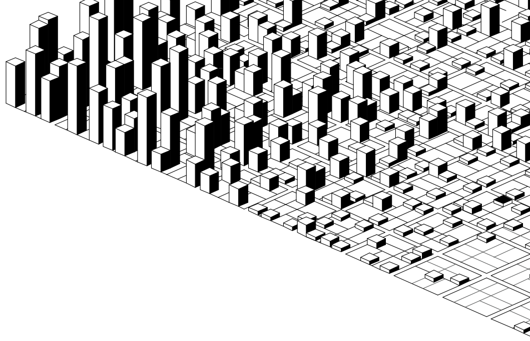
11.1 WORKSHOP INSIGHTS

As discussed in section 9, the building industry recognises the importance of Industry 4.0, emphasising digitisation, automation, and data-driven decision-making for improved productivity and sustainability. Integrating design, manufacturing, and assembly processes through digitisation and automation is crucial. Efforts are underway to determine meaningful data, establish data ownership, and enhance data integration. Upskilling the workforce in AI, robotics, and data management is essential. Collaboration among stakeholders, government, and research institutions is needed to address regulatory support, ethical implications, and data privacy. The industry sees opportunities in smart cities, cloud computing, AI, and GIS mapping. Digitisation offers faster predictive modelling and improved performance assessment. Data integration is prioritised for leveraging construction data.

11.2 PEOPLE, UPSKILLING, EDUCATION, AND TRAINING

As mentioned in the top six recommendations to government (see section 11.5), skills development and education policies are essential for the building industry to adopt Industry 4.0. The Vocational Education and Training (VET) sector is a critical component of Australia's building industry, because it prepares current and future employees with the necessary technical, personal, and interpersonal skills. The building industry employs approximately 1.16 million individuals, representing about 8.8% of Australia's total workforce. In 2020, VET-related qualifications accounted for approximately 43.5% of the construction workforce. By 2024, this proportion is projected to increase to almost 74.2%, largely due to the growing demand for licensing requirements. However, the industry currently faces challenges such as a decline in apprentice training rates, an increased cancellation rate of apprenticeships, and quality issues within the VET system (Toner, 2003; Mangan & Trendle, 2008; Snell & Hart, 2007).

Addressing these challenges and modernising the building industry involves upskilling the workforce in areas such as AI, robotics, and data management. Manufacturers need to transition and modernise their production processes, necessitating the upskilling of their workforce. It is also important to balance teaching fundamental principles and thinking methods and providing training on specific software applications. Additionally, customised training and upskilling programs should be developed for different roles, such as providing template robotic system integration plans for building designers and offering training on specific systems for on-site workers.



11.3 TECHNOLOGY INSIGHTS

There have been significant discussions around the role of technologies in delivering Industry 4.0 in the building sector. Robotics and automation (mechanisation) in Australia are not standardised and involve high costs. An option for overcoming this issue is for manufacturers to rent single-task robots suitable to the components they sell (robot as a service).

Diverse Data Collection	• Collect data from different types of sensors and devices • Data from heterogeneous devices provide more insightful
Artificial Intelligence and Big Data Analytics	• AI and Big Data Analytics will help to uncover hidden patterns from the data and provide actionable knowledge
Automation Routines	• Bots can do repeating tasks with the help of AI to automate the processes, enabling humans to focus on critical aspects of the project
Autonomous Decision-Making	• Respond to a range of situations rapidly without waiting for human operators. This will be enabled bu AI
Cloud and Edge Computing	• Cloud and edge computing are necessary for providing supportive infrastructure for data storage and AI computers
Data Storage (Immutable)	• Store all types of data using immutable (Unchangeable) technology such as block chain fro security and meet legal requirements
Multi-experience Open Access	• Provide access to a range of interactive applications to consumers • Preserve the activities for future usage and product customisation

11.4 INDUSTRY RECOMMENDATIONS

This report investigated what Industry 4.0 means for the Australian building industry. The following recommendations aim to realise the potential benefits for industry actors. This summary should be read in conjunction with the recommendations for government (Section 11.5).

1. Collaborative Efforts: Transitioning to Industry 4.0 requires collective efforts from industry, government, and research institutions. Education, communication, and regulatory support should be prioritised to incentivise and realise the potential benefits of Industry 4.0. Collaboration creates synergy, provides a holistic perspective, facilitates knowledge sharing, and enables regulatory support and incentives.
2. Whole-Asset-Life Approach: Building organisations should embrace future operating models to foster an ecosystem that considers the entire lifecycle of assets, similar to Product Lifecycle Management in manufacturing. This approach ensures long-term sustainability and optimisation throughout the asset's lifespan. By considering the entire lifecycle, organisations can make informed decisions about design, construction, operation, and maintenance, leading to improved efficiency, cost savings, and enhanced asset performance.
3. Integration of Design, Manufacturing, and Assembly: Digitisation and automation of the design, manufacturing, and assembly stages are crucial for achieving Industry 4.0 principles in building. Seamless integration enables greater efficiency, quality control, and information exchange. By digitising and automating these stages, organisations can streamline processes and reduce errors, leading to faster project delivery, higher productivity, and improved overall project outcomes.
4. Building-specific Industry 4.0 Processes: The unique challenges of the building environment require tailored Industry 4.0 processes. These specialised approaches (such as BIM) address the dynamic nature of building and offer industry-specific solutions. Automation is instrumental in increasing efficiency, but automation technologies and processes must ensure solutions suit the application.
5. Embrace Relevant Technologies: In addition to core Industry 4.0 technologies, building should embrace smart cities, cloud computing, AI, machine learning, and GIS-enabled mapping. These technologies enable efficient resource management, secure data storage, automation, predictive analytics, and improved site planning, leading to cost savings and competitive advantage. Opportunities to optimise and streamline traditionally manual and time-consuming tasks are core to adopting the latest technology.
6. Leveraging Digitisation: Digital tools and platforms enable faster and more accurate predictive building modelling, facilitating comprehensive assessments of lifecycle, energy efficiency, compliance, and structural performance. Digitising the supply chain is important to minimise disruption and delays. Digitisation also enables a more inclusive customer experience, empowering clients and consumers to better understand design and built choices leading to more informed decision-making.
7. Data Integration: The building industry generates vast amounts of data. Prioritising data integration allows for effective utilisation of this data. Integrated data provides valuable insights, supports informed decision-making, and drives improvements. By leveraging data and AI, companies can gain deeper insights into project performance, identify trends and patterns, and make more informed decisions. This enables proactive risk management, optimised resource allocation, improved project planning and scheduling, and enhanced overall operational efficiency. Data integration also facilitates collaboration among project stakeholders, enabling real-time information sharing and fostering a more integrated and streamlined approach to building processes. Training and upskilling the workforce will be necessary to create, maintain, integrate, and benefit from data throughout the building lifecycle.

11.5 TOP SIX RECOMMENDATIONS FOR GOVERNMENT

This report highlights the need for policy makers to aid in the accelerated adoption of Industry 4.0 in the construction industry with six key areas highlighted:

1. Skills Development and Education Policies: This research identified the need for upskilling digital capabilities while increasing capabilities of those new to the workforce.
2. A National Strategy: Developing a national strategy is crucial for successful technology implementation, encouraging building companies to adopt new technologies.
3. Financial Support: The constraints associated with investing in new technologies is readily apparent in an already challenging sector. Policymakers can assist by providing financial support, such as grants, subsidies, or tax incentives, to encourage the building industry to invest in the latest technologies.
4. Collaboration and Knowledge Sharing: Promoting collaboration and knowledge sharing among industry stakeholders can foster innovation and adoption of Industry 4.0 technologies.
5. Regulatory Frameworks: Policymakers should establish supportive regulatory frameworks that promote the adoption of Industry 4.0 technologies in the building industry. This includes addressing data privacy and security concerns, standardising digital processes, and ensuring interoperability among different technologies and systems.
6. Research and Development: Investing in research and development initiatives focused on Industry 4.0 technologies specific to the building industry can drive innovation and provide practical solutions to industry challenges. Policymakers should encourage collaboration between academia, research institutions, and industry players to accelerate technological advancements such as the case in the Building 4.0 CRC.

In conclusion, the significance of understanding and integrating Industry 4.0 into the building industry cannot be understated. Our research delved deep into the multifaceted implications of Industry 4.0, exploring its transformative potential and the distinctive challenges it presents to an industry poised for evolution. By bringing to the forefront the benefits and hurdles observed in other sectors, we have sought to furnish the Australian building industry with actionable insights. Adopting a proactive approach, informed by international best practices and backed by strategic investments, can usher the Australian building sector into a future of efficiency, innovation, and growth.

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info@building40crc.org
www.building4pointzero.org
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