

# Understanding workforce-technology co-evolution in Australia's Modern Methods of Construction (MMC) transition

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## Abstract

**Purpose** – Modern Methods of Construction (MMC) represent a potential pathway towards addressing Australia's long-lasting housing undersupply and construction productivity challenges. Yet MMC constitutes not merely a technological change but a socio-technical transition that reconfigures workforce practices and knowledge systems. This study aims to examine how built environment workforce dynamics co-evolve with MMC adoption through the identification and resolution of systemic contradictions.

**Design/methodology/approach** – This research adopted a multi-method qualitative methodology combining semi-structured interviews and fieldwork. Twenty interviews were conducted with participants across diverse MMC company profiles, including designers, manufacturers and builders. Fieldwork using an observational-interview hybrid method was undertaken at 15 companies across five Australian states. Data were analysed using Framework Analysis, with Expansive Learning Theory providing the analytical lens for interpreting contradictions within activity systems.

**Findings** – The analysis identifies eight interconnected contradiction themes driving workforce transformation, including temporal resequencing of decision-making, coordination locus shift, professional knowledge boundary tensions and education system-industry pace mismatch. These contradictions do not operate in isolation but cascade across domains – temporal resequencing exposes knowledge limitations, generating coordination distortions that reveal education misalignment. This cascading dynamic reshapes workforce requirements differently across design/engineering, manufacturing and assembly.

**Originality/value** – This study demonstrates how contradictions function as interconnected drivers of workforce transformation rather than discrete problems. The findings extend taxonomic approaches that conceptualise skills as specifiable occupational attributes by revealing skills as emergent properties – arising when workers, technologies and organisational arrangements encounter incompatible demands. The integration of Expansive Learning Theory with socio-technical transitions theory positions workforce transformation as integral to MMC transition rather than a downstream consequence.

**Keywords** Culture, Housing, Design and construction, Industrialisation, Construction production, Lean construction, Education/Training

**Paper type** Research paper



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## 1. Introduction

Australia is facing a housing crisis driven by a decades-long underlying supply problem (Pawson *et al.*, 2025). The Australian Commonwealth Government has established ambitious targets requiring the construction of 1.2 million new dwellings by 2029 – averaging to 60,000 dwellings per quarter (Australian Government, 2022). Yet recent data reveals the construction industry's persistent inability to meet these demands, with dwelling commencements falling 4.4% to just 45,156 units in June 2025 (BuildSkills Australia, 2025). This shortfall represents not only a temporary setback but the continuation of a decades-long pattern of inadequate housing supply that increasingly positions the national housing targets as unachievable.

Central to this crisis lies the construction industry's chronically low productivity, which has remained stagnant for over three decades (ACA, 2023). The Australian Productivity Commission's (2025) latest analysis presents clear evidence of this decline. Physical productivity – measured as dwellings completed per hour worked – has dropped by 53%, while labour productivity, which accounts for quality improvements and housing size increases, has fallen by 12%. These figures reveal a sector constrained by outdated construction paradigms, unable to leverage the efficiency gains that have transformed other industries (Ghasemi Poor Sabet and Chong, 2020). The Commission further identifies systemic innovation deficits, with construction demonstrating markedly lower innovation activity and spending compared to other sectors, alongside persistent struggles to adopt digital technologies and process improvements that could enhance productivity (Productivity Commission, 2025; Perera *et al.*, 2025).

In response to these structural challenges, the construction industry has increasingly turned to Modern Methods of Construction (MMC) as a potential pathway towards transformation (Bertram *et al.*, 2019). MMC represents a departure from traditional project-specific, site-based construction approaches, instead seeking to industrialise construction (Lessing, 2015; Lessing, 2006). While MMC is sometimes incorrectly framed as merely prefabrication, it requires a holistic shift across the built environment value chain. It demands new skills and approaches to achieve product and process improvements (Koskela, 1992), with a greater emphasis on customer engagement, building systems, technical platforms and integrated logistics throughout the entire value chain (Lessing, 2006). Through an emphasis on standardised products, production strategies and process-oriented thinking borrowed from manufacturing sectors (Koskela, 1992), MMC requires a shift towards continuous process improvement that may ultimately necessitate resolving *contradictions* inherent in traditional construction (Lessing *et al.*, 2015; Cast, 2020). This shift promises significant benefits through the integration of coordinated design approaches (e.g. Design for Manufacturing and Assembly), off-site production facilities and streamlined site assembly processes (Blismas and Wakefield, 2009). The approach has gained substantial policy traction, with Australian federal and state governments positioning MMC as crucial for accelerating quality social housing delivery (Soltani *et al.*, 2025b). Notable initiatives include QBuild's MMC program and Homes NSW's MMC Program, both designed to demonstrate public sector leadership in industry transformation.

MMC's technical and commercial dimensions have received extensive scholarly attention. Drawing on manufacturing advancements, this research has documented key considerations including design innovations (Maxwell and Aitchison, 2017, Kuzmanovska, 2020), the adoption of supporting technologies (Bock and Linne, 2015) and production processes (Doan *et al.*, 2024). Yet technical progress also is insufficient. As Bock and Linne (2015) argued, the successful deployment of automation and robotics in construction depends on the emergence of new skills, markets and professions. Existing literature has largely overlooked how workforce systems and platforms must evolve to support MMC implementation (cf., Lessing, 2006). Less

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attention has been paid to how the skills, knowledge and cultural practices of built environment workers co-evolve with this technological change (Li *et al.*, 2025). Previous attempts to identify MMC skill requirements have typically produced static competency lists (Ginigaddara *et al.*, 2022). These lists fail to recognise skills as dynamic capabilities that emerge through the interaction of workers, technologies and organisational systems (Onyia, 2025). While such approaches inform curriculum design, they cannot explain how an incremental transition towards MMC reshapes workforce dynamics, nor how technological innovations and workforce adaptations are mutually constitutive (e.g. Sackey *et al.*, 2019).

This limitation becomes particularly problematic because the built environment's transition to MMC is not merely a technical upgrade but a socio-technical and cultural transformation (Soltani *et al.*, 2025a). Workers – both blue and white-collar – who are familiar with solving problems on-site through craft-based knowledge must now engage with digital designs and factory-based production logic (Ginigaddara *et al.*, 2022). Traditional trade boundaries that once clearly delineated responsibilities become blurred in integrated manufacturing systems coordinated through digitalisation (Szalavetz, 2022). Work shifts from responsive, site-based problem-solving to anticipatory factory planning (Montazeri *et al.*, 2024). These changes generate tensions and *contradictions* that training alone cannot resolve. They require systemic learning and adaptation across the entire built environment value chain.

To address this gap, this paper uses Expansive Learning Theory (ELT) as an analytical framework (Engeström, 2001; Engeström and Sannino, 2010). ELT examines how new forms of activity emerge when existing systems encounter *contradictions* that cannot be resolved within current practices (Kamanga and Alexander, 2021). By analysing these *contradictions* as drivers of learning, this research reveals that workforce transformation occurs not through linear skill acquisition but through collective efforts to resolve systemic tensions (e.g. Sackey *et al.*, 2019). This shifts focus from identifying static skill requirements to understanding the dynamic processes through which new skills, practices and organisational forms emerge (Kamanga and Alexander, 2021). Against this background, this paper addresses the research question: How do built environment workforce dynamics and systems co-evolve through the resolution of contradictions to facilitate the transition towards MMC?

## 2. Background

### 2.1 Modern Methods of Construction

MMC refer to a family of construction approaches that aim to shift the industry from fragmented and labour-intensive site practices towards more industrialised, standardised and technology-enabled processes. MMC commonly includes offsite manufacturing, prefabricated volumetric and panelised systems, modular construction and digitally supported production and site-based workflows (Cast, 2020). These approaches seek to improve construction productivity, reduce waste and enhance quality and safety by transferring activities into controlled factory environments (Blismas and Wakefield, 2009). Studies have shown that offsite construction can significantly improve productivity and reduce exposure to weather-related disruptions, leading to more consistent performance outcomes (Assaad *et al.*, 2023). The wider MMC knowledge base also emphasises the sustainability potential of prefabrication, especially in relation to resource efficiency and environmental performance benefits (Muñoz *et al.*, 2025).

Different MMC typologies (Cast, 2020) have been developed in response to material systems, regulatory requirements and environmental objectives. Wood-based prefabricated construction, for example, demonstrates strong performance in thermal efficiency and user-centred sustainability criteria (Švajlenka and Kozlovská, 2018). This diversity highlights the need for context-specific evaluation of MMC performance and the development of

appropriate regulatory and technical frameworks. Recent scholarship notes that MMC introduces new fire-performance characteristics, necessitating updated inspection, certification and compliance mechanisms to ensure safe delivery of prefabricated components (Meacham, 2022). Likewise, robotics and automation present emerging opportunities for higher production accuracy and defect reduction, although industry adoption remains constrained by workforce readiness, cost and organisational barriers (Pradhananga *et al.*, 2021).

As MMC continues to expand, the implications for education and workforce development have become increasingly significant. MMC requires new technical competencies, particularly in DfMA, automated manufacturing, prefabrication logistics and the safe assembly of modular systems (e.g. process owner in Lessing, 2006). Research highlights that reskilling and upskilling are essential to support the transition to MMC, as traditional construction roles do not align with industrialised workflows (Li *et al.*, 2025). Adaptability and workforce learning capacity are also critical for enabling innovation and improving organisational performance. Educational systems therefore need to embed competencies such as DfMA, project coordination across factory and site interfaces, digital literacy and sustainability-focused construction knowledge (Ginigaddara *et al.*, 2022).

Moreover, the shift to offsite factories and controlled production environments changes occupational health and safety considerations. While MMC can reduce many site-based hazards, the sector must address new challenges related to transporting and installing large, prefabricated units, which require updated training and regulatory approaches (Ali *et al.*, 2024). Safety frameworks must evolve alongside MMC technologies, particularly as automation and robotics become more integrated into production systems.

## 2.2 Modern Methods of Construction skills and training literature

Existing research on MMC workforce development has sought to understand how the transition to and adoption of MMC will reconfigure occupational roles and skill requirements in the built environment workforce, and what capabilities are required to navigate this shift. One stream of enquiry, adopting the terminology of offsite construction (OSC), addresses this by identifying, classifying and cataloguing specific skills, workforce categories and competency gaps, through mixed methods (Onyia, 2025; Assaad *et al.*, 2022; Ginigaddara *et al.*, 2022; Ginigaddara *et al.*, 2021).

In the USA, Assaad *et al.* (2022) examined the impact of OSC on five broad workforce categories (offsite, onsite, engineering and design, construction and fabrication and administrative workforce) and compiled lists of OSC occupations derived through a literature review and existing national classification frameworks. Through a survey with 100 respondents, the study found all occupations within the offsite and onsite workforces (reflecting blue-collar occupations) require upskilling, and that while demand for offsite occupations will increase, demand for 79% of onsite occupations will decrease. Complementary semi-structured interviews investigated the impact of OSC on the remaining three workforce categories (reflecting white-collar roles) and identified priority skills including offsite construction philosophy, DfMA and logistics and transportation. The occupations most impacted by OSC ranged from traditional construction roles (e.g. construction managers) to more specialised OSC positions (e.g. onsite modules/components installation and set-up personnel).

Similar research has been conducted in the Australian context. Ginigaddara *et al.* (2021) used a single case study of a mass timber project to analyse OSC skill profiles against current national occupational classifications. Through document review and semi-structured interviews, they found the existing classifications insufficiently capture specialised and

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emerging skill sets, such as “three-dimensional draftsman” and “OSC project manager”, demonstrating the need for OSC-specific classifications. Extending this work, [Ginigaddara et al. \(2022\)](#) conducted a multi-case study of 13 Australian OSC projects, selected to reflect a broader range of methods available in the Australian context, including both volumetric and non-volumetric types. Through semi-structured interviews, they compiled a master list of 67 skills across six categories (managers, professionals, technicians and trade workers, clerical and administrative workers, machinery operators and drivers and labourers) and identified 13 redundant and 16 emerging OSC skills, including “architects with BIM and DfMA capabilities”, “3D visualisation technicians” and “OSC estimators”. Their findings indicate that current skill sets are insufficient to support a transition from traditional onsite methods to offsite in Australia.

[Onyia \(2025\)](#) extended this cataloguing work in a Nigerian context through an explicitly human-centric lens that reflects a growing attention to sociocultural dimensions of workforce change. Using surveys and semi-structured interviews with practitioners, they developed and statistically validated a framework of 48 construction management skills and competencies for OSC, mapped into six thematic clusters and ranked by both “perceived importance” and “difficulty to acquire”. This differentiation reveals variation among high-value skills and competencies. More accessible skills within the “core operations” cluster include “training and learning” and “team building”, while more difficult-to-acquire include “sourcing finance”, and skills within the “sociocultural adaption” cluster such as “managing local culture/tradition”. [Onyia’s \(2025\)](#) human-centric approach contrasts with the earlier studies, in part owing to the narrowed focus on construction managers – whose work is inherently more interpersonally than technically oriented – and partly to its foregrounding of sociocultural attuned dimensions that receive less attention in the work of [Assaad et al. \(2022\)](#).

[Li et al. \(2025\)](#) advanced further in this direction. Adopting the language of MMC, they conducted semi-structured interviews with 25 construction industry participants in Western Australia to investigate the role of workforce adaptability and reskilling initiatives in driving innovation. They explicitly criticise prior works for producing “a limited, static list of skills, which neglects the essence of change” ([Li et al., 2025](#)). Drawing upon socio-technical theory, the researchers adopt a dynamic and transformation-oriented view of workforce development. Their analysis highlights how factors such as scepticism and concerns about perceived limitations temper the benefits of adaptive skills and targeted reskilling for MMC. Their findings include recommendations for educational institutions and insights for policy makers on supporting MMC related change.

Taken together, these works articulate two complementary approaches for understanding MMC-related workforce change. The first, a *taxonomic approach*, is reflected in [Assaad et al. \(2022\)](#), [Ginigaddara et al. \(2021\)](#), [Ginigaddara et al. \(2022\)](#) and [Onyia \(2025\)](#), who provide detailed contextual snapshots of current and emerging MMC roles and skill sets conceptualised as specifiable attributes of occupations and project types. These attributes can be classified and mapped onto projected labour market shifts and used to specify the structural requirements for transformation toward MMC. However, such studies say relatively little about how this transformation will unfold in practice. [Li et al. \(2025\)](#) reflected a *dynamic approach*, focusing on the human and organisational dynamics that shape how these requirements are – will be – taken up in practice. These two approaches are not in conflict; rather, they occupy similar problem spaces and share the aim of contributing evidence and insights to guide education providers, industry bodies and governments in planning for MMC workforce transformation. [Onyia \(2025\)](#) represented a bridging work, incorporating elements of both approaches by attending to human and sociocultural dimensions while operating within a cataloguing framework. The study’s methodology adds insight by indicating where workforce development

efforts might be best directed across the various skills and competencies identified, though the authors acknowledge the context-specificity of their findings and the limits to applicability beyond the Nigerian setting.

However, in focusing on constructing static lists of competencies derived from broader existing occupational classifications and prevailing industry perspectives, this line of research risks overlooking skills as dynamic capabilities that emerge through systemic interaction. This limitation is significant because, as the literature has established, the transition to MMC generates systemic contradictions that trap actors between the incompatible requirements of old and new systems (Lessing, 2006, Soltani *et al.*, 2025a). The knowledge gap therefore lies in understanding the mechanisms of transformation needed to resolve these tensions and contradictions. The present study seeks to address this by examining MMC workforce development as expansive learning driven by contradictions.

### 2.3 Theoretical framework for Modern Methods of Construction workforce transformation

This study adopts a dual theoretical lens, drawing upon Socio-Technical Transitions (STT) (Geels, 2002) and ELT (Engeström, 2001) to analyse how the built environment workforce co-evolves with MMC adoption through the surfacing and resolution of *contradictions*.

STT provides the macro-level perspective, framing MMC as a socio-technical system characterised by interdependence between technical, organisational and institutional dynamics (Geels and Schot, 2007, Soltani *et al.*, 2025a). From this perspective, successful MMC implementation requires the joint transformation of both technical dimensions, such as manufacturing and production strategies; and social dimensions, including organisational structures, workforce practices across design, manufacturing and assembly and vertically integrated business model arrangements (Lessing, 2015). Optimising either dimension in isolation inevitably leads to deficient outcomes (Li *et al.*, 2025).

The socio-technical framing carries significant implications for workforce dynamics. It posits that new construction and MMC technologies cannot simply be inserted into existing workplace arrangements (Onyia, 2025). Rather, the processes of labour organisation, technological engagement and knowledge development must co-evolve with the technical incremental innovation (Parker *et al.*, 2025). Consequently, this research positions the built environment workforce transformation not as a downstream result of MMC adoption, but as an integral and inherent element of the transition itself.

While STT theory, particularly through the Multi-Level Perspective (MLP), has conceptualised how technological transitions unfold and how systems destabilise (Geels, 2002), it is less attentive to the micro-level processes through which organisations and workers learn to operate within emerging technical configurations. STT does not fully elucidate how workers collectively make sense of new practices or develop capabilities that do not yet exist. To address this limitation, insights from ELT were incorporated (Engeström, 2001). ELT offers an analytical framework for understanding collective learning processes originated from the transformation of practices that become inadequate—in this case, traditional construction practices (Engeström, 2001; Engeström and Sannino, 2010). This inadequacy is driven by *contradictions* arising from factors such as new technologies (e.g. production systems), division of work (e.g. vertically integrated business models), or evolving regulations (Lessing *et al.*, 2015).

*Contradictions* are central in ELT and hold particular significance for this research. They represent historically accumulated structural tensions within and between elements of the activity system (Kamanga and Alexander, 2021). These contradictions manifest as disturbances, dilemmas and breakdowns in everyday practice. It is through their collective surfacing, analysis and resolution that expansive learning occurs (Engeström, 2001). In the

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context of MMC, for example, professionals encounter tensions when moving from narrow, project-specific solutions to working with standardised components and platform-driven approaches (Hijazi *et al.*, 2025). Craftspeople experience contradictions when shifting from traditional on-site tasks to streamlined production systems leveraging technology and automation (Xu *et al.*, 2025). This theoretical framing aligns well with MMC transitions, wherein neither individual organisations nor the broader industry possesses complete understanding of what must be learned or how such learning should proceed (Li *et al.*, 2025). Given that MMC adoption remains limited in contexts such as Australia, with few targeted training programs available, organisations must collectively construct new understandings and develop novel competencies while simultaneously transforming operational processes.

The co-evolutionary dynamic – whereby innovations in practice drive workforce development, and workforce learning in turn enables further practice innovation – is central to this research’s analytical approach. By examining the contradictions that built environment worker and MMC-engaged organisations encounter, and the expansive learning processes through which they respond, this research renders visible the collaborative, emergent and often contested nature of workforce transformation during socio-technical transitions.

### 3. Methodology

This research adopted a multi-method qualitative methodology, underpinned by a combination of pure and applied research aims – an approach common in built environment and construction disciplines (Fellows and Liu, 2015). On one hand, the research is pure in its aim to develop new knowledge and contribute to theoretical understanding by exploring how workforce transformation co-evolves with MMC transitions. On the other hand, the project sought to address an immediate societal problem, reflecting the applied research tradition commonly conducted in collaboration with government and industry partners (Hedrick *et al.*, 1993). This approach aligns with calls for construction research that bridges academic inquiry and industry relevance (Schweber, 2015).

This research forms part of a wider project funded by the Building 4.0 CRC, an Australian government-funded, industry-led research initiative dedicated to transforming Australia’s building and construction industry. Additional funding was provided by three national Jobs and Skills Councils, BuildSkills Australia, the Manufacturing Industry Skills Alliance, and Skills Insight, representing Australia’s built environment, manufacturing, and agrifood sectors respectively. The initial problem statement provided by these partners guided the conceptualisation of the project: to investigate the workforce, training and skilling implications arising from the increasing adoption of MMC across the Australian built environment value chain, with the aim of driving and facilitating industry transition towards modern construction methods and higher productivity.

#### 3.1 Data collection

Data collection methods comprised semi-structured interviews and fieldwork using an observational-interview hybrid approach. This combination enabled methodological triangulation between participants’ accounts and observed practices (Bryman, 2016), strengthening the validity of findings and providing richer contextual understanding of MMC workforce dynamics (Dainty, 2008).

Semi-structured interviews were used to balance a predetermined protocol informed by the research aims with the flexibility necessary for participants’ perspectives to emerge and for in-depth probing (Brinkmann and Kvale, 2014). A purposive sampling strategy was adopted to gather first-person accounts regarding MMC knowledge and skill requirements, workforce dynamics, recruitment challenges and distinctions from traditional construction practices.

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Participants were drawn from MMC-engaged companies, Vocational Education and Training (VET) providers, industry associations and representatives from companies that had unsuccessfully attempted MMC adoption. This diversity of perspectives enabled examination of MMC workforce dynamics across different stakeholder positions within the value chain.

The interview protocol addressed participants' awareness of MMC, personal and company profiles, current skill and training gaps, forecasting of future knowledge and skill needs and the alignment of current VET training with MMC requirements. A total of 20 interviews were conducted with 21 participants, who were predominantly in senior and leadership positions across a diverse range of company profiles spanning consultancy, design/engineering, manufacturing, supply, building and development (see Table 1 in Supplementary Material Appendix 1). All interviews were conducted virtually using Zoom videoconferencing software by two researchers: one leading the questioning and the other providing follow-up questions. This dual-interviewer approach enhanced data quality by enabling real-time probing while maintaining interview flow (Brinkmann and Kvale, 2014). Interview duration ranged from 20 min 54 s to 1 h 28 min 42 s, with a total recorded time of 15 h 58 min 48 s.

To complement interview data, fieldwork was conducted at 15 companies across the five mainland states of Australia, using an observational-interview hybrid method. These site visits extended beyond passive observation. Each visit was guided by a company representative who responded to researcher questions in an interview-style format while demonstrating facilities and practices. This approach enabled exploration of real practices, working conditions, technological solutions, degrees of automation, material approaches and the division of labour within MMC settings (Pink *et al.*, 2010).

An observation protocol guided data collection, with researchers documenting company layout, team structure, MMC skills gaps and needs, training initiatives, production practices and workflow arrangements. The observed companies represented diverse MMC typologies, with volumetric approaches predominating (see Table 2 in Supplementary Material Appendix 1). Visits lasted between one and two hours and were conducted by at least two researchers to enhance observational reliability and enable post-visit debriefing.

Ethical approval was obtained from Monash University Human Research Ethics Committee (project number: 47960). All participants provided informed consent prior to participation and were advised of their right to withdraw at any time without consequence. To protect confidentiality, participants and organisations have been assigned pseudonyms throughout this paper.

### 3.2 Data analysis

Interview transcripts and observation field notes were analysed using a team-based approach following the five-stage framework analysis method (Ritchie and Spencer, 1994). Framework Analysis was selected for its systematic approach to qualitative data management and its suitability for research with specific *a priori* questions while remaining open to emergent themes, consistent with an abductive analytical approach (Dubois and Gadde, 2002).

In the first stage, researchers familiarised with the data. For interviews, this process commenced with verification of transcript accuracy against audio recordings. For fieldwork, collective reflection and preliminary analysis were undertaken following each site visit. The second stage involved development of the initial coding framework, guided by the lead author and informed by both the theoretical framework and emergent patterns within the data. During the third stage, the thematic framework was systematically applied to all data sources using NVivo Version 15. This stage involved regular project meetings to discuss

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preliminary findings among researchers and industry partners, resolve points of disagreement and refine coding decisions. In the fourth stage, data were synthesised and organised thematically, enabling comparison across data sources and cases (workers and companies). Analysis considered a range of attributes including professional knowledge, company automation levels and workforce qualification levels. Triangulation between interview accounts and fieldwork data was evaluated at this stage to identify convergence and divergence across data sources (Love *et al.*, 2002).

The final stage focused on interpreting patterns and themes through the theoretical framework, with particular attention to identifying contradictions experienced by built environment workers during MMC transitions. This theoretically informed analysis enabled identification of structural tensions within and between activity system elements that drive workforce transformation (Engeström, 2001). The iterative movement between empirical data and theoretical constructs reflects the abductive logic underpinning this research, whereby theoretical refinement occurred through ongoing engagement with empirical observations (Dubois and Gadde, 2002).

#### 4. Findings

The findings are organised into eight themes, summarised in Table 1. These contradictions capture the points at which established construction practices, knowledge systems and organisational arrangements encounter the demands of MMC, generating tensions that cannot be resolved within existing traditional approaches. Table 1 presents each contradiction theme alongside its differentiated implications for workforce dynamics and skills across three primary workforce segments: design/engineering, manufacturing and assembly.

Readers are encouraged to refer to Table 1 throughout the following sections, as each theme is discussed in relation to its implications for design/engineering, manufacturing and assembly workforce segments.

##### 4.1 Theme 1: Temporal resequencing of decision-making

Theme 1 focuses on how MMC inverts traditional construction's temporal distribution of decision-making effort. In traditional construction, on-site work typically commences with architectural and technical designs at approximately 30% completion. Design details, technical coordination and logistics requirements are then progressively resolved throughout the construction phase. This end-loaded approach accommodates on-site problem-solving and adaptive decision-making as construction unfolds.

MMC, by contrast, demands *design freeze* and early decision-making before manufacturing can commence. Design documentation must achieve near-complete resolution prior to production. This includes technical coordination, tolerance specifications, logistics constraints and quality assurance protocols. This temporal resequencing creates a contradiction between the end-loaded workflow patterns of traditional construction and the front-loaded planning requirements of MMC. Workers and organisations equipped for progressive, adaptive on-site problem-solving must now operate within systems where all major design decisions are finalised and approved before manufacturing begins. One participant described this shift:

Traditional construction often solves problems on site. With MMC, you need to solve them upfront, sometimes months in advance. That means stronger digital literacy is important, being comfort with BIM and clash detections and an understanding of manufacturers processing. It's a shift in my mindset, much as a skill". (Participant A)

**Table 1.** Contradiction themes and implications for design/engineering, manufacturing and assembly workforce

| Contradiction theme  | Design/Engineering   | Manufacturing   | Assembly  |
|--|--|---|---|
| 1. Temporal resequencing of decision-making                | Must fully complete designs and documentation before manufacturing commences. Requires manufacturing and construction knowledge for front-loaded decision-making   | Dependent on design details and feasibility, limited design adaptability during production and manufacturing  | Must trust up front design decisions and considerations   |
| 2. Knowledge boundaries                                    | Must extend beyond design to understand manufacturing tolerances, transport constraints and assembly sequences   | If the information is incomplete, must bridge gap between structural specifications and production realisation  | Understand design rationale and manufacturing logic. Recognise why components are configured as delivered. Connect assembly sequence to upstream decisions  |
| 3. On-site problem-solving vs process thinking orientation | Design for systematic and production system development rather than bespoke solutions. Must anticipate manufacturing constraints rather than defer to construction-phase resolution  | Core orientation shift from reactive problem-solving to proactive process optimisation. Lean manufacturing principles. Root-cause analysis rather than firefighting                                     | Follow documented procedures for assembly. Understand rationale for standardised processes. Contribute to continuous improvement rather than individual problem-solving (e.g. retrofit to design) |
| 4. Multi-skilled trades                                    | DfMA literacy. System selection knowledge  | Combine trade skills with machinery operation and QA  | Multi-trade capabilities  |
| 5. Education systems pace renewal                          | University curricula lag MMC developments  | Proprietary systems require company-specific training   | Trade qualifications assume on-site contexts  |
| 6. Coordination locus                                      | Cede coordination to manufacturers but still providing input   | Become coordination leader, while driving design team alignment   | Receive completed assemblies. Limited coordination input  |
| 7. Assembly-installation interface                         | Design for assembly from outset. Determine which services are manufactured off-site vs. installed on-site. Coordinate service interfaces and access provisions. Involve builders early to align factory production with installation sequences | Produce modules with clear installation and handling specifications. Embed services coordination in manufacturing documentation. Communicate protection requirements and sequencing logic to site teams | Execute installation according to specifications and sequences  |
| 8. Digital literacy and adaptability                       | BIM mastery with platform flexibility across fragmented software ecosystem. Clash detection and resolution. Self-directed learning to maintain skill set as tools evolve   | Operate QA software for production documentation. Manage robotics and automation interfaces. Develop adaptive capacity to learn new digital systems as manufacturing technologies advance               | Access current documentation in real-time. Digital QA recording: platform flexibility to navigate multiple software formats. Scheduling and control using BIM                                     |

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The temporal resequencing demands an evolution in both mindset and skills among architects, designers and consultants. A further example is the integration of design and manufacturing thinking:

MMC also requires a different angle of thinking, because unlike the traditional where we would just design and then think how this is getting constructed, MMC needs to have that lined up simultaneously, design and how this is being constructed in a most efficient way. [These] need to go hand in hand, together, if the design does not facilitate for a most efficient, standardised form, the design cannot be worked out". (Participant C)

Participant C highlights that MMC does not simply shift decision-making earlier, it restructures the relationship between design and construction. Design and manufacturing feasibility proceed in parallel rather than sequentially. This requires designers and architects to possess manufacturing and construction knowledge as a foundation for their work, challenging established practices where design decisions were made independently of construction considerations.

#### 4.2 Theme 2: Professional knowledge boundary tensions

The second theme describes how professional knowledge boundaries become increasingly blurred under MMC. Architects must understand manufacturing constraints, engineers need to comprehend logistics and consultants must provide manufacturing-ready information rather than deferring to subcontractors. These demands are partly driven by the temporal resequencing contradiction (Theme 1). They create tensions between professional segments whose boundaries have historically remained distinct.

The proliferation of Design and Construct (D&C) procurement over recent decades allowed professionals to defer detailed construction decisions to subcontractors. This created a progressive loss of construction knowledge among design professionals. Participants suggested this deficit must now be addressed through university education:

From university perspective, giving them [architects] the mere understanding of how things are constructed on site, how pieces come together. And as an architect, our knowledge should not be just limited to design [...] I often say we are like the music composers, not just the conductors. We don't need to know every single music instrument, how it plays to the fullest core. We only need to know how it can be played". (Participant C)

The "composer not conductor" metaphor captures the nature of the required knowledge expansion. Professionals need not become experts in manufacturing or logistics. They must, however, possess sufficient understanding to make informed design decisions. This includes accounting for manufacturing tolerances, transportation constraints, panel size limitations, sequencing requirements and logistics planning.

MMC also demands new patterns of inter-disciplinary engagement. In traditional construction, professional disciplines operate relatively independently, coordinating at discrete interface points such as technical design handovers (Winch, 2009). MMC reduces these interfaces, requiring continuous cross-disciplinary dialogue. One structural engineer described this knowledge gap within his discipline:

Most engineers, I think, their job stops at deciding how thick a wall needs to be, or thick a floor panel needs to be. They might have some rough idea about connections, but they don't often have the experience of how they go together, how they're manufactured". (Participant D)

Engineering education focuses on determining *what* is required structurally. It does not address *how* those specifications translate into manufactured components, factory processes, or site assembly sequences. The same participant reflected on how transitioning from

engineering consultancy to a manufacturing role transformed his professional perspective. He noted that as an engineer, he “thought he knew a lot about timber”, only to discover he “only knew a lot about a tiny little part of the puzzle” (Participant D). This boundary-crossing enabled him to design for simplicity in manufacturing and assembly.

#### 4.3 Theme 3: On-site problem-solving vs value chain process thinking integration

This theme captures a shift in work orientation. Traditional construction cultivates adaptive on-site problem-solving capabilities, where workers address issues as they emerge on-site through improvisation and craft-based judgement. This rewards flexibility, rapid diagnosis and the ability to devise solutions within evolving site conditions. MMC, by contrast, requires systematic process thinking focused on production flow optimisation, continuous improvement and waste elimination. Principles drawn from manufacturing methodologies, such as lean thinking and Six Sigma (Koskela, 1992).

This represents a contradiction between existing worker capabilities and the demands of MMC production environments. Workers whose professional identities have been shaped by on-site problem-solving must reorient towards process adherence and continuous improvement.

This contradiction was evident across different workforce segments. In factory settings, traditional construction mindsets manifested as ad-hoc responses to production issues rather than systematic root-cause analysis:

Quality assurance was people taking photos on iPhones and stuff, and then never doing anything with it. They didn't have that process built up. So, everything was quite ad hoc, and they were just constantly kind of firefighting on the floor, going ‘ah it's all right, we'll just do this, we'll fix this thing up this way.’ It's constantly doing this, but no one was going back to the start and go right. Why did it go wrong? How do we make this more efficient?” (Participant D).

Firefighting orientations that work in traditional construction become counterproductive in factory environments. Standardised and repeatable processes are essential for driving optimisation and productivity. Bridging these two orientations require a hybrid skill set:

There is a skill set that is a kind of combination of blue-collar carpentry, metal worker kind of sort of skills, and a kind of manufacturing skill set that you need to find a way to marry those together. And there's not many people that have a background like that, so you can tend to take a carpenter to bring them into a factory, but you have to work on their mindset and their ability to see things as a process”. (Participant D)

Fieldwork observations confirmed this challenge extend beyond factory floor workers. One visited company had implemented Failure Mode and Effects Analysis (FMEA) workshops specifically for their design and operations teams. This structured approach to anticipating and mitigating failures illustrates how manufacturing-derived process-thinking methodologies can be adapted for professional roles within MMC organisations.

#### 4.4 Theme 4: Multi-skilled trade requirements

This theme captures the contradiction between trade qualifications built around on-site, craft-based work, and the hybrid capabilities required in MMC factory environments. Traditional trade training develops skills for site-based problem-solving within variable conditions. MMC factory settings, by contrast, demand integration of trade knowledge with manufacturing process skills, machinery operation and systematic quality assurance. A combination that existing vocational frameworks do not address.

The nature of this multi-skill set varies with the degree of factory automation. In more automated companies, recruitment from automotive and manufacturing sectors proved

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effective, though these workers required upskilling in construction domain knowledge. Conversely, traditional trades transitioning to factory environments needed new capabilities including CNC machinery operation, documented process adherence, quality assurance protocols and precision measurement. One participant articulated this distinction:

If you look at other customers that have automation, so they've got sort of machinery producing the panels, wall panels, floor panels, roof panels, that go down a manufacturing line. That needs a mitigation of skill set, because the way I view that is you're skilling labour in machinery and a documented process, or a manufacturing process and a QA process, as opposed to a trade skill". (Participant E)

Automated factory production represents a different skill paradigm rather than simply an extension of trade skills into a new environment. The knowledge required centres on machinery operation and process adherence rather than craft-based judgement. This creates recruitment challenges, as few workers hold capabilities spanning both domains:

Trades also are highly skilled but can be hesitant about the factory-based methods. That makes it a bit tricky to find people who straddle comfortably in both worlds. Sometimes we've recruited from outside the construction, like automotive or from manufacturers background, because they have that thinking of process and precision". (Participant A)

Fieldwork observations revealed that multi-skilling served purposes beyond bridging on-site and off-site contexts. In visited companies, rotating workers across production tasks helped prevent burnout from repetition, built workforce versatility and improved worker engagement. Workers with a broader understanding of the full production system were better positioned to offer improvement suggestions. One worker noted that he valued his employment specifically because management listened to his suggestions.

#### 4.5 Theme 5: Education system-industry pace mismatch

This theme describes a contradiction between the pace of MMC innovation and the responsiveness of formal educational systems. Vocational and higher education providers operate under governance structures that impose multi-year cycles for curriculum accreditation and renewal. Programs designed to address specific industry needs may become obsolete by the time accreditation is obtained and delivery commences. While participants' accounts predominantly referenced vocational education systems (TAFEs, RTOs), fieldwork observations revealed similar challenges at higher education levels. One participant illustrated the scale of this mismatch:

We started the process of developing our own in line training system with the TAFEs at about the same time, and that would have been about six years ago, and the first TAFE course is only coming out now at the end of this year. So, one, the TAFE courses just take too long. Two, the thing with steel framing is that actually there's no common steel framing system. Each steel framing system is proprietary, so all of them are slightly different". (Participant F)

This account reveals two compounding challenges. Firstly, a six-year development cycle risks rendering content outdated before it reaches learners. Secondly, the proprietary nature of MMC systems means that even current content may lack relevance to specific workplace contexts. Each manufacturer's system differs, yet formal qualifications must necessarily generalise. This creates complications for qualifications targeted to specific occupations. Participants noted that responsibility for ongoing learning increasingly falls to individual workers:

Education needs to be faster. Because, you know, we've put a hold on the NCC. I taught 2019 version and 2022 version. And you have to update all the time. By the time, if you've spent two

years, three years, studying 2022, by the time you get out, it's out of date. And it's on you to keep yourself up to date". (Participant G)

This expectation of self-directed learning is rarely made explicit by vocational pathways. In response to these systemic limitations, some MMC companies have developed their own training mechanisms and internal guidelines (e.g. company-specific DfMA protocols) to fill the gap that formal education cannot.

#### 4.6 Theme 6: Coordination locus shift

This theme describes a disruption to established roles and organisational boundaries around project coordination. In traditional construction, coordination occurs predominantly on-site under project manager direction (Winch, 2009). Design disciplines provide documentation that is progressively refined through the construction phase. MMC inverts this logic. Coordination must occur before anything is manufactured, linking design and fabrication to ensure components integrate correctly, arrive when needed and can be installed safely and efficiently.

In principle, effective MMC coordination requires each party to fulfil a defined role. Designers provide documentation resolved to a level suitable for fabrication. Builders confirm on-site conditions, manage trade sequencing and approve fabrication documentation. Fabricators translate design intent into producible specifications. In practice, however, interviews and observations reveal that builders and designers in the Australian context increasingly default to the manufacturer, expecting them to absorb the full coordination burden.

This pattern manifests in two ways. Firstly, designs developed without manufacturing constraints are handed to manufacturers, who must re-engineer them to align with their systems and production capabilities. Secondly, builders disengage from early coordination, leaving site-related decisions unresolved until manufacturing is underway. One participant described this dynamic:

A lot of the time, that design, project management stuff sits within the manufacturer in a lot of cases, because they're the ones that are ultimately making this their 3D model that will start to be the single source of truth for everything. So, everything feeds in through that, and they're the ones that are often best placed to coordinate it". (Participant D)

This account reflects a coordination gap driven by knowledge deficits rather than intentional role allocation. When designers lack manufacturing knowledge and builders are unfamiliar with MMC workflows, the manufacturer becomes the default coordinator, regardless of whether they are equipped for that expanded role.

This ambiguity is driving the emergence of new roles. These include BIM coordinators with manufacturing knowledge, independent DfMA coordination consultants who can advise across multiple suppliers, and manufacturer-embedded project managers who drive design team alignment from within the supply chain. MMC coordination is becoming a distinct skill set, separate from both traditional architectural project administration and conventional construction project management.

#### 4.7 Theme 7: Assembly-installation interface tensions

This theme captures contradictions at the interface between manufacturing and on-site construction. In traditional construction, site variability is expected and accommodated through adaptive problem-solving by trades. MMC operates differently. On-site assembly should involve minimal variability, with installation sequences predetermined by upstream design and manufacturing decisions. When interface tensions arise, they typically signal

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failures in design for assembly coordination rather than inherent limitations of MMC. Participants described cases where trades arriving on site encountered completed or closed panels that disrupted their expected workflows:

With MMC, especially, when you're building prefab, you might get sections coming in that are finished and closed, like closed wall sections, where normally the trades can get into them, and they're having to either drill into beautifully finished panels now or pull them off and put them back on again. So, the sequencing of how a building like that goes together, because it's different to the sequence of normal". (Participant H)

When trades must drill into finished panels or remove completed work, it indicates that service routes, access requirements and installation sequences were not adequately resolved during design. It also suggests these decisions were not sufficiently communicated to site teams. Designers bear responsibility for determining upfront which services are manufactured off-site and embedded within panels, which require on-site installation, and how the design accommodates access without compromising factory-finished assemblies. Where interface challenges cannot be eliminated, they should at least be anticipated and clearly communicated to site workers.

When coordination failures accumulate, frustration can escalate into active resistance. One participant recounted an experience where interface tensions extended into cultural opposition:

When they were delivered, and partly a logistics situation, all the ceilings were cracked. And so, then we had this repair of ceiling. Then when we had these bathroom pods open, all of a sudden, there were these damages that didn't look like they were logistics damage [...] there was kind of this deliberate - didn't want this to work. And so, they would create damage [...] there was pushback from the trades on site, not wanting to see it succeed". (Participant I)

The deliberate damage described here suggests that some trades perceived factory-produced elements as threats to their established roles. This reflects cultural attitudes that require change management interventions. However, the conditions that enabled this resistance (e.g. modules arriving damaged, unclear responsibilities, repeated repair requirements) point back to failures in design for assembly and logistics coordination. Addressing the cultural dimension alone is insufficient. The upstream coordination failures that generate these tensions must also be resolved.

#### 4.8 Theme 8: Digital literacy and adaptability

This theme captures a contradiction arising from MMC's intensified reliance on digital tools. Digital skill requirements are well recognised for professional roles such as architects and engineers. This theme extends that demand to factory and on-site trades, workforce segments where digital literacy expectations have historically been minimal.

Fieldwork observations revealed that factory workers increasingly require digital capabilities beyond traditional trade skills. These include interpreting digital models to understand assembly specifications, operating quality assurance software to document production compliance, and managing robotics and automation interfaces in more advanced facilities. For on-site assembly workers, digital literacy enables real-time coordination for accessing current documentation, interrogating models to resolve ambiguities and recording installation progress. One participant described this emerging expectation:

The trades, should they be digitally literate? They should be. So, the ones that are more effective on site, they're walking around with iPads [...] The better trades will be wandering around with an iPad, with the model and the drawings available to them, and interrogating those. They're not all like that, though, unfortunately". (Participant J)

Digitally literate trades perform more effectively, yet this capability remains unevenly distributed. Some workers leverage digital tools to enhance performance while others remain dependent on traditional paper-based documentation that may be outdated or incomplete. This is not only a worker capability issue. Observations reveal that many companies have not established the processes or infrastructure that would enable trades to engage digitally, even if they possessed the requisite skills. The software ecosystem itself presents further barriers:

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Across the processes, definitely a lot of builders would use different packages, for instance, for design as to what an architect uses. A lot of even the design for manufacturing programs operate with Revit, and most builders operate using ArchiCAD. So, there's even a skills shortage in the software development of making modern methods of construction more seamless, from the integration of more of a volume project builder when it's not a bespoke architect". (Participant K)

Software fragmentation means workers cannot rely on mastering a single platform. They must develop the ability to navigate multiple systems and translate information across incompatible formats. This demands not only technical proficiency but also adaptive capacity and self-directed learning. Digital adaptability, the capacity to learn new tools independently and transfer skills across platforms, emerges as a foundational competency for MMC work. This is distinct from proficiency in any specific software application.

## 5. Discussion

This research aimed to examine how built environment workforce dynamics and systems co-evolve through the resolution of contradictions to facilitate the transition towards MMC. The findings reveal that MMC transitions generate multiple and interconnected contradictions that drive expansive learning and workforce transformation across the built environment value chain (Table 1). A central finding of this research is that the eight contradiction themes identified do not operate as isolated tensions. Rather, they form an interconnected system in which tensions in one domain propagate across others, creating cascading effects throughout the MMC activity system. This interconnected character has significant implications for understanding workforce transformation during industry transitions.

This discussion examines the key implications for workforce skills and emerging roles, organised around three interconnected dynamics: 1) the temporal-coordination nexus, 2) a professional boundary reconfiguration and 3) the education system-industry alignment challenge.

### 5.1 *The temporal-coordination nexus and its workforce implications*

The temporal resequencing of decision-making (Theme 1) emerges as a foundational contradiction with cascading implications across the MMC activity system. In traditional construction, design is progressively resolved during the construction phase. MMC inverts this logic, requiring front-loaded decision-making before manufacturing can commence (see Figure 1 in Supplementary Material Appendix 2). This restructures when, where and by whom project decisions are made. It also elevates the importance of early conceptualisation and design driven by DfMA principles – a skill increasingly recognised as essential for the engineering and design workforce (Ginigaddara *et al.*, 2022; Assaad *et al.*, 2022). The imperative to introduce design thinking earlier resonates with MacLeamy's time-effort distribution curves, which highlight the benefits of early stakeholder engagement in avoiding costly on-site modifications (Lu *et al.*, 2015). However, MMC goes further. Beyond information flow and decision quality, it introduces additional demands around manufacturing tolerances, transportation constraints and assembly sequences that traditional design education does not address.

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This temporal shift directly causes the coordination *locus* shift (Theme 6). Effective coordination must occur before manufacturing commences. This is consistent with previous literature identifying logistics, sequence management and supply chain planning as high-impact occupational domains in MMC transitions (Assaad *et al.*, 2022). Industrialised Building theory posits that coordination should be distributed across design, production and assembly phases. Lessing (2006) proposed the emergence of a dedicated “Process Owner” role to formalise this upstream control and manage the design-manufacturing interface. This role also ensures process thinking integration across the value chain (Theme 3).

These coordination demands echo longstanding challenges in construction. Winch (2009) noted that design and execution have historically operated as separate processes. Those responsible for coordination are rarely trained in project management and often carry competing responsibilities. Koskela (1992) warned that industrialised construction demands considerably tighter integration across design and planning than traditional methods. The contradictions identified in this study suggest these challenges have deepened rather than resolved as MMC adoption has grown.

In the Australian context, the findings reveal a significant gap exists between theoretical prescription and observed practice. Designers and builders increasingly default to the manufacturer, expecting them to absorb the full coordination burden. Two interrelated factors explain this pattern. Firstly, Australia’s relatively young MMC market means that design professionals and builders often have limited knowledge of manufacturing processes. Secondly, when this knowledge gap emerges, manufacturers – by virtue of controlling the production process – become default coordinators. This occurs regardless of whether they possess the project management capabilities the role demands. Revolving this contradiction requires more than developing manufacturer capability. It requires parallel development of DfMA knowledge among designers (Ginigaddara *et al.*, 2022) and MMC workflow familiarity among builders, an aspect further discussed below.

### 5.2 Professional boundary reconfiguration and multi-skill requirements

The temporal-coordination nexus confirms the necessity for professionals and workers to acquire knowledge beyond their historical disciplinary boundaries, connecting directly to professional knowledge boundary tensions (Theme 2) and multi-skilled trade requirements (theme 4). These contradictions manifest differently across workforce segments but share a common underlying dynamic. MMC narrows tolerance margins and compresses decision timelines in ways that challenge traditional disciplinary silos as dysfunctional. This dynamic aligns with Bock and Linne’s (2015) argument that the successful deployment of automation and robotics in construction depends on the ability to manage innovation across the complete value chain. In their view, this transition will inevitably create new markets, qualifications, skills and professions, requiring what they describe as augmented skill formation that cuts across disciplinary boundaries. The contradictions identified in this study reflect precisely this cross-disciplinary demand.

For design phase professionals, whether architects or engineers, the findings reveal that MMC demands knowledge of both design and manufacturing – domains traditionally treated as separate areas of expertise. Architects increasingly require BIM proficiency integrated with DfMA knowledge, understanding not only how to model buildings digitally but how design decisions translate into manufacturing feasibility and assembly sequences (Ginigaddara *et al.*, 2022). Similarly, engineering roles are being reconfigured as technical design consultants, project managers (Ginigaddara *et al.*, 2021) and into manufacturer-embedded coordination roles, where engineering education emphasises process thinking and lean manufacturing principles (theme 3). These reconfigurations suggest that MMC transitions do not simply add

competencies to existing roles but fundamentally restructure how professional work is organised and distributed (see Figure 2 in Supplementary Material Appendix 2).

For trade workers, the findings highlight the convergence of traditional craft skills with factory operations, necessitating hybrid capabilities that current training frameworks do not adequately develop. The emergence of occupations such as CNC technicians and other specialised factory operators reflects this convergence, yet these roles occupy an ambiguous position within existing qualification structures (Ginigaddara *et al.*, 2022). Workers may possess trade backgrounds that provide foundational construction knowledge while lacking formal credentials in manufacturing operations, or conversely, may bring manufacturing experience without construction knowledge. This multi-skill requirement – the capacity to integrate craft knowledge with process-oriented factory operations – represents a distinctive competency demand that neither traditional apprenticeship models nor manufacturing training pathways currently address.

The findings further reveal that digital literacy gaps (theme 7) aggregate these multi-skill requirements. MMC workflows demand digital capabilities extending beyond software proficiency to involve platform flexibility and self-directed learning capacity. The fragmented software ecosystem – where designers, manufacturers and builders frequently operate on incompatible platforms – requires workers to navigate multiple digital environments and translate information across formats. The findings indicate that digital engagement in current practice often defaults to individual discretion, particularly among subcontractors who determine their own engagement with digital protocols. This observation suggests that digital literacy in MMC contexts cannot be conceived as individual capability but must be understood as embedded within organisational systems that either enable or constrain digital workflow participation (Perera *et al.*, 2025).

### 5.3 Education system-industry alignment and systemic contradictions

The skill transformation demands identified above connect directly to theme 5 (Education system-industry pace mismatch), revealing a systemic contradiction between the pace of MMC innovation and the adaptability of education systems that ultimately inform the responsiveness of formal education and training institutions. Trade certification frameworks assume on-site work contexts, creating regulatory misalignment where factory-based production roles lack formal recognition. Workers operating manufacturing equipment may possess practical competence while lacking credentials that regulatory frameworks require, whereas workers holding traditional trade qualifications may lack the process-oriented capabilities that factory environments demand (theme 3). Another example is the accreditation guidelines for architectural and engineering programs, which might not prioritise DfMA and MMC systems, and even if they do the pace for curriculum renewal is super low to align with industry needs (e.g. Desha *et al.*, 2009).

The findings suggest that when formal training systems cannot maintain currency with industry evolution, responsibility for capability development transfers to individual workers and employing organisations. Workers are increasingly expected to engage in continuous self-directed learning to maintain relevance as technologies and processes evolve – an expectation that remains largely implicit and for which support structures are underdeveloped. Organisations, meanwhile, invest in proprietary training initiatives and manufacturer-specific certifications that operate outside formal qualification frameworks. While these arrangements demonstrate industry adaptability, they also fragment the training landscape and potentially limit workforce mobility across employers and MMC systems.

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#### 5.4 The co-evolutionary dynamics of Modern Methods of Construction workforce transformation

Considered together, the three dynamics examined above – the temporal-coordination nexus, professional boundary reconfiguration, and education system-industry alignment – reveal that the eight contradiction themes form an interconnected system rather than a collection of independent challenges. Temporal resequencing exposes knowledge boundary limitations, which generate coordination distortions, which in turn reveal education and training system inadequacies. This cascading character means that interventions targeting isolated contradictions are unlikely to achieve systemic impact. Effective workforce development strategies must address contradiction clusters rather than individual skill gaps.

Moreover, the analysis reveals a co-evolutionary relationship between workforce capabilities and MMC implementation. Workforce upskilling enables innovative practice, while practice innovation simultaneously generates new workforce development demands. This dynamic suggests that MMC transitions cannot be understood through linear models of technology transfer followed by workforce adaptation. Instead, workforce transformation is constitutive of the transition itself.

The findings hold significant implications across three domains: practice, education and policy. For industry, coordination responsibilities should be explicitly defined across designers, builders and fabricators from project inception; rather than defaulting to manufacturers. Cross-disciplinary exposure, such as embedding designers within manufacturing facilities, would build the mutual understanding MMC workflows demand. For education and training providers, agile curriculum renewal processes are needed to keep pace with industry change. Work-integrated learning models placing students within MMC facilities would develop hybrid capabilities that classroom-based training cannot replicate. For policymakers, three priorities emerge. Firstly, a national MMC occupational framework should formally recognise factory-based construction roles. Secondly, cross-sector training pathways bridging construction and manufacturing need dedicated funding. Thirdly, procurement requirements for publicly funded MMC projects should incentivise early adoption of DfMA principles.

### 6. Conclusions

This study examined how workforce systems and dynamics co-evolve during the transition to MMC in the Australian built environment sector. Drawing on ELT, the analysis identified eight interconnected contradiction themes that function as drivers of workforce transformation, including the temporal resequencing of decision-making, the shift in coordination *locus*, professional knowledge boundary tensions and education system-industry pace mismatch. The most significant finding is the cascading nature of these contradictions. Tensions in one contradiction theme propagate across others, exposing systemic inadequacies in traditional construction practices and reshaping workforce requirements across design, manufacturing and assembly domains.

The theoretical contribution of this research is twofold. Firstly, it extends *taxonomic approaches* in MMC skills and training literature (e.g. *Assaad et al., 2022; Onyia, 2025*) by demonstrating that skills are not fixed occupational attributes but emergent properties of contradiction systems. Findings suggest that new emerging and dynamic skills arise when workers, technologies and organisational arrangements encounter incompatible demands from traditional and industrialised construction practices. Secondly, the findings position workforce transformation as constitutive of the MMC transition rather than a downstream consequence. The contradictions identified are not problems to be eliminated but generative tensions that, when productively engaged, drive the expansive learning processes through

which workforce capabilities, knowledge systems and industry structures co-evolve (Kamanga and Alexander, 2021). Overall, the findings reveal a fundamental reconfiguration of the built environment value chain that privileges early, upstream and integrated decision-making capabilities – a transformation likely to accelerate as MMC adoption expands.

This study has limitations that inform future research directions. The analysis is situated within the Australian context. While the underlying theoretical mechanisms are transferable, the specific manifestation of contradictions may differ across national policy settings, market structures and industrial relations frameworks. The sample, while purposively selected to reflect diverse stakeholder positions and MMC typologies, is relatively small. This limits the generalisability of findings across the full breadth of the Australian MMC sector. Future research should address this through larger-scale national surveys capable of testing and quantifying the contradiction dynamics identified. The team-based coding process and regular inter-researcher discussions strengthened analytical consistency. However, as with all qualitative research, the interpretive nature of the analysis carries potential for researcher bias. Comparative studies across other national contexts (particularly more mature MMC markets such as Sweden, the UK and Singapore) would further test the transferability of the theoretical framework and findings. In addition, although the findings reveal what is changing in workforce requirements, they provide a theoretical foundation rather than the detailed occupational profiles needed for direct curricular reform. Future research should translate these insights into actionable educational frameworks, dynamic occupational profiles and alternative pedagogical approaches that explicitly address contradiction resolution and foster the expansive learning processes identified in this study.

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### Supplementary material

The supplementary material for this article can be found online.

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