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Technical Note / Technical Report

Digital Technologies as Regulatory Enablers in Off-Site Construction

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Abstract

Industrialised and off-site construction challenges regulatory systems historically designed around sequential, on-site inspection practices. As fabrication shifts to controlled factory environments, traditional compliance mechanisms, particularly stage-based statutory inspections, become misaligned with manufacturing workflows. This paper examines how digital technologies can reposition compliance from episodic site inspection toward continuous, verifiable production assurance. Drawing on two empirical case studies, the study investigates (1) the application of image recognition technologies for automated quality control in off-site manufacturing, and (2) digital chain-of-custody frameworks for product traceability across the supply chain. The first case study explores how computer vision systems can capture, analyse, and archive progressive installation stages within prefabrication lines, enabling defect detection, dimensional verification, and auditable compliance records prior to enclosure. The second case study analyses national traceability initiatives aimed at strengthening evidence-of-suitability requirements through persistent digital product identities linked across the supply chain. Together, these technologies shift compliance from reactive inspection to proactive verification, embedding regulatory evidence directly within manufacturing processes. The findings highlight a structural tension in current regulatory frameworks between “product” compliance under national codes and “process” compliance enforced through state-based inspection regimes. Image recognition and digital traceability offer a pathway to reconcile this divide by providing scalable, standardised, and interoperable compliance artefacts that within manufacturing processes. The paper argues that regulatory reform must formally recognise such technologies as legitimate compliance infrastructure, supported by harmonised classification systems and third-party certification models. Without this transition, off-site construction will continue to be constrained by regulatory assumptions rooted in traditional site-based practices.

Keywords: Off-site construction; Prefabrication; Regulatory reform; Chain of custody

Highlights

- Digital verification reframes compliance from episodic inspection to continuous assurance.
- Image recognition enables auditable QA/QC for concealed off-site construction works.
- Digital traceability bridges product certification and process-based regulatory compliance.

1 Introduction

Industrialised construction, particularly off-site prefabrication and volumetric assembly, is increasingly positioned as a strategic response to Australia's housing supply pressures and productivity challenges. Project 21: Regulatory Reform for Industrialised Construction examined how existing regulatory systems, historically structured around traditional on-site construction, create structural misalignments when applied to factory-based production environments. While the National Construction Code (NCC) remains largely neutral regarding construction processes, state-based inspection regimes and compliance mechanisms continue to assume sequential, site-based construction workflows. This creates duplication, delay, jurisdictional inconsistency, and reduced efficiency when assemblies are fabricated off-site (Forsythe *et al.*, 2025).

A key finding of the broader project was the tension between “product” compliance under the NCC and “process” compliance under state inspection and licensing frameworks. Off-site assemblies, particularly panelised and volumetric systems, function as complex products composed of multiple compliant subcomponents, yet they remain subject to traditional inspection assumptions designed for in situ construction. As a result, mandatory inspection regimes can become redundant, impractical, or incapable of verifying concealed elements once factory production is complete (Australian Building Codes Board, 2022).

Within this context, Project 21 identified technological reform as a critical pathway for future-proofing regulatory systems. The study emphasised the need for faster, simpler, reliable, and organisationally implementable compliance mechanisms, alongside strengthened evidence-of-suitability frameworks and traceability systems. In particular, digital technologies were identified as potential enablers of continuous compliance verification, quality assurance, and transparent evidence trails (Forsythe *et al.*, 2025).

This paper focuses specifically on the technological dimension of regulatory re-form, drawing on two case studies of the Project 21. First case study investigates the application of image recognition technologies within prefabrication production lines to capture progressive construction stages, detect defects, verify tolerances, and generate auditable compliance records prior to enclosure (Forsythe *et al.*, 2025). Second case study examines the development of digital chain-of-custody and product traceability frameworks aimed at strengthening NCC evidence-of-suitability requirements through persistent product identities and supply chain transparency (Forsythe *et al.*, 2025).

Together, these case studies explore how compliance might transition from epi-sodic statutory inspection toward embedded, data-driven verification integrated within manufacturing systems. Rather than viewing technology as supplementary to regulation, this paper positions digital image recognition and traceability frameworks as foundational compliance infrastructure for industrialised construction.

By analysing these technologies through a regulatory lens, the paper argues that meaningful reform requires formal recognition of digital verification systems within national and state compliance pathways. Without such integration, off-site construction will continue to be constrained by regulatory assumptions rooted in traditional site-based practices, limiting its capacity to deliver scalable, efficient, and high-quality building outcomes in Australia.

2 Research Design and Methodology

Remote This research is part of Project 21: Regulatory Reform for Industrialised Construction¹, a one-year research collaboration under the Australian research group Building 4.0 CRC involving government regulators, industry partners, and standards bodies. The broader project investigated structural

¹ <https://building4pointzero.org/projects/21-regulatory-reform-for-industrialised-building/>

misalignments between Australia's regulatory frameworks and emerging industrialised construction practices, with a particular focus on off-site prefabrication and volumetric construction.

The present paper isolates the technological dimension of regulatory reform, focusing specifically on Case Study 1 (Image Recognition Technologies in Off-Site Inspection) and Case Study 2 (Chain of Custody and Product Traceability). These case studies were selected because they directly address identified gaps in inspection regimes and evidence-of-suitability mechanisms within the National Construction Code (NCC) and state-based regulatory systems.

2.1 Research Approach

The research adopts a qualitative, exploratory case study methodology. Case studies were selected as an appropriate method because regulatory reform in industrialised construction involves complex interactions between legislation, compliance mechanisms, production systems, and technological innovation. A case study approach allows detailed examination of emerging practices within their regulatory and operational contexts.

The two technological case studies were not treated as isolated technical demonstrations. Rather, they were analysed through a regulatory lens, examining how each technology interacts with:

- NCC evidence-of-suitability provisions (Australian Building Codes Board, 2021),
- State-based inspection and certification regimes (Forsythe *et al.*, 2025),
- Quality assurance (QA) and quality control (QC) systems (Forsythe *et al.*, 2025),
- Broader reform agendas such as the Building Confidence Report and the National Building Product Assurance Framework.

This approach enabled evaluation of the technologies not only in terms of technical capability, but also in terms of regulatory fit, scalability, and reform potential.

2.2 Case Selection Rationale

Case Study 1 (Image Recognition Technologies) was selected because it directly addresses one of the most persistent regulatory challenges identified in Project 21: the redundancy or impracticality of traditional stage-based onsite inspections when construction occurs in factory environments. The case explores how computer vision and automated image capture systems can document progressive installation stages, detect defects, verify tolerances, and create auditable compliance records prior to enclosure (Forsythe *et al.*, 2025).

Case Study 2 (Chain of Custody and Product Traceability) was selected due to its relevance to strengthened evidence-of-suitability requirements and product identification reforms under the National Building Product Assurance Framework. This case examines emerging national traceability initiatives designed to assign persistent digital identities to building products and assemblies, improving transparency, accountability, and compliance verification across supply chains (Forsythe *et al.*, 2025).

Together, the two case studies were chosen to represent complementary dimensions of regulatory reform:

- Process-oriented compliance assurance (image recognition within manufacturing),
- Product-oriented compliance assurance (digital traceability across supply chains).

2.3 Analytical Framework

Analysis of both case studies was guided by a central conceptual tension identified in the broader project: the distinction between “product” compliance under the NCC and “process” compliance enforced through state-based inspection regimes.

Each case study was examined against the following analytical criteria:

- Alignment with NCC evidence-of-suitability mechanisms;
- Interaction with state inspection and certification processes;
- Capacity to reduce duplication or delay in compliance;
- Scalability across jurisdictions;
- Potential for formal recognition within regulatory frameworks.

Rather than evaluating technological performance alone, the analysis focused on whether these technologies could function as legitimate components of regulatory infrastructure. In doing so, the study shifts the discussion from technology as an optional efficiency tool to technology as an enabler of structural regulatory reform.

3 Case Study 1 - Image Recognition Technologies in Off-Site Inspection Practices

A recurring issue identified throughout examining regulatory reform for industrialised and off-site construction in Australia was the misalignment between traditional stage-based inspection regimes and factory-based off-site production systems (Darko *et al.*, 2020). State regulatory frameworks assume sequential, on-site construction processes in which building surveyors or certifiers attend prescribed stages of work prior to concealment. These statutory inspections are designed to verify compliance with approved documentation and the National Construction Code (NCC) before critical elements become inaccessible (Forsythe *et al.*, 2025).

However, in industrialised construction environments, panelised and volumetric assemblies are manufactured within controlled factory settings. Critical components, such as fire-rated penetrations, waterproofing layers, service interfaces, structural fixings, and cavity barriers, are often concealed during production long before the assembly reaches the construction site. Once delivered and installed, traditional inspection stages may be redundant, unable to verify concealed work, or duplicative of factory-based quality assurance processes.

The broader study identified that such misalignments could result in multiple inspections of the same assembly, delays while awaiting onsite verification, and uncertainty regarding regulatory responsibilities. These inefficiencies undermine the productivity and cost advantages that industrialised construction seeks to achieve. Case Study 1 therefore investigates whether image recognition technologies can provide a structured and auditable alternative to episodic on-site inspection, by embedding compliance verification directly within manufacturing processes.

Image-based inspection technologies assessed in this study include machine vision systems, X-ray non-destructive testing (NDT), and reality capture technologies (laser scanning and RGBD cameras). Machine vision systems utilise industrial-grade cameras, optical sensors, and image-processing algorithms to automate defect detection, dimensional measurement, and pattern recognition within production environments. Triggered capture mechanisms and pixel-level segmentation enable verification of tolerances, alignment, and fixing patterns at progressive stations along prefabrication lines (Konstantinidis *et al.*, 2021; Ren *et al.*, 2022; TELEDYNE, 2024). X-ray NDT extends inspection capability beyond surface analysis by detecting internal defects such as voids, fractures, and inclusions through volumetric imaging, supported by machine learning models trained on labelled datasets. While more capital-intensive, X-ray systems offer high-value inspection for structurally critical components (du Plessis and Boshoff, 2019; Mery and Arteta, 2017).

Reality capture technologies provide spatial verification through 3D data acquisition. Terrestrial Laser Scanning (TLS) generates dense point clouds using triangulation or time-of-flight principles, enabling millimetre-level dimensional validation and comparison with CAD/BIM models. RGBD cameras combine colour and depth sensing to produce 3D mesh representations suitable for crack detection and geometric assessment at lower cost (Aryan *et al.*, 2021; Fang *et al.*, 2023; Gamage and Xie, 2009; Li

et al., 2021). Together, these technologies enable progressive, non-contact inspection of prefabricated assemblies prior to enclosure, shifting compliance verification from manual, episodic checks toward automated, data-driven production-stage assurance.

3.1 Case Study 1 Findings

The study identified four principal outcomes listed below:

- **Enhanced Quality Assurance and Process Transparency:** Image recognition systems strengthen factory-based QA/QC by replacing manual checks with automated, consistent documentation. Progressive image capture creates a traceable record of concealed elements, improving transparency and reducing un-certainty regarding compliance with approved design specifications.
- **Repositioning Inspection from Episodic to Continuous Verification:** A key finding is the shift from stage-based, presence-driven inspections to continuous, data-driven verification embedded within production workflows. Inspection becomes automated and ongoing rather than event-based, aligning compliance practices more closely with industrial manufacturing models.
- **Limitations and Regulatory Gaps:** Despite technical capability, image recognition lacks formal recognition within statutory inspection regimes. Existing regulations continue to require physical attendance, and uncertainties remain regarding evidentiary status, system accreditation, data governance, and accountability.
- **Implications for Regulatory Reform:** Image recognition technologies have the potential to reduce redundant inspections and strengthen compliance documentation. However, their effectiveness depends on regulatory reform that formally recognises digital verification systems as legitimate components of compliance infrastructure.

Case Study 1 therefore illustrates that technological innovation alone is insufficient. Meaningful reform requires integration of digital verification systems into the formal architecture of compliance.

Table 1. Image Capture and Processing Technologies for Inspection and Defect Identification (Source: authors).

Technology	Function	Potential implication
Machine Vision	Automates visual inspection using cameras and algorithms to detect defects.	Identifies defects invisible to the human eye, such as cracks and scratches, improving quality control and reducing human error in off-site manufacturing processes.
X-rays	Non-destructive testing to detect hidden defects.	Allows for deeper analysis of components, detecting voids, fractures, or other issues within materials, ensuring structural integrity in off-site-manufactured products.
Reality Capture (Laser Scanning, RGBD Cameras)	Laser Scanning- Captures 3D spatial data and generates digital models for inspection. RGBD Cameras- Capturing colour information and depth measurements from the camera to the object.	Provides accurate digital 3D models for quality control, inspection, and compliance verification of prefabricated components, improving production efficiency.

4 Case Study 2 - Digital Chain of Custody and Product Traceability

Case Study 2 examines product-based compliance assurance across the supply chain. In response to strengthened NCC evidence-of-suitability requirements and national product assurance reforms, digital traceability frameworks aim to establish persistent product identity and continuous chain-of-custody verification for prefabricated com-ponents and assemblies (Batista *et al.*, 2023; Prayudi and Sn, 2015).

Digital traceability systems address structural weaknesses in existing evidence-of-suitability pathways by transforming static certification documents into persistent, lifecycle-linked compliance records (International Organization for Standardization, 2015). Under conventional regulatory frameworks, evidence often relies on product technical statements, certification certificates, or manufacturer declarations that may become disconnected from the physical product once it progresses through transport, storage, or installation. Traceability frameworks mitigate this fragmentation by assigning a unique digital identifier to each product or assembly and linking it to structured compliance metadata that travels with the product throughout its lifecycle (Chang-Richards *et al.*, 2019; Darko *et al.*, 2020).

This capability is particularly significant in off-site construction, where prefabricated assemblies integrate multiple regulated sub-components and move between jurisdictions before installation. Rather than merely confirming that a product type is certified, traceability verifies that a specific unit installed in a specific in situ location corresponds to an approved and documented product (Wu *et al.*, 2022). For example, a volumetric bathroom pod can be digitally linked to its WaterMark certification, mapped to its final installed position, and appended with installation timestamps and contractor data. This establishes continuity between Commonwealth-level product compliance under the NCC and state-based process verification regimes (Forsythe *et al.*, 2025). By embedding authenticity validation, substitution risk detection, cross-project verification, and retrievable certification histories within a persistent digital identity, traceability systems create a unified compliance narrative and enable retrospective auditability beyond a single inspection event (National Building Products Coalition, 2024; Xu *et al.*, 2023).

Although technically feasible, the implementation of digital traceability systems presents several governance and operational challenges. Effective deployment re-quires nationally harmonised data standards to ensure interoperability across manufacturers, regulators, and certification bodies, avoiding further regulatory fragmentation. Clear data governance frameworks must define ownership, access rights, retention requirements, and privacy protections to maintain trust and accountability. In addition, scalable and cost-sensitive models are necessary to ensure accessibility for small-to-medium enterprises, which may lack the resources to adopt complex ERP-integrated systems (Bakhtiarzadeh *et al.*, 2021; Li *et al.*, 2021). Most critically, regulatory authorities must clarify the evidentiary status of digital traceability records under NCC assessment methods; without formal recognition, such systems risk remaining industry-led efficiency tools rather than accepted components of compliance infrastructure (National Building Products Coalition, 2024). Table II outlines the technical architecture of such systems.

Table II. Technical Architecture of Digital Traceability Systems for Off-Site Construction (Source: authors).

System Layer	Technical Component	Function	Compliance Relevance
Identification Layer	Unique Identifier (UID) embedded via QR code, RFID tag, serialised barcode, or digital product passport	Assigns persistent digital identity to each product or assembly	Enables unambiguous product authentication and traceability
Data Layer	Structured compliance metadata (manufacturer, batch number, material specification, certification status, test reports, conformity declarations)	Stores product performance and certification information	Supports NCC Evidence of Suitability requirements
Transaction Layer	Time-stamped lifecycle logging (manufacture → QA → dispatch → site receipt → installation → certification)	Creates digital chain-of-custody record	Strengthens accountability and prevents substitution risk
Verification Layer	Integration with BIM models and project databases	Links product identity to in situ location within project	Bridges product compliance and installation verification

Governance Layer	Cloud-based database or distributed ledger (optional blockchain)	Secures data integrity, access control, and auditability	Establishes evidentiary reliability for regulatory acceptance
Interoperability Layer	API integration with ERP systems, regulatory portals, and certification schemes (CodeMark/WaterMark)	Enables cross-platform data exchange	Supports inter-jurisdictional compliance continuity

4.1 Case Study 2 Findings

The study identified four principal outcomes listed below:

- **Enhanced Transparency:** Persistent digital identifiers significantly reduce product misidentification and substitution risks, particularly for prefabricated assemblies incorporating multiple regulated components.
- **Inter-Jurisdictional Continuity:** Traceability systems offer strong potential to support cross-border manufacturing and installation by maintaining nationally accessible compliance records. This is particularly important for scaling industrialised construction.
- **Lifecycle Compliance Value:** Unlike traditional documentation, traceability data persists beyond construction completion. This supports maintenance, warranty claims, future refurbishments, and regulatory audits.
- **Regulatory Dependency:** The transformative value of traceability depends on formal recognition within statutory compliance pathways. Without regulatory endorsement and harmonised standards, digital traceability cannot fully resolve structural fragmentation in current systems.

5 Conclusion

This paper examined the technological dimension of regulatory reform for industrialised construction, focusing on image recognition systems and digital traceability frameworks as potential compliance infrastructure for off-site manufacturing. The broader Project 21 study identified structural inefficiencies in existing regulatory pathways, including fragmented product and process oversight, unclear inspection expectations, and the disruption caused by complex performance-based solutions. These issues undermine the speed, predictability, and commercial viability that off-site construction seeks to achieve.

The two case studies demonstrate that digital technologies offer a pathway to re-position compliance from episodic, site-based inspection toward continuous, data-driven verification. Image recognition systems enable real-time defect detection and dimensional validation within factory environments, improving transparency for concealed components and reducing reliance on manual inspection. Digital traceability frameworks strengthen evidence-of-suitability by establishing persistent product identity and chain-of-custody records across the supply chain, bridging the divide between Commonwealth-level product certification and state-based installation oversight. Together, these technologies provide scalable mechanisms for improving reliability, accountability, and inter-jurisdictional consistency. However, their trans-formative potential depends on formal regulatory recognition, harmonised standards, and clear governance structures. Without integration into statutory compliance pathways, digital systems will remain efficiency tools rather than enablers of systemic reform.

Ethical Approval Declaration

Not Applicable

Informed Consent Statement

Not Applicable

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Data Availability Statement

This paper is derived from selected findings and analysis presented in Project 21: Regulatory Reform for Industrialised Construction, specifically Case Studies 4 and 5 of the project's final report. The original report is publicly available through the Building 4.0 CRC website².

Conflicts of Interest

The authors declare no conflict of interest.

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