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FROM COMPETENCY MAPPING TO DIGITAL TWIN INTEGRATION: DEVELOPING A NEXT-GEN DIGITAL PROJECT MANAGER MODEL FOR SMART CONSTRUCTION

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***SUMMARY**: The digital transformation of the construction industry has outpaced the evolution of traditional project management competency frameworks, leaving many Project Managers (PMs) underprepared to meet the demands of emerging technologies such as Digital Twins (DTs). This study develops and validates a Next-Gen Digital PM Competency List tailored to the Smart Built Environment (SBE) through a structured two-stage methodology. Stage 1 applied a three-phase process comprising (1) a Systematic Literature Review (SLR), (2) NVivo-based thematic analysis, and (3) Large Language Model (LLM)-driven synthesis. These phases identified, categorised, and defined 55 digital PM competencies, systematically organised into Skills, Knowledge, and Core Personality Traits. Stage 2 evaluates the practical relevance of these competencies by mapping them against six thematic functional requirements of DTs, including interoperability and integration, real-time data management, simulation and predictive modelling, cybersecurity and data governance, stakeholder collaboration, and scalability and lifecycle continuity. DTs were selected as an exemplar because they integrate multiple digital technologies, Building Information Modelling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing, making them a representative test case for evaluating competency alignment in digital transformation. The mapping confirmed strong alignment in digital integration and collaboration while exposing gaps in cybersecurity readiness and lifecycle resilience. The resulting framework provides a validated reference for competency benchmarking, targeted training, and digital leadership development. By equipping PMs with the competencies to lead, manage, and support digitally enabled projects, this research contributes directly to advancing smart and sustainable construction practices in the digital built environment.*

***KEYWORDS**: Digital Project Manager, Digital Competencies, Digital Twin, Digital Transformation, Smart Built Environment (SBE), Construction Management, Smart Construction.*

***REFERENCE**: Omar A. Owais, Mani Poshdar, Ali GhaffarianHoseini, Fei Ying, Kamal Jaafar, Saad Sarhan & Moslem Sheikhkhoshkar (2025). From Competency Mapping to Digital Twin Integration: Developing a Next-Gen Digital Project Manager Model for Smart Construction. Journal of Information Technology in Construction (ITcon), Special issue: 'Smart and Sustainable Built Environment (SASBE 2024)', Vol. 30, pg. 1431-1458, DOI: 10.36680/j.itcon.2025.058*

1. BACKGROUND AND LITERATURE REVIEW

The construction industry remains vital to economic development but faces intensifying pressures from urbanisation, sustainability demands, and rising expectations for efficiency, speed, and quality (Sarhan & Pretlove, 2021; van Wyk et al., 2024). Historically labour-intensive and slow to modernise, the sector has lagged in embracing digital innovation. This has resulted in persistent inefficiencies, delays, and cost overruns(Dlamini & Cumberlege, 2021; Whyte et al., 2024). In recent years, however, the adoption of advanced digital technologies has begun to reshape the industry and enable the emergence of the Smart Built Environment (SBE).

This shift is driven by the integration of digital tools such as Building Information Modelling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, and Digital Twins (DTs), which are redefining how construction projects are conceived, managed, and delivered (Liu et al., 2022; Papuraj et al., 2025; Tran & Nguyen, 2024). These technologies promote real-time collaboration, data-informed decision-making, and improved sustainability and performance across project lifecycles. While multiple technologies underpin digital transformation in construction, this study uses DTs as a representative exemplar because they embody the convergence of these tools, integrating BIM, IoT, AI, and cloud computing into a single, lifecycle-oriented system. Accordingly, the subsequent focus on DTs does not diminish the relevance of other digital tools but reflects their role as an integrative platform through which PM competencies can be most effectively examined. This makes DTs a suitable test case for evaluating how validated digital competencies align with the operational demands of advanced digital transformation technologies.

Digital transformation in construction is best understood across three progressive stages: digitisation (conversion of analogue to digital formats), digitalisation (optimising workflows using digital tools), and full digital transformation, in which technology reshapes business models and decision-making cultures (Parviainen et al., 2017; Vial, 2021; Yoo et al., 2010). This evolution supports integrated delivery, data-driven analysis, and smarter collaboration.

Emerging tools such as BIM and IoT are enhancing planning accuracy and on-site responsiveness (Aghimien et al., 2020; Samuelson & Stehn, 2023). AI is increasingly used to power predictive analytics and support data-informed decision-making (Naji et al., 2024). Meanwhile, robotics are streamlining repetitive construction tasks (Zharov, 2024). Collectively, these advances are shifting project delivery toward more integrated and interdisciplinary processes. These developments call for a new type of leadership at the core of project teams.

As digital transformation accelerates, the role of the Project Manager (PM) is being redefined. PMs must move beyond tool usage and become digital leaders, capable of managing innovation, orchestrating digital ecosystems, and aligning strategy with technology. While foundational skills in stakeholder engagement, scheduling, and risk remain relevant, PMs must also possess competencies to manage digital workflows, interpret real-time data, and lead strategic transformation initiatives (Liu et al., 2022; Vuorikari et al., 2022; Wu, 2022).

Several recent studies have begun to address this competency shift. For instance, Kissi et al. (2025) ranked PM digital competencies using Fuzzy Synthetic Evaluation, focusing on tool adoption and usage but with limited attention to leadership and innovation. Papuraj et al. (2025) highlighted the growing role of BIM and training needs but fell short of defining the comprehensive set of competencies required to lead digital transformation across projects and systems.

Despite growing awareness, a significant digital skills gap persists. Many professionals lack the capabilities to deploy emerging tools effectively (Kissi et al., 2025; Papuraj et al., 2025), a problem compounded by outdated curricula, minimal training in disruptive technologies such as blockchain and DTs (Zharov, 2024), and organisational resistance to change (Leontie, 2022). The speed of innovation continues to exceed the sector’s upskilling capacity (Carvalho et al., 2024; Mandicak et al., 2020).

The shift toward digital construction has intensified the need for PMs to develop competencies that extend beyond conventional technical and managerial skills. In response, several frameworks have been proposed in recent years, aiming to capture the digital capabilities required for effective project delivery. Although several frameworks propose digital competencies for construction PMs, few studies have systematically developed and validated a future-oriented competency list that is explicitly aligned with the operational demands of advanced digital technologies such as DTs. As Omrany et al. (2023) highlight, despite the increasing interest in DTs, integration with project-level competencies remains fragmented and lacks standardisation.

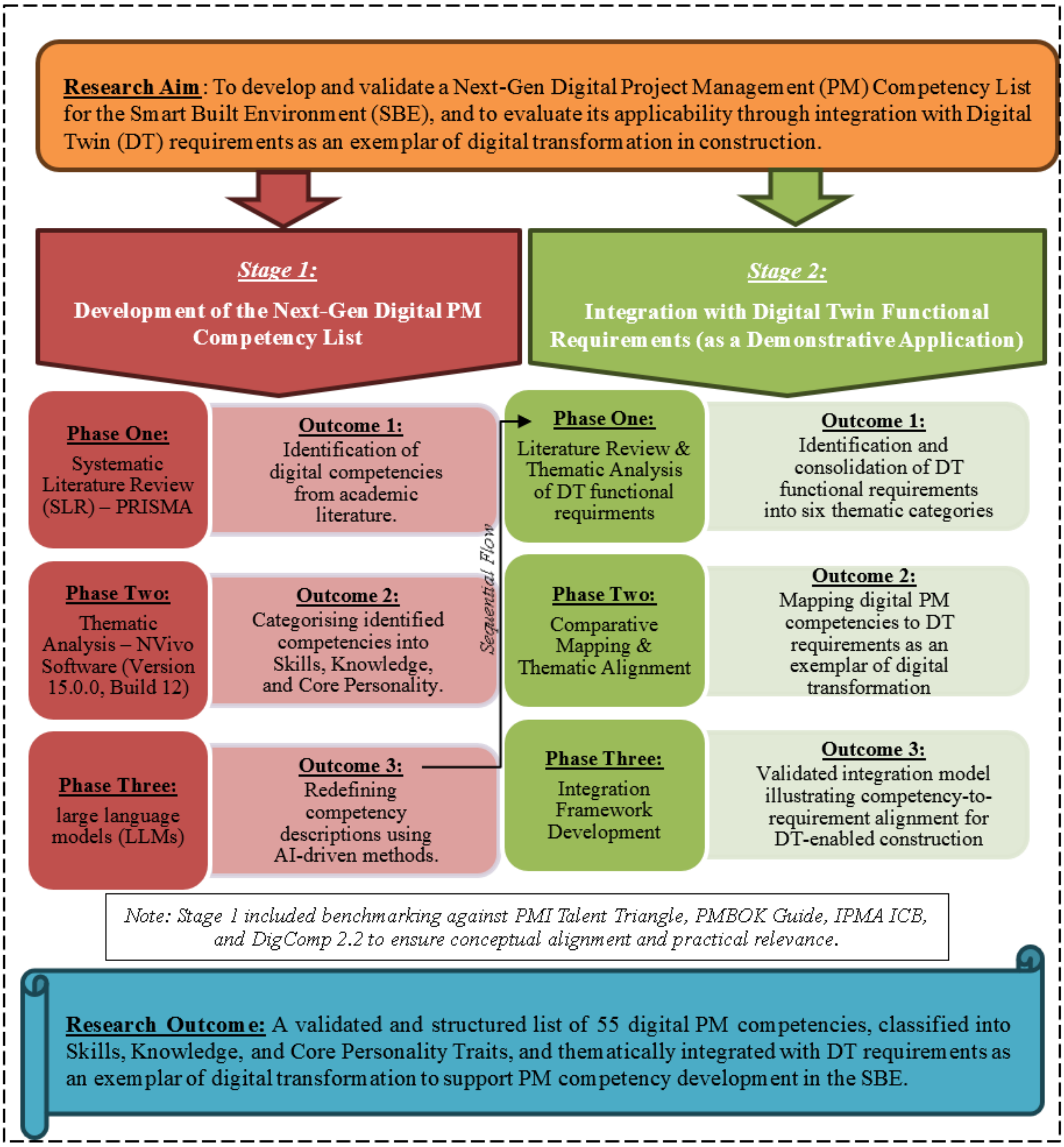

Figure 1: Research Design Framework.

Similarly, Madubuike et al. (2022) point out that while DT applications are growing in construction, there is limited evidence of formalised frameworks linking these technologies to project management capabilities. This study addresses that gap by developing a structured, evidence-based list of digital competencies tailored to support PMs in managing complexity and leading innovation in digitally enabled construction contexts. To demonstrate the practical relevance of these competencies, the study uses DT functional requirements as a representative exemplar of advanced digital systems shaping the SBE.

To guide this investigation, the study addresses the following research question: *What are the validated digital competencies required for construction project managers to effectively support and align with emerging digital technologies, exemplified by Digital Twin functional requirements, in the Smart Built Environment?*

To answer this question, the study adopts a two-stage design: Stage 1 develops and validates a Next-Gen Digital PM Competency List, while Stage 2 demonstrates its practical relevance by aligning the competencies with DT functional requirements. Full methodological details are provided in Section 2, while the following sections present the findings and integration outcomes.

The remainder of this paper is organised as follows. Section 2 outlines the methodological design, detailing the two-stage process used to identify and integrate digital competencies. Section 3 presents the development of the Next-Gen Digital PM Competency List through a structured process involving systematic literature review (SLR), thematic analysis, and LLM-based definition synthesis. Section 4 examines the integration of the validated competencies with functional requirements of DTs, demonstrating their applicability within the SBE. Finally, Section 5 concludes the paper, highlighting the study's contributions and outlining recommendations for future research and practical application.

2. METHOD

This study employed a structured, two-stage research design. *Stage 1* focused on developing and validating a Next-Gen Digital PM Competency List for the construction industry, while *Stage 2* was conducted sequentially after Stage 1, using the validated competencies as the input to demonstrate their practical relevance by aligning them with the core functional requirements of DTs in the SBE. The overall approach is grounded in a multi-phase methodological process involving literature synthesis, qualitative analysis, and comparative mapping, as illustrated in Figure 1.

2.1 Stage 1: Development of the Next-Gen Digital PM Competency List

Stage 1 involved three interconnected methodological phases: a SLR, Thematic Analysis using NVivo, and LLM-based definition refinement. This methodological combination has not previously been applied to the classification of digital PM competencies in relation to DT technologies.

2.1.1 Phase One: Systematic Literature Review (SLR)

The first phase employed a SLR to identify digital competencies required of PMs operating in the evolving digital construction environment. To ensure transparency, replicability, and methodological rigour, the review followed the PRISMA 2020 guidelines (Page et al., 2021), which offer a structured protocol for identifying, screening, and reporting literature.

1. **Search Strategy and Identification:** The literature search was conducted using the Scopus database, selected for its extensive coverage of peer-reviewed journals in engineering, construction, and management domains. A structured Boolean search was used to retrieve relevant studies by combining terms related to construction (e.g., "Construction," "building," OR "Civil") with terms related to digital technologies (e.g., "digital technolog*," "digital transformation," "construction technolog*," "smart construction," "construction 4.0," "digital twin," "BIM," "building information modelling," "Internet of Things," "IoT," "construction automation," "construction software," "augmented reality," "virtual reality," "drones," "robotics," "AI," "artificial intelligence," "machine learning," OR "cloud computing"). These were further combined with project management terms (e.g., "project manage*," "PM," "project leadership," "project planning," "project execution," "project delivery," "project control," "project performance," OR "project success") and competency-related terms (e.g., "competenc*," "skill*," "capabilit*," "knowledge," "proficiency," OR "attribute*"). The search encompassed studies published up to 2024 to capture recent advancements, and was limited to English-language, peer-reviewed journal articles, conference proceedings, and industry reports.

2. **Screening and Eligibility Process**: The study followed a multi-stage screening procedure, including deduplication (using EndNote and manual cross-checking), title/abstract screening, and full-text eligibility review based on predefined criteria, Table 1. after screening, a total of 15 high-quality studies were selected for inclusion.

3. **Data Extraction and Classification:** Each selected study was reviewed and coded using a structured data extraction framework, Table 2. Key fields included citation, research aim, method/technique, technology focus, and identified digital competencies.

Table 1: Eligibility Criteria for Systematic Literature Review.

Inclusion criteria	Exclusion criteria
o Studies explicitly investigating digital competencies relevant to PM in construction	o Research not addressing PM digital competencies
o Integration/application of digital technologies in PM	o Tech-focused studies not linked to PM competency
o Peer-reviewed journal articles/conference papers	o Non peer-reviewd publications
o English-language publications	o Non-English publications
o Studies within engineering, management, or computer science domains	o Studies outside relevant disciplines

Table 2: Data Extraction and Classification Framework.

Data Catefory	Discription
o Study Reference	o Citation details (authors, year).
o Research Aim	o The purpose of the study and relevance to digital competencies.
o method/technique	o The research design and methods employed (e.g., qualitative, quantitative, mixed methods, literature review).
o Technology Focus	o The digital tools studied (e.g., BIM, AI, IoT, DTs).
o Key Findings	o The main conclusions regarding competencies and their implications.

4. **Validation and Quality Assurance:** Competency findings were benchmarked against established project management frameworks, namely the PMI Talent Triangle, PMBOK Guide, and IPMA ICB, to ensure conceptual alignment and practical relevance. This process involved cross-checking the three competency domains identified in this study (Skills, Knowledge, and Core Personality Traits) against the structural categories of these frameworks to confirm consistency and coverage across cognitive, technical, and behavioural areas. The benchmarking was conducted after the thematic classification (Section 3.2.3) to validate the domain logic and competency grouping. To further ensure reliability, the screening and extraction processes were independently reviewed by a second researcher, achieving inter-coder agreement following O'Connor and Joffe (2020). Additionally, external expert peer review was conducted to confirm methodological rigour and relevance of the included studies.
5. **PRISMA Flow Diagram:** The complete review process, covering identification, screening, eligibility assessment, and final inclusion, is illustrated in Figure 2.

By following the PRISMA framework, this phase established a methodologically sound foundation for the subsequent classification and definition phases (see Results, Section 3.1).

2.1.2 Phase Two: Thematic Analysis of Digital Competencies

The competencies identified from the SLR were thematically organised using Braun and Clarke (2006) six-phase framework, which includes: (1) familiarisation with the data, (2) generating initial codes, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the final thematic map. This structured sequence guided the development of a consistent and theoretically grounded competency classification. NVivo software (version 15.0.0, build 12) supported this process by enabling systematic coding, classification, and visualisation. The competencies were grouped into three overarching categories: Skills, Knowledge, and Core Personality Traits.

This thematic structure was benchmarked against leading project management and digital competency frameworks, including the PMI Talent Triangle, IPMA ICB, and DigComp 2.2, to ensure conceptual alignment and practical relevance. The process focused on structural logic, confirming consistency and coverage across cognitive, technical, and behavioural domains rather than replicating framework content. This benchmarking served as a secondary validation of the category design and reinforced the practical coherence of the competency grouping.

NVivo enhanced the consistency, transparency, and replicability of the thematic classification. A more detailed explanation of the classification results is presented in the Results section (see Section 3.2).

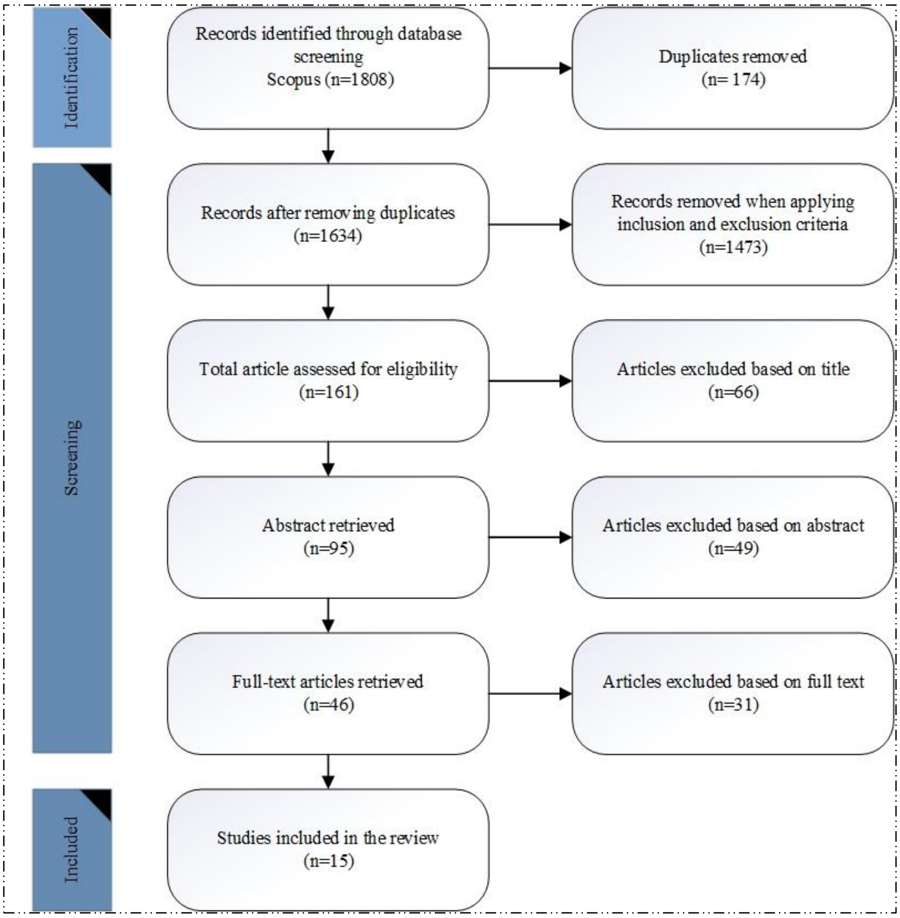

Figure 2: PRISMA 2020 Flow Diagram.

2.1.3 Phase Three: Competency Definition Using Large Language Models (LLMs)

The third phase of Stage 1 focused on the synthesis of clear, consistent, and practically usable definitions for the 55 digital PM competencies already identified and clustered in Phases One and Two. The use of LLMs in this study was strictly limited to definition synthesis, with all content sourced from validated literature and subsequently reviewed by domain experts. While Phase One extracted digital competencies from academic literature and Phase Two categorised them, Phase Three consolidated these findings into refined definitions by employing LLM as a synthesis tool.

LLMs, such as those built on transformer-based architectures, have emerged as valuable tools in qualitative research for summarising, integrating, and clarifying complex textual data (Bender et al., 2021; Floridi & Chiriatti, 2020). Unlike traditional manual synthesis, which can be time-consuming and inconsistent in tone or scope, LLMs provide standardised linguistic consolidation across large textual datasets, offering efficiency and consistency without compromising conceptual accuracy. In this study, the LLM was used solely to synthesise multiple academic definitions, previously extracted during the SLR and Thematic Analysis phases, into a single, consolidated definition per competency. The purpose was not to generate new knowledge but to eliminate redundancy, enhance terminological consistency, and ensure conceptual clarity across the finalised list.

The input to the LLM consisted of clustered definitions grouped under each competency theme, as derived from NVivo-assisted coding. Prompt engineering was applied to ensure that the outputs reflected academic tone, consistency, and alignment with the digital construction context. To avoid overreliance on the model's generalisation competencies, the LLM's role was restricted to definition refinement and synthesis only. It was not used to define competencies independently or to perform any evaluative judgment. For detailed examples and explanation of the prompting procedures and validation process, see Section 3.3.

To ensure the reliability and contextual accuracy of each definition, a multi-step expert validation process was employed. Two independent subject-matter experts with over ten years of combined experience in construction project management and digital transformation were assigned to review each LLM-generated definition. They assessed the technical fidelity, domain relevance, and alignment with recognised standards as a benchmark, including the PMBOK Guide (PMI, 2021), the IPMA Individual Competence Baseline (IPMA, 2015), and the European Commission's DigComp 2.2 framework (Vuorikari et al., 2022). While the number of experts was limited, their specialised domain expertise ensured focused, high-quality review. This approach aligns with contemporary qualitative validation practices, where small expert panels are considered sufficient for domain-specific synthesis and refinement tasks (Pilcher & Cortazzi, 2024). Where discrepancies in interpretation arose, definitions were revised collaboratively to reach mutual agreement. In total, 89% of the definitions were accepted with only minor adjustments, while 11% required substantive revision to improve specificity or contextual relevance.

This combined process, sourcing definitions from validated literature, refining them through LLM support, and verifying them through expert review, ensured that each competency was articulated in a way that is academically sound, industry-relevant, and ready for future implementation, benchmarking, or empirical testing. These definitions formed the final input for Stage 2, where the validated competencies were evaluated through functional mapping to DTs, used here as a representative exemplar of digital transformation in the construction sector. The complete list of definitions is available in Appendix C (online supplement), and a summary of their structure, validation process, and traceability is discussed in the Results (see Section 3.3).

2.2 Stage 2: Integration with Digital Twins Requirements

Building on the validated outcomes of Stage 1, which resulted in a structured list of 55 digital PM competencies, Stage 2 was conducted sequentially and aimed to assess their practical relevance within a real-world technological context. To achieve this, the second stage of the study involved integrating the competency list with the functional and technical requirements of DTs, used in this research as a demonstrative exemplar of digital technologies driving digital transformation in the SBE. This stage adopted a comparative analysis method, originally introduced in Owais et al. (2025), to systematically align the validated competencies with the demands of DT-enabled construction projects.

The integration involved three steps:

1. **Identification and Extraction of DT Requirements:** A targeted literature review was conducted to identify the core functional and strategic capabilities of DTs (see Results, Section 4.1). Building on the twelve DT requirement themes identified in Owais et al. (2025), these were further consolidated into a structured six-part framework to enhance clarity and analytical utility. The final themes, interoperability and integration, real-time data management, simulation and predictive modelling, cybersecurity and data governance, stakeholder collaboration, and scalability and lifecycle continuity, represent the most frequently cited and functionally relevant capabilities of DTs in the SBE (Boschert & Rosen, 2016; Cellina et al., 2023; Grieves & Vickers, 2017). These categories served as the reference structure for mapping competencies in the subsequent steps of the integration process.
2. **Comparative Mapping of DT Requirements to Digital PM Competencies:** Using a comparative analysis approach (Owais et al., 2025), each DT requirement was thematically compared with the 55 digital PM competencies developed in Stage 1. The mapping process involved a qualitative matching exercise in which each DT capability theme was reviewed against the core functions, definitions, and objectives of each competency. Competencies were evaluated and coded to determine whether they directly enable (core function match), support (partial or enabling function), or complement (adjacent or facilitating function) the DT requirement. These relationships were then mapped against the six thematic DT requirement categories to ensure structured alignment and thematic coherence.
3. **Interpretive Analysis and Competency Development Implications:** The alignment outcomes were analysed to identify strengths, gaps, and strategic recommendations for digital PM development in DT-enabled environments. This stage informed insights related to industry capability planning and workforce transformation (see Results, Section 4.3).

This second stage introduces an application-focused dimension to the validated competency list, showcasing its relevance in guiding PM competencies for emerging digital technologies. The resulting integration framework is illustrated in Figure 8.

Together, these two stages form the methodological backbone of this study, enabling the construction of a validated, evidence-based competency list and its strategic alignment with DT requirements. The next section presents the outcomes of this integration in detail.

3. DEVELOPMENT OF THE NEXT-GEN DIGITAL PM COMPETENCY LIST

This section outlines the multi-phase development process forming Stage 1 of this study, which resulted in the construction of the Next-Gen Digital PM Competency List tailored for the evolving construction sector. Conducted in three interlinked phases, the process begins with the identification of digital competencies through a SLR, followed by thematic categorisation using NVivo-supported Thematic Analysis, and culminates in the refinement of competency definitions using LLM synthesis. Together, these phases establish a validated, structured, and future-ready competency list across the domains of Skills, Knowledge, and Core Personality Traits. The following subsections detail the methodological steps and outputs of each phase.

3.1 Phase One: Systematic literature review (SLR)

The first phase of this study employed a SLR to identify the digital competencies required for PMs in the evolving construction sector. This phase aimed to establish a comprehensive, evidence-based identification of competencies by systematically reviewing existing academic literature. SLR is a structured, transparent, and replicable method for synthesising knowledge from multiple sources while ensuring methodological rigor (Grant & Booth, 2009). To enhance reliability and objectivity, this study adhered to the PRISMA 2020 guidelines (Page et al., 2021), which provide a standardised approach to identifying, screening, selecting, and reviewing relevant academic studies.

The findings from this phase serve as the foundation for the subsequent phases of the study, where competencies are categorised using Thematic Analysis in Phase Two and refined using LLM-based synthesis in Phase Three. This structured approach ensures that digital competencies for PMs are systematically mapped, validated, and classified, thereby bridging the gap between traditional PM competencies and emerging technological requirements in the construction industry. The following sub-sections present the study selection process, data extraction, and mapping of competencies across studies.

3.1.1 Study Selection Process

The study selection process was conducted in accordance with the PRISMA guidelines (Page et al., 2021), to ensure a transparent, rigorous, and replicable identification of digital competencies for construction PMs.

The process involved six structured steps:

1. **Identification:** Relevant studies were systematically retrieved using predefined search strategies in Scopus, ensuring a comprehensive collection of academic literature.
2. **Screening:** Retrieved articles underwent title and abstract screening to eliminate irrelevant, duplicate, or low-quality studies that did not explicitly address digital competencies for PMs.
3. **Eligibility:** The remaining studies underwent a full-text review to ensure alignment with the study's objectives and methodological standards.
4. **Inclusion:** Final studies were selected based on predefined eligibility criteria, Table 1, and formed the foundation for competency extraction categories, Table 2.
5. **Ensuring reliability and validation:** Rigorous checks were conducted to ensure accuracy, consistency, and reliability in the selected studies, reducing bias and enhancing credibility.
6. **PRISMA Flow Diagram:** To enhance clarity and transparency, visually represents the selection process, illustrating the number of studies retrieved, screened, excluded, and included in the final analysis, Figure 2.

This structured selection process ensures that only high-quality, thematically relevant research contributes to the identification of digital competencies for PMs in the evolving construction sector.

3.1.2 Data Extraction and Competency Identification

Following study selection, data extraction was conducted in a structured and systematic manner to ensure that the findings are accurate, reliable, and reproducible. A data extraction framework was applied to synthesise information from each study, categorising it based on research aim, methods/techniques, technology focus, and key findings. These 15 studies represent the final set of articles retained after full-text review based on PRISMA criteria and form the core data for competency extraction, as presented in Table 3.

This process ensured that each digital competency identified in the literature was systematically documented and prepared for thematic categorisation in the next phase. The structured extraction strategy also enabled the identification of recurrent themes, emerging trends, and competency gaps in existing literature. Table 3 presents the structured extraction of key elements from the reviewed studies, providing an overview of how digital competencies were identified across multiple academic sources and mapping each study's technological focus to relevant digital innovations, such as BIM, AI, IoT, and DT technologies.

This structured approach ensures clarity, consistency, and methodological rigor, providing a strong foundation for competency classification and analysis in the next phase.

3.1.3 Digital Competencies Identified in the Literature

After extracting key information from the selected studies, the next step involved systematically mapping the identified digital competencies across the literature. The objective was to understand the frequency, distribution, and thematic emphasis placed on each competency within academic research.

To achieve this, each study was reviewed in full to identify which competencies were explicitly addressed. Competency mentions were coded based on full-text analysis, rather than relying solely on abstracts, to enhance validity and minimise interpretive bias. Each competency was then linked to its corresponding source, producing a traceable and transparent dataset that laid the foundation for thematic categorisation in Phase Two of Stage 1. This mapping process identified a total of 55 distinct digital competencies across the final study set, forming the validated input for thematic classification.

This mapping process enabled a systematic comparison across studies and revealed distinct patterns in emphasis. Technical competencies, particularly those associated with digital technologies, data analytics, and digital collaboration, emerged as recurring priorities. Leadership-related competencies also featured prominently, especially those concerning digital team coordination and stakeholder engagement. By contrast, competencies related to cybersecurity, AI integration, and digital ethics appeared less frequently. These were identified as emerging, yet underexplored, domains that may require increased attention in future competency development efforts.

Appendix A: `Mapping of Final Studies to Identified Competencies` (online supplement) provides a detailed visual representation of how each study contributed to the identification of digital competencies for PMs in the construction sector. This enhances methodological transparency, supports traceability, and reinforces the evidence-based nature of the resulting competency framework.

The SLR phase thus successfully identified 55 digital competencies by systematically analysing peer-reviewed academic literature. Using PRISMA-guided screening and structured data extraction, these competencies were documented and aligned with relevant themes and research domains.

However, while this phase provided a robust empirical foundation, it did not yet organise the competencies into a structured framework. To address this, the next phase applied NVivo-based Thematic Analysis to classify the 55 competencies into three overarching domains: Skills, Knowledge, and Core Personality Traits. The dataset generated through the SLR served as the direct input for this classification process, ensuring continuity, analytical rigour, and alignment with established PM competency models. The following section details how NVivo was used to support this thematic classification effort.

Table 3: Data Extraction Categories.

Stud. Num.	Study Reference	Research Aim	Method/Technique	Technology Focus	Key Findings
1.	Rodrigues et al. (2023)	Identify core competencies required for PMs in smart building projects.	Two-step approach using PRISMA for systematic review and meta-analysis.	Smart building technologies, including IoT, BIM, and DTs.	Key competencies for smart building PMs: technical competencies, leadership, communication, budgeting, attitudes toward risk, strategic management, organisation, and specifying real requirements.
2.	Liu et al. (2022)	Develop a competency model for construction PMs in the digital era.	Data mining method analysing 2387 recruitment advertisements.	Digital capability in construction project management.	Identifies digital capability as a crucial emerging competency with three levels: technology, knowledge, and management.
3.	Vuorikari et al. (2022)	Define a general digital competency framework for citizens (DigComp 2.2).	Policy analysis and literature review.	Digital skills, AI, cybersecurity, and digital safety.	Provides structured digital competencies applicable across various sectors, including construction project management.
4.	Mesaros et al. (2020)	Investigate the impact of BIM technology on digital and managerial competencies of PMs.	Case studies and literature review.	BIM technology in project management.	BIM adoption enhances digital and managerial competencies, necessitating training for PMs.
5.	Lukianov et al. (2021)	Examine digital competency transformation in project management.	Comparative analysis of PMI and IPMA competency models.	Digital transformation in project management.	Proposes integrating digital competency assessment into project management standards.
6.	Hosseini et al. (2018)	Assess the viability of BIM manager as a distinct role.	Text mining of 199 job advertisements.	BIM role evolution in construction.	BIM expertise will be absorbed into general project management roles over time.
7.	Mandičák et al. (2020)	Explore the development of digital and managerial competencies in construction project management.	Theoretical review and expert analysis.	Digitalisation and managerial competencies.	Emphasises the growing need for digital skills alongside managerial competencies.
8.	Kissi et al. (2025)	Identify essential competencies for PMs in the digital era.	Fuzzy synthetic evaluation (FSE) with survey data.	Digitalisation in construction project management.	Technical knowledge, leadership, and interpersonal skills are critical for digital PMs.
9.	Inguva et al. (2014)	Analyse skill differences in construction professionals using BIM/VDC.	Survey of 122 professionals across the US.	BIM and Virtual Design Construction (VDC).	Professionals using BIM/VDC report enhanced problem-solving and digital skills.
10.	Waqar et al. (2023)	Model the relationship between BIM and construction project success.	Structural Equation Modelling (SEM).	BIM adoption in project success.	BIM integration significantly impacts project success, requiring digital proficiency among managers.
11.	Raza et al. (2023)	Identify potential features of BIM for project management knowledge areas.	SLR and factor analysis.	BIM adoption in construction project management.	BIM enhances PMs' capabilities in project integration, cost, time, quality, and risk management.
12.	Atuahene et al. (2023)	Examine the transformative role of big data in construction through capability recognition.	Interviews with construction professionals and literature review.	Big data applications in construction management.	Big data requires PMs to develop analytical, strategic, and digital transformation competencies.
13.	Omer et al. (2022)	Analyse constructive and destructive leadership behaviours in BIM-based projects.	Explorative qualitative study with interviews and thematic analysis.	BIM-based leadership and management.	Effective leadership skills and adaptability are crucial for managing BIM-integrated projects.
14.	Uhm et al. (2017)	Analyse BIM jobs and competencies using industry terminology.	Social Network Analysis (SNA) and job postings review.	BIM job roles and competency frameworks.	Identifies essential BIM competencies and their application in various project management roles.
15.	Lee et al. (2021)	Assess BIM competencies and their correlation with career characteristics.	Survey and correlation analysis of construction professionals.	BIM competency assessment for project participants.	PMs must develop strong BIM capabilities to optimise digital workflows in construction.

3.2 Phase Two: Thematic Analysis of Digital Competencies

The competencies identified from the SLR were thematically organised using Braun and Clarke (2006) six-phase method. NVivo software (version 15.0.0, build 12) supported this process by enabling systematic coding, classification, and visualisation. The competencies were grouped into three overarching categories: Skills, Knowledge, and Core Personality Traits. This three-domain structure was adapted to ensure thematic alignment with established project management frameworks, including the PMI Talent Triangle, IPMA ICB, and DigComp 2.2, thereby enhancing conceptual coherence and facilitating cross-framework comparability. NVivo further contributed to the consistency, traceability, and transparency of the categorisation process. A more detailed explanation of the thematic procedures and validation steps is provided in Sub-sections 3.2.1 and 3.2.2.

This phase plays a pivotal role in transitioning the study from a broad list of extracted competencies to a structured, thematically grouped framework. It categorises digital competencies into three overarching domains:

- Skills: Action-based capabilities for applying digital tools and technologies in project contexts.
- Knowledge: Theoretical and technical understanding essential for managing digital transformation.
- Core Personality Traits: Behavioural and leadership attributes needed to navigate complexity and innovation in construction projects.

The following subsections detail the analytical process, competency classification results, and validation techniques.

3.2.1 Thematic Analysis Approach

To ensure transparency and replicability, this phase followed the six-phase Thematic Analysis framework proposed by Braun and Clarke (2006), adapted with the support of NVivo software. The thematic process focused on organising the 55 competencies, identified through the SLR, into a structured classification that could support both theoretical grounding and practical benchmarking. The six steps were applied as follows:

1. **Familiarisation with Data:** Competency definitions and terms from Phase One were imported into NVivo. An initial review involved text scanning and keyword recognition. NVivo's word frequency analysis, Figure 3, identified frequently cited terms such as "digital," "skills," "technologies," "communication," and "change process," which helped guide early theme formation.

Figure 3: NVivo Word Cloud Showing Frequency of Key Competency Terms.

2. **Generating Initial Codes:** NVivo's auto-coding tool was used to label digital competencies based on similarities in meaning, language patterns, and context (see Appendex B, Figure B1). Manual refinement followed auto-coding to improve accuracy.

3. **Searching for Themes:** Codes were grouped into broader thematic categories using NVivo's node matrix, cluster mapping, and coding similarity analysis (see Appendex B, Figure B2). Competencies were initially clustered by functional similarity and digital relevance. The clustering stage helped uncover dominant themes emerging across multiple studies, offering insight into competency interdependencies.

4. **Reviewing Themes:** Emerging themes were reviewed and refined for clarity, exclusivity, and coherence. NVivo's hierarchical node structures and visual relationship diagrams (see Appendex B, Figure B3 and B4), supported this process by identifying redundancies and overlaps. pecial care was taken to minimise ambiguity and ensure that categories were mutually exclusive and conceptually distinct.

5. **Defining and Naming Themes:** After reviewing and confirming theme boundaries, final descriptive labels were applied. NVivo's cluster tools helped confirm distinctions between themes, Figure 4. The naming process was informed by recurring terminology in the literature and benchmarked against high-level PM domains.

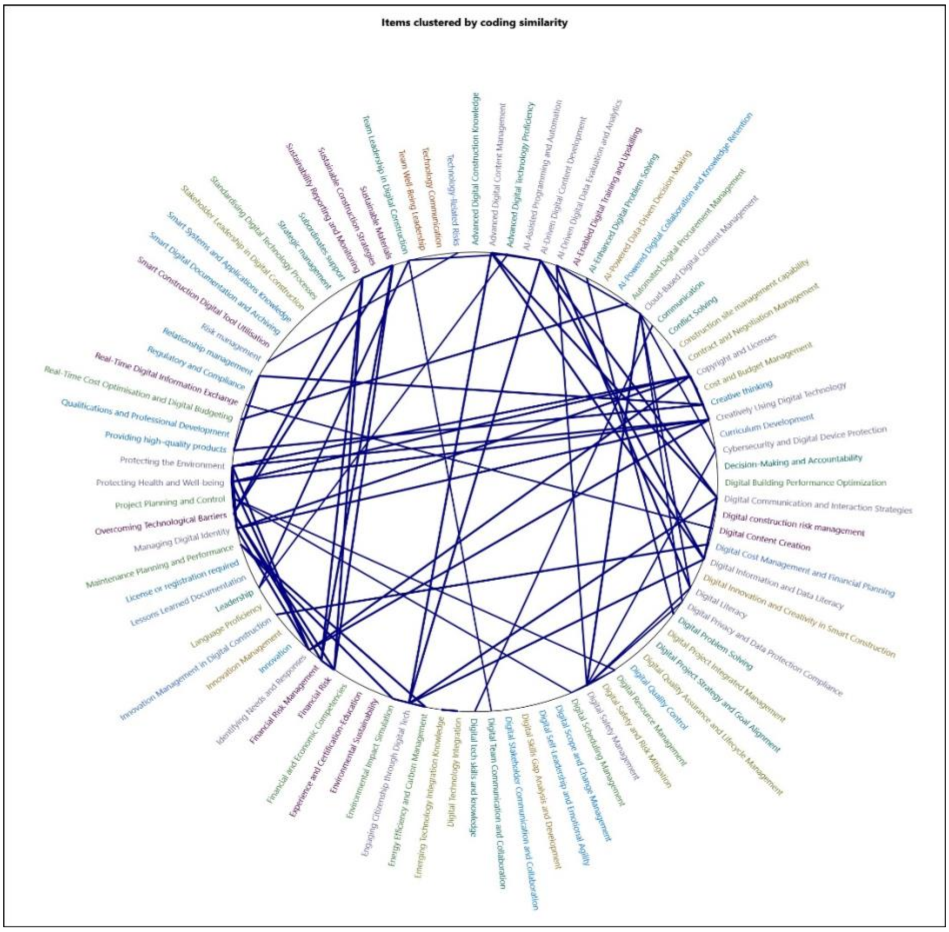

Figure 4: NVivo's Cluster Analysis by Coding Similarity.

Figure 4 presents a cluster analysis of digital PM competencies based on coding similarity, as generated through NVivo. This visual illustrates how various competencies are interconnected by linguistic and conceptual patterns observed during qualitative coding. The circular node map links items with similar coding references, where the thickness of connecting lines reflects the strength of co-occurrence across coded segments.

Several distinct thematic clusters emerged from this analysis. For example, competencies related to data handling and privacy (e.g., "Digital Information and Data Literacy," "Cybersecurity and Digital Device Protection," and "Data Protection Compliance") formed one cluster, reflecting the importance of secure digital practices in project environments. Another prominent group centred on project planning and optimisation, including competencies such as "Digital Building Performance Optimisation," "Digital Cost Management," and "Real-Time Digital Information Exchange." A third cluster highlighted collaborative and communication-related digital practices, encompassing terms like

"Digital Communication and Interaction Strategies," "Digital Collaboration Tools," and "Stakeholder Engagement."

These clusters confirm the coherence of the thematic structure, reinforcing the classification into Skills, Knowledge, and Core Personality Traits presented later in the paper. Furthermore, the visual mapping helped to identify thematic redundancies and clarified the boundaries between overlapping competency areas. Additionally, this three-domain structure was guided by thematic alignment with established PM competency frameworks, including the PMI Talent Triangle (PMI, 2021), the IPMA Individual Competence Baseline (IPMA, 2015), and DigComp 2.2 (Vuorikari et al., 2022). While the themes themselves were derived inductively from the data, this benchmarking step provided a practical and theoretical scaffold to ensure that the domains resonate with globally accepted standards.

6. **Producing the Final Thematic Map:** Competencies were categorised under the three domains: Skills, Knowledge, and Core Personality Traits. NVivo outputs thematic mapping, Figure 5, were used to visualise and validate the final classification.

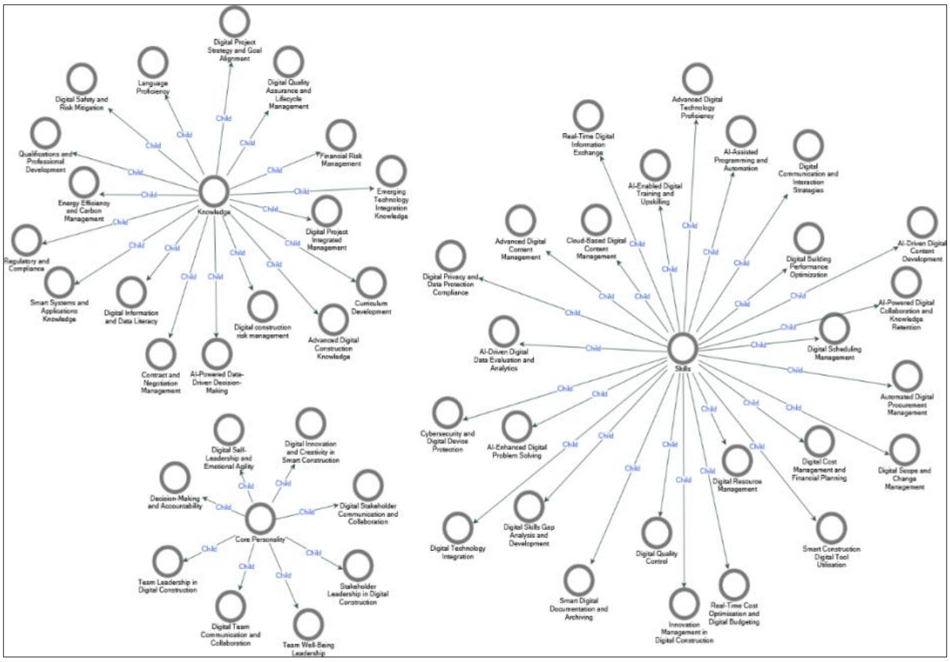

Figure 5: Final Thematic Mapping in NVivo – Structured Categorisation of Digital Competencies.

Figure 5 presents a cleaned and finalised structure of the competency classification as output by NVivo. This rigorous thematic approach ensured logical grouping, reduced subjectivity, and improved alignment with established project management competency models. The process also enhanced the traceability and reliability of category assignments, laying a robust foundation for definition synthesis and further integration in Stage 2.

3.2.2 Thematic Classification of Digital Competencies

Following the systematic identification of digital competencies in Phase One, this stage categorised them into three competency groups based on their practical application, theoretical foundation, and behavioural attributes. NVivo-supported Thematic Analysis played a critical role in enabling a transparent, structured, and data-driven classification process. Through visual tools and analytic functions, NVivo validated coding consistency, thematic relevance, and frequency distribution across the dataset. These 55 competencies, identified through rigorous literature mapping, served as the raw input for thematic classification and were categorised into Skills, Knowledge, and Core Personality domains as shown in Figure 6.

- **Skills**: Practical, action-oriented capabilities were identified that enable PMs to effectively implement digital tools and technologies in the construction sector, improving project efficiency, enhancing automation, and increasing accuracy. These include Advanced Digital Technology Proficiency, such as expertise in BIM systems, project management software, and digital design tools such as AutoCAD and Navisworks (Mesaros et al., 2020); Digital Technology Integration, such as the ability to operate IoT systems, manage digital data, and coordinate digital teams for innovation-driven execution (Waqar et al., 2023); Digital Building Performance Optimisation, such as the use of BIM and related tools for optimising the lifecycle performance of building systems (Rodrigues et al., 2023); and Digital Scheduling Management through the use of digital tools such as 4D BIM to control and optimise timelines (Liu et al., 2022). NVivo frequency analysis highlighted common terms such as "digital," "skills," and "technology," validating the prominence of skill-based competencies (see Appendix B, Figure B5).

- **Knowledge**: This category provides the intellectual foundation needed to navigate digital transformation. Key competencies include Advanced Digital Construction Knowledge that refers to integrating technical data into deliverables and using digital workflows (Mandičák et al., 2020); Emerging Technology Integration Knowledge, such as understanding AI, VR, drones, and IoT (Atuahene et al., 2023); Quality and Lifecycle Data Management, like the use of BIM for quality tracking and sustainability (Raza et al., 2023); and Regulatory and Compliance Knowledge to navigating laws and standards such as NEC, BS 1192, and PAS 1192 (Hosseini et al., 2018). NVivo cluster analysis confirmed the conceptual proximity and thematic coherence of these groupings (see Appendix B, Figure B6). These knowledge domains were cross-referenced with DigComp and IPMA ICB dimensions to ensure academic alignment and industry relevance.
- **Core Personality**: This category refers to non-technical attributes essential for managing technology-driven projects. These include Team Leadership in Digital Construction to inspire collaboration in digital environments (Mesaros et al., 2020); Stakeholder Leadership for relationships managing across diverse project actors (Kissi et al., 2025); Self-Management and Emotional Agility to navigate stress and maintaining morale in digital contexts (Omer et al., 2022); and Digital Change Management and Innovation Leadership for leading tech integration while promoting continuous learning (Rodrigues et al., 2023).

  NVivo sentiment analysis revealed clear patterns in how Core Personality competencies were perceived across the dataset. As shown in Appendix B Figure B7, traits like Team Leadership in Digital Construction and Digital Team Communication and Collaboration were predominantly coded as neutral or positive, reflecting broad acceptance in digital project contexts. In contrast, competencies such as Digital Self-Leadership and Emotional Agility and Team Well-Being Leadership showed a higher proportion of mixed and negative sentiment, highlighting the challenges of emotional regulation, stress, and well-being in tech-driven environments.

  Interestingly, emotional agility and innovation-related traits showed more mixed views, suggesting recognition of their importance but also practical difficulties in applying them effectively. Meanwhile, Decision-Making and Accountability and Digital Innovation and Creativity were viewed more consistently positively, indicating their perceived value in enabling transformation.

  These patterns align with the IPMA's emphasis on behavioural competencies and echo DigComp's attention to digital awareness, adaptability, and self-regulation. This reinforces the role of emotional intelligence, adaptability, and leadership as critical non-technical competencies, while also underscoring the need for stronger institutional support to embed them in practice.

This structured categorisation supports a clearer understanding of how PMs must adapt their competencies in the digital construction era. The final thematic map summarising all competencies is shown in Figure 6, which visualises the hierarchical structure of the classified competencies across the three overarching domains: Core Personality, Knowledge, and Skills. Each parent node represents a thematic domain, branching into child nodes that reflect specific, validated competencies. This NVivo-generated hierarchy confirms the integrity of the three-domain structure developed during thematic analysis and illustrates how each competency is distinctly yet thematically situated. It also highlights the wide-ranging scope of the Skills domain, spanning from AI-assisted programming to real-time digital budgeting, while clarifying how Knowledge competencies are grounded in regulatory, environmental, and technological understanding. The Core Personality domain shows clear leadership and emotional intelligence dimensions, reinforcing their non-technical yet strategic importance. This domain-level classification was benchmarked against the PMI Talent Triangle, IPMA ICB 4.0, and DigComp 2.2 to validate its alignment with recognised project management standards.

By mapping competencies visually, Figure 6 enhances both the thematic coherence and practical utility of the competency classification, aligning the final competency model with established digital project management needs.

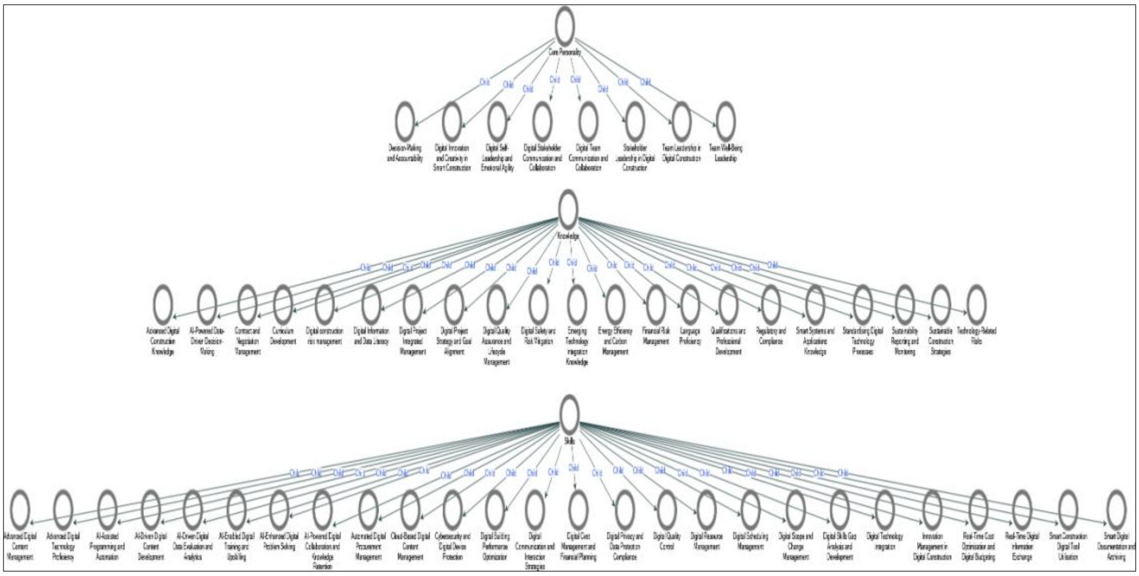

Figure 6: Final NVivo Thematic Map of Categorised Digital Competencies.

3.2.3 Ensuring Reliability and Validity

To enhance the reliability and credibility of the thematic classification, three key validation strategies were applied. First, an inter-coder agreement process was conducted to validate the consistency of qualitative coding during NVivo-assisted Thematic Analysis in Phase Two of Stage 1. Multiple researchers independently reviewed the coded data, and iterative consensus-building resulted in an 85% agreement rate, confirming coding reliability and minimising subjectivity (O'Connor & Joffe, 2020).

Second, an external expert peer reviewed the thematic grouping for clarity, coherence, and alignment with industry expectations (Bryman, 2016). This expert reviewer, familiar with digital transformation and PM frameworks, offered domain-specific critique, which helped refine domain boundaries and ensured thematic cohesion.

Third, the final classification was benchmarked against established project management competency frameworks, including the PMBOK Guide, PMI Talent Triangle, and IPMA ICB. This benchmarking was conducted through qualitative comparison, where the categorised competencies were cross-referenced with core elements from each framework. For instance:

- Technical and procedural competencies were compared with PMI's Technical Project Management domain;
- Behavioural and interpersonal competencies were aligned with IPMA's 'People' competence elements;
- Digital literacy and emerging technology themes were reviewed against DigComp 2.2 dimensions.

This comparative review confirmed that the thematic domains of Skills, Knowledge, and Core Personality Traits reflect current expectations for digital PMs and ensure consistency with globally recognised PM standards. The final NVivo-generated thematic map, see Figure 6, visualises the classification resulting from the inductive coding process, which was developed inductively and subsequently benchmarked against elements from the PMBOK, PMI Talent Triangle, IPMA ICB, and DigComp 2.2 frameworks to ensure alignment with established competency structures.

Figure 7: Next-Gen Digital PM Competency List for Construction (Overview of the Three-Domain Model.

Phase Two of Stage 1 successfully categorised the 55 digital competencies into three well-defined domains. These categories form the foundation for Phase Three, which focuses on refining the competency definitions using LLM synthesis. The transition from identification (Phase One) to classification (Phase Two) ensures a structured and evidence-based pathway toward developing a practical digital PM competency framework for construction. The triangulated validation approach adopted here, inter-coder reliability, expert review, and framework benchmarking, strengthens both the credibility and generalisability of the resulting model. This ensures that the thematic groupings reflected in Figure 6 are not only empirically derived but also theoretically grounded in globally recognised project management standards.

3.3 Phase Three: Finalised Competency Definitions Synthesised Using LLM

The final phase of Stage 1 involved synthesising clear and coherent definitions for each of the 55 digital competencies identified and categorised in the earlier phases. A LLM, GPT-4, was used to refine and merge multiple definitions from various academic sources (OpenAI, 2023), generating a single, consolidated definition for each competency. The model was prompted using thematic clusters of competency descriptors derived from earlier stages. Each prompt included clear instructions to consolidate these clusters into a coherent definition, maintain academic tone, and express the content using project management terminology, without altering the underlying meaning.

These definitions were not generated from scratch but were refined from existing literature-based inputs. The source content was drawn directly from the final studies retained in the systematic review, which are mapped to each competency in Appendix A: Mapping of Final Studies to Identified Competencies. This ensured that each definition remained grounded in published evidence and traceable to original literature.

LLMs, as advanced AI tools capable of generating human-like text, have become increasingly valuable for qualitative research synthesis (Bender et al., 2021; Floridi & Chiriatti, 2020; Steiss et al., 2024). In this study, GPT-4 was used specifically to consolidate clustered textual data into competency definitions that were both linguistically coherent and contextually aligned with digital PM practices. The model's prompts consisted of thematically grouped textual data drawn from the SLR and thematic analysis phases, accompanied by specific instructions to refine the language while preserving original conceptual intent.

To guide this process, the research team applied a standardised prompting framework that included: (1) a descriptive title for each competency, (2) a list of extracted textual descriptors and keyword phrases, and (3) instructions for tone, length, and industry alignment. These inputs ensured controlled generation while retaining fidelity to the original source material. All interactions with the LLM were manually reviewed and revised when necessary to ensure quality control and prevent distortion of the intended meaning.

Rather than producing novel content, the LLM was used solely as a linguistic synthesis tool. Its outputs were intended to standardise terminology and enhance clarity without introducing any new conceptual material. Following generation, each definition was reviewed by the core research team and then validated through a review process involving two domain experts in construction project management and digital transformation. This validation process ensured technical accuracy, conceptual consistency, and practical relevance. Any definitions that failed to meet clarity or relevance standards were revised in collaboration with the reviewers until mutual agreement was reached.

The finalised definitions are presented in Appendix C: Full Definitions of the 55 Next-Gen Digital PM Competencies (online supplement) and are organised according to the three overarching thematic domains: Skills, Knowledge, and Core Personality Traits. These outputs represent the validated results of the multi-phase methodological steps.

For further traceability, readers may refer to Appendix A, which links each competency back to its original literature sources and thematic categorisation. For instance, the definition of "S2. Digital Technology Integration" synthesises key terminology and contextual insights from four foundational sources. Rodrigues et al. (2023) contributed descriptions of IoT system operation and real-time data integration. Liu et al. (2022) emphasised leadership in managing integrated digital systems and innovation. Atuahene et al. (2023) highlighted collaboration with technology providers for data capture and big data management. Inguva et al. (2014) reinforced the importance of BIM model viewing, analysis, and integration to ensure seamless collaboration in digital project delivery. All of this input was derived from literature reviewed during the SLR and coded thematically. The LLM's role was confined to shaping the final wording, consolidating phrasing and maintaining tone, without introducing any new information beyond the reviewed sources.

Together, these definitions, developed through integrated literature evidence, thematic coding, and LLM-supported synthesis, offer a clear and validated reference for digital PM competencies. They directly inform the competency-to-requirement alignment presented in Stage 2. Furthermore, they form the conceptual and analytical foundation of the Next-Gen Digital PM Competency List Model, introduced in the following Sub-section (3.4), as a unified representation of digital skills, knowledge, and core personality traits. These competencies are essential for PMs to effectively navigate digital transformation in the SBE.

3.4 The Next-Gen Digital PM Competency List for Construction

This section presents the Next-Gen Digital PM Competency List for Construction, which consolidates all 55 expert-validated digital competencies into three overarching categories: Skills, Knowledge, and Core Personality Traits. The list was developed through a rigorous three-phase methodological process comprising a SLR, NVivo-supported thematic analysis, and LLM-assisted definition synthesis, as detailed in Sub-sections 3.1 to 3.3. It provides a structured, transparent, and evidence-based overview of the digital competencies essential for modern construction PMs navigating the SBE.

Figure 7 below provides a high-level thematic summary of the competency model, not the full definitions. It is intended as a visual consolidation of the three-domain structure that emerged from the earlier phases. The full validated definitions are presented in Appendix C (online supplement), while Section 3.3 explains the synthesis and expert validation process in detail.

To further enhance transparency and traceability, Appendix A provides a crosswalk between each competency and the academic sources from which it was derived, offering visibility into the literature-to-framework development path.

This competency list serves as the conceptual and empirical foundation for Stage 2 of this study, where it will be integrated with DT functional and strategic requirements. That integration, presented in Chapter 5, will demonstrate how digital PM competencies can be mapped to a real-world digital transformation tool exemplar.

While this study focuses specifically on digital PM competencies, these are not intended to override or replace traditional PM competencies. Instead, they build upon and enhance traditional capabilities to address the evolving demands of data-driven, technology-enabled construction projects.

4. INTEGRATION WITH DIGITAL TWIN REQUIREMENTS

Following the development of the validated Next-Gen Digital PM Competency List in Stage 1, this section presents the outcomes of Stage 2, where the competencies were integrated with the functional and strategic requirements of DTs. DTs are used in this study as a representative exemplar of advanced digital tools that characterise the broader trajectory of digital transformation in the construction industry. This framing allows for a practical demonstration of how the competencies identified through the SLR, thematic analysis, and LLM synthesis can be applied to real-world scenarios requiring high levels of digital integration, collaboration, and lifecycle data management.

The integration framework presented in this section is adapted from the work of Owais et al. (2025), originally developed for the International Conference on Smart and Sustainable Built Environment (SASBE 2024). In that study, the competency list was systematically mapped against a core set of DT requirements. This approach not only demonstrates the applied relevance of the competency model within the SBE but also helps identify the critical competencies PMs must possess to support, manage, and lead DT-enabled construction initiatives.

The integration process followed three key steps: (1) extraction of DT requirements from the literature, (2) comparative mapping of digital PM competencies to DT requirements, and (3) interpretive analysis and identification of strategic implications, which are discussed in detail in Section 4.3. Figure 8 illustrates the integration framework that underpins this mapping.

4.1 Extraction of Digital Twin Requirements

DTs represent a transformative technology within the SBE (Rotilio et al., 2023), providing a virtual replica of physical assets that can be used for various purposes, including simulation, monitoring, and optimisation (Cellina et al., 2023). DTs are defined in this study as data-driven digital models that dynamically mirror real-time processes and asset conditions, enabling predictive and operational decision-making across the asset lifecycle. While DTs can span the entire lifecycle of an asset, this study scopes their application specifically to the construction phase, where PMs play a central role in coordinating data flows, managing digital processes, and supporting lifecycle continuity. To inform the integration process, DT requirements were extracted from the existing literature, with a particular focus on the functional and strategic competencies that PMs must demonstrate in DT-enabled construction projects. These requirements represent the key digital functions that PMs need to align with to lead effective DT adoption and deployment during construction, while also contributing to longer-term lifecycle integration.

Building upon the 11 discrete DT requirements identified in Owais et al. (2025), namely data integration and management, real-time monitoring and analysis, simulation and modelling, interoperability and integration with existing systems, scalability and flexibility, security and privacy, collaboration and communication, maintenance and updates, digital content creation, problem-solving, and data analysis and management, this study aimed to conceptually clarify, reduce redundancy, and improve alignment with the digital PM competencies developed in Stage 1.

As a result, the 11 requirements were consolidated into six broader thematic categories. This restructuring preserves the full functional scope of the original items while offering a more accessible and structured foundation for integration mapping (Boschert & Rosen, 2016; Cellina et al., 2023; Grieves & Vickers, 2017). The six consolidated thematic DT requirements are as follows:

1. **Interoperability and Integration:** Ensuring seamless data exchange across digital platforms such as BIM, IoT, Geographic Information Systems (GIS), and cloud systems to enable synchronised workflows, enhance model interoperability, and allow multi-system collaboration (Grieves & Vickers, 2017; Lee et al., 2015).
2. **Real-Time Data Management:** Capturing, analysing, and updating project data dynamically to enable continuous feedback loops, informed decision-making, and proactive project control. This includes capabilities for live monitoring, data analysis, and content creation (Boschert & Rosen, 2016; Kukushkin et al., 2022).
3. **Simulation and Predictive Modelling:** Supporting scenario-based simulations, forecasting, and behavioural modelling through digital replicas of physical assets. This enables risk management, performance optimisation, and future state analysis (Boschert & Rosen, 2016; Cellina et al., 2023).
4. **Cybersecurity and Data Governance:** Securing digital assets through robust privacy protocols, access control, and regulatory compliance. This includes protecting sensitive project data, ensuring transparency, and maintaining stakeholder trust (Faleiro et al., 2022; Grieves & Vickers, 2017).
5. **Stakeholder Collaboration:** Facilitating integrated communication, real-time coordination, and engagement among project stakeholders via digital platforms. This enhances team decision-making and transparency across the project lifecycle (Boschert & Rosen, 2016; Omrany et al., 2023).
6. **Scalability and Lifecycle Continuity:** Ensuring that DT systems are adaptable, sustainable, and capable of scaling across project phases and asset life cycles. This includes provisions for ongoing maintenance, updates, and long-term system viability (Boschert & Rosen, 2016; Cellina et al., 2023).

These categories provide a structured representation of DT's core functionalities, offering a practical lens for aligning digital competencies with real-world technological demands. They serve as the analytical basis for mapping the digital PM competencies to DT requirements in Section 4.2.

4.2 Mapping Digital PM Competencies to Digital Twin Functional Requirements

To demonstrate the applicability of the validated competency list to the SBE, this section maps the Next-Gen Digital PM Competency List developed in Stage 1 against the six thematic DT functional requirements outlined in Section 4.1. The objective is to evaluate how well-equipped the identified competencies are to support the technological and operational dimensions of DT-enabled construction projects. DTs are used here as a demonstrative test case to validate the practical relevance of the competency list in a real-world, high-complexity digital transformation context. This process validates the relevance of the competency list by assessing its alignment with real-world DT functional demands.

This mapping was conducted using a manual thematic alignment process. Each DT requirement was analysed to identify its core functional needs. Individual competencies were then examined to determine whether they directly enable, support, or complement those needs. A competency was coded as "*enable*" if it directly facilitated the execution of a DT function. It was coded as "*support*" if it played an indirect or contributory role and "*complement*" if it addressed adjacent capabilities that enhance or sustain DT implementation.

The process involved systematically comparing competency definitions with DT requirement descriptions. This comparison was informed by both literature sources and the thematic structure established in earlier phases. Thematic alignment was conducted by the core research team and independently reviewed by two domain experts in construction PM and digital transformation. This dual review approach ensured consistent interpretation, reduced subjective bias, and strengthened the credibility of the mapping outcomes. A comparative analysis method, originally introduced in Owais et al. (2025), was retained to guide this alignment process and ensure analytical consistency.

Figure 8: Mapping of Next-Gen Digital PM Competencies to Digital Twin Functional Requirements (as a Demonstrative Application).

Figure 8 illustrates the resulting integration model. It was originally developed in Owais et al. (2025) and has been updated in this version to reflect refined competency names, updated definitions, and the six consolidated DT requirement categories. The model presents a cross-domain alignment between Digital PM Competencies, grouped into Skills, Knowledge, and Core Personality Traits, and the six DT functional requirements: Interoperability and

Integration, Real-Time Data Management, Simulation and Predictive Modelling, Cybersecurity and Data Governance, Stakeholder Collaboration, and Scalability and Lifecycle Continuity.

The integration shows that each competency category, Skills, Knowledge, and Core Personality Traits, plays a distinct role in supporting different DT functional requirements, as illustrated in Figure 8. Skills-based competencies, such as technical proficiency with digital tools, are most strongly aligned with DT requirements like Real-Time Data Management and Simulation and Predictive Modelling. These areas reflect the importance of hands-on capabilities for managing data flows, applying analytics, and operating AI-based systems. Knowledge-based competencies are more prominent in areas such as Cybersecurity and Data Governance and Scalability and Lifecycle Continuity. These requirements rely on an in-depth understanding of regulatory compliance, data protocols, and long-term digital asset planning. Core Personality Traits, including leadership, emotional agility, and communication, are particularly relevant in Stakeholder Collaboration and Lifecycle Continuity. In these domains, the ability to manage people, relationships, and organisational change is essential.

The rationale for this integration is threefold: (1) to demonstrate that the competencies developed in this study are functionally relevant to advanced digital use cases like DTs; (2) to reveal competency gaps in areas such as lifecycle resilience and cybersecurity; and (3) to provide a practical roadmap for applying the competency list to real digital transformation strategies in the AEC sector.

Overall, Figure 8 highlights that effective digital PM requires a balanced combination of technical skills, strategic knowledge, and human-centred leadership to meet the complex functional demands of DT-enabled construction environments.

The following integration explanations detail how digital PM competencies directly enable, support, or complement each DT functional requirement:

1. **Interoperability and Integration**
   - → **S1. Advanced Digital Technology Proficiency:** Directly enables seamless digital operations across BIM and IoT platforms.
   - → **S2. Digital Technology Integration:** Supports the use of interoperable systems and tools across project teams and platforms.
   - → **K1. Advanced Digital Construction Knowledge:** Complements technical coordination across multiple digital systems, enhancing integration and communication.
2. **Real-Time Data Management**
   - → **S5. Real-Time Digital Information Exchange:** Directly enables live data sharing, model updates, and coordination across stakeholders.
   - → **S7. Digital Data Evaluation and Analytics:** Supports real-time analysis and validation for proactive decision-making.
   - → **K11. Digital Information and Data Literacy:** complements effective data structuring and access protocols, ensuring quality and clarity in data-driven environments.
3. **Simulation and Predictive Modelling**
   - → **K15. AI-Powered Data-Driven Decision-Making:** Directly enables predictive simulations and scenario forecasting based on analytics.
   - → **S3. Digital Building Performance Optimisation:** Supports the simulation of building systems, enabling energy, lifecycle, and performance forecasting.
   - → **S11. AI-Assisted Programming and Automation:** Complements automated modelling and behaviour-driven DT systems.
4. **Cybersecurity and Data Governance**
   - → **S17. Cybersecurity and Digital Device Protection:** Directly enables secure project operations and protects digital infrastructure.

→ **K9. Regulatory and Compliance:** Supports adherence to national and international data protection and cybersecurity standards.

→ **K12. Digital Construction Risk Management:** Complements data governance through proactive identification and mitigation of digital risks.

5. **Stakeholder Collaboration**

→ **CP1. Team Leadership in Digital Construction:** Directly enables project team coordination across digital environments.

→ **CP7. Digital Stakeholder Communication and Collaboration:** Supports real-time engagement with external partners and multidisciplinary teams.

→ **S4. Digital Communication and Interaction Strategies:** Complements effective dialogue and clarity across digital platforms.

6. **Scalability and Lifecycle Continuity**

→ **S14. Smart Digital Documentation and Archiving:** Directly enables structured data and model archiving for long-term system maintenance.

→ **CP5. Team Well-Being Leadership:** Supports sustained team engagement and adaptability through project phases.

→ **K7. Digital Quality Assurance and Lifecycle Management:** Complements consistency in digital standards throughout project lifecycles.

This match confirms a strong alignment between DT functional needs and the validated PM competencies. It also validates the model's real-world relevance by demonstrating its operational fit within a cutting-edge digital application. As shown in Appendix A (online supplement), competencies related to cybersecurity and lifecycle resilience, particularly S17. Cybersecurity and Digital Device Protection and K7. Digital Quality Assurance and Lifecycle Management were referenced less frequently across the literature and appeared primarily in technical or siloed contexts. This identifies emerging gaps in strategic and behavioural capabilities, such as crisis readiness in digital security, or long-term thinking for managing digital assets across a project's lifecycle. These insights offer practical direction for refining future competency models.

Importantly, this model has direct real-world applicability. The identified competencies can inform digital training programs, professional development, and upskilling strategies in the AEC sector. Employers may use this framework to revise role descriptions, support digital hiring initiatives, and build project teams that are better aligned with digital transformation objectives. Additionally, education providers and certification bodies can incorporate the validated list into curriculum design, ensuring that graduates are equipped to engage with DT-enabled environments and broader smart construction practices.

4.3 Implications for PM Competency Development in Digital Twin Contexts

This section presents the key findings of the study's two-stage process. Stage 1 resulted in a validated list of 55 digital PM competencies, grouped under Skills, Knowledge, and Core Personality Traits, developed through a SLR, NVivo-based Thematic Analysis, and LLM synthesis. Stage 2 mapped these competencies to six DT functional requirements to evaluate their practical relevance. This structured mapping revealed both alignment patterns and capability gaps (e.g., in cybersecurity and lifecycle resilience), demonstrating the framework's operational value for digital transformation in construction.

The integration of DT requirements with the Next-Gen Digital PM Competency List presents critical insights for capability development in digitally enabled construction environments. This represents one of the study's key results: demonstrating how theoretically derived competencies align with operational digital requirements. Building on the detailed alignment in Section 4.2, this section explores the implications of these findings for workforce planning, training initiatives, and long-term strategic transformation in construction.

Firstly, the mapping reinforces the importance of evolving PM competencies beyond conventional project delivery domains. As DT adoption accelerates, PMs are increasingly expected to interface with advanced technologies, interpret real-time data, and coordinate across integrated digital ecosystems. Consequently, digital competencies, particularly in data analysis (e.g., S7), digital modelling (e.g., K1, K3), and collaboration (e.g., CP6, CP7), should be prioritised in both formal education and on-the-job training. This highlights a shift in PM functional expectations, emphasising digital proficiency and system interoperability as essential competencies.

Secondly, the alignment underscores the need to embed digital leadership attributes into PM development pathways. Traits such as emotional agility (CP3), accountability (CP4), and stakeholder engagement (CP2, CP7) are vital for leading change in complex digital environments. These behavioural competencies enhance PMs' ability to champion digital transformation efforts while navigating human, regulatory, and ethical complexities. This behavioural layer of digital leadership is often underemphasised in current PM frameworks, revealing a practical area for curriculum enhancement.

Finally, the integration model provides a strategic roadmap for institutions and industry bodies to align competency frameworks, certification programs, and Continuing Professional Development (CPD) modules with emerging digital construction trends. For instance, a conventional leadership training module for PMs, traditionally focused on stakeholder engagement and communication, could be redesigned as "Leading in Digital Construction," incorporating competencies such as Digital Stakeholder Communication (CP7), Emotional Agility (CP3), and AI-powered Decision-Making (K15). This would equip PMs not only to manage relationships but to lead within data-rich, AI-integrated environments where decisions must be made in real time and communicated across interdisciplinary, tech-enabled teams. The model can also guide performance evaluation systems by linking observable digital behaviours with specific DT-related outcomes. Such translation of the competency framework into applied training and performance tools demonstrates a clear pathway for real-world implementation.

From a research perspective, this integration approach illustrates how domain-specific digital technologies (e.g., DTs) can serve as validation mechanisms for competency models, bridging theoretical constructs with applied functionality. The implications presented here stem directly from the structured mapping process described in Section 4.2, where the comparative analysis method (Owais et al., 2025) was used to evaluate whether each competency directly enables, supports, or complements the six identified DT requirement categories. This thematic alignment not only validates the practical utility of the competency list but also informs future competency development strategies aligned with DT functionality in the SBE.

5. CONCLUSION

This study developed and validated a Next-Gen Digital Project Manager (PM) Competency List tailored to the evolving demands of the Smart Built Environment (SBE). Using a structured two-stage methodological process, the research first identified, classified, and defined 55 digital PM competencies through a rigorous three-phase approach comprising a Systematic Literature Review (SLR), NVivo-assisted Thematic Analysis, and Large Language Model (LLM)-driven definition synthesis. These competencies were systematically categorised under three overarching domains: Skills, Knowledge, and Core Personality Traits.

In the second stage, the validated competencies were integrated with the functional requirements of Digital Twins (DTs), which were used in this study as a demonstrative exemplar of digital transformation technologies in construction. DTs represent one of the most comprehensive and integrative innovations in the construction sector, requiring PMs to coordinate real-time data flows, simulate performance outcomes, manage security protocols, and foster collaborative digital environments. The integration process mapped competencies against six thematic DT capability areas: interoperability and integration, real-time data management, simulation and predictive modelling, cybersecurity and data governance, stakeholder collaboration, and scalability and lifecycle continuity. This mapping revealed strong alignment across most areas, particularly in digital integration and stakeholder engagement, while also identifying important gaps in cybersecurity preparedness and lifecycle resilience.

Together, the two stages of this study produced the central outcomes: Stage 1 established a validated and structured digital competency model for construction PMs, and Stage 2 demonstrated its real-world relevance by applying it to DT-functional requirements. This confirmed both the conceptual integrity and applied value of the framework in supporting the broader goals of digital transformation in the construction industry. Using DTs as an integration test case underscores the model's scalability and adaptability to other advanced digital tools and environments.

The model offers clear implications for capability development. It equips PMs with a comprehensive structure to lead, manage, and support digitally enabled projects, and provides institutions with a targeted framework to inform curriculum development, training programs, and recruitment strategies. The competencies are not intended to replace traditional PM capabilities but rather to digitally extend them, ensuring alignment with the rapidly evolving technological landscape in construction.

While the model demonstrates strong conceptual grounding, it also carries limitations. Its current validation is based primarily on literature and expert input. Thus, results should be viewed as an early-stage framework that requires further empirical testing. Applicability may vary depending on regional digital maturity, organisational readiness, and project scale. Future research should engage a broader cross-section of industry professionals across diverse regions and sectors to validate the framework's generalisability and real-world functionality.

The key contribution of this study lies in two actionable outcomes: (1) a validated and structured list of digital competencies that helps PMs adapt to the evolving demands of digital construction, and (2) a competency-to-technology integration model that illustrates how these competencies can support the deployment of complex digital systems like DTs. These outcomes offer immediate relevance to educators, employers, and certification bodies, all of whom are under increasing pressure to prepare PMs for digital transformation.

Looking ahead, future research will focus on transforming this theoretical framework into a robust, data-driven model through survey-based validation, behavioural assessments, and performance benchmarking. This next phase will help confirm the model's structural integrity and ensure its practical utility for workforce development and strategic planning. Additionally, the model can serve as a foundation for broader digital transformation initiatives in construction, including integration with emerging technologies such as AI-driven project delivery, 6D/7D BIM, and smart platform ecosystems. It may also support the development of digital maturity assessment tools, readiness benchmarks, and specialised leadership training programs tailored to smart and sustainable construction.

By using DTs as an exemplar throughout this study, we demonstrated not only how PMs must adapt to emerging digital demands, but also how well-designed competency frameworks can inform broader digital transformation strategies in the construction industry. The framework developed here offers a scalable, evidence-based foundation for equipping PMs with the tools, behaviours, and mindsets needed for the next era of construction delivery.

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APPENDIX A: MAPPING OF FINAL STUDIES TO IDENTIFIED COMPETENCIES

This appendix presents a cross-reference matrix showing which digital competencies were identified across the final 15 studies included in the systematic review.

Digital Competencies \ **Study Numbers**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1. Advanced Digital Technology Proficiency	✓	✓		✓		✓	✓		✓				✓	✓	✓
2. Digital Technology Integration	✓	✓							✓			✓			
3. Digital Building Performance Optimisation										✓					✓
4. Advanced Digital Construction Knowledge	✓	✓					✓	✓				✓		✓	
5. Emerging Technology Integration Knowledge		✓							✓			✓			
6. Smart Systems and Applications Knowledge								✓		✓				✓	✓
7. Team Leadership in Digital Construction	✓	✓		✓		✓	✓	✓	✓				✓	✓	
8. Stakeholder Leadership in Digital Construction	✓	✓									✓				
9. Digital Self-Leadership and Emotional Agility				✓				✓	✓				✓	✓	
10. Decision-Making and Accountability				✓			✓	✓					✓		
11. Team Well-Being Leadership													✓		
12. Digital Project Strategy and Goal Alignment	✓	✓		✓			✓					✓			
13. Digital Project Integrated Management									✓		✓				
14. Digital Safety and Risk Mitigation		✓								✓	✓				

15. Digital Quality Assurance and Lifecycle Management		✓								✓					
16. Contract and Negotiation Management		✓						✓	✓						
17. Regulatory and Compliance		✓								✓				✓	✓
18. Digital Team Communication and Collaboration	✓	✓		✓			✓					✓	✓	✓	
19. Digital Stakeholder Communication and Collaboration	✓							✓			✓			✓	
20. Language Proficiency		✓												✓	
21. Digital Communication and Interaction Strategies	✓		✓		✓			✓							
22. Real-Time Digital Information Exchange			✓		✓	✓	✓	✓		✓					✓
23. Digital Collaboration and Knowledge Retention			✓		✓	✓		✓		✓		✓			
24. Digital Information and Data Literacy			✓		✓										
25. Digital Data Evaluation and Analytics			✓		✓		✓					✓			✓
26. Cloud-Based Digital Content Management			✓		✓							✓			✓
27. Digital Content Development Skills			✓		✓										
28. Advanced Digital Content Management			✓		✓										
29. AI-Assisted Programming and Automation			✓					✓							
30. Smart Construction Digital Tool Utilisation					✓	✓	✓	✓						✓	✓
31. Digital Technologies Training and Development						✓				✓		✓		✓	

32. Smart Digital Documentation and Archiving														✓	
33. Digital Problem Solving and Technical Support			✓	✓			✓	✓					✓	✓	
34. Digital Skills Gap Analysis and Development			✓		✓										
35. Cybersecurity and Digital Device Protection			✓		✓							✓			
36. Digital Privacy and Data Protection Compliance			✓		✓										✓
37. Digital Construction Risk Management	✓										✓				
38. Digital Technology Adoption Risk Mitigation	✓									✓		✓			
39. Financial Risk Management	✓														
40. Emerging Technologies Cost Management	✓											✓			
41. Real-Time Cost Optimisation and Digital Budgeting		✓		✓							✓				✓
42. Automated Digital Procurement Management				✓							✓				✓
43. Digital Scheduling Management	✓			✓						✓	✓		✓	✓	✓
44. Digital Resource Management	✓	✓		✓			✓			✓	✓		✓	✓	✓
45. Digital Quality Control	✓										✓			✓	
46. Digital Scope and Change Management								✓			✓				
47. Innovation Management in Digital Construction	✓											✓			
48. Digital Innovation and Creativity in Smart Construction	✓				✓			✓						✓	

49. AI-Powered Data-Driven Decision-Making					✓				✓			✓			
50. Standardising Digital Technology Processes						✓				✓					
51. Energy Efficiency and Carbon Management	✓									✓					
52. Sustainability Reporting and Monitoring	✓		✓												
53. Sustainable Construction Strategies	✓								✓						
54. Qualifications and Professional Development		✓				✓								✓	✓
55. Curriculum Development												✓		✓	

APPENDIX B: NVIVO OUTCOMES: THEMATIC, CLUSTER, AND SENTIMENT ANALYSIS OF DIGITAL COMPETENCIES

Appendix B presents thematic and cluster analysis outcomes generated using NVivo, including coding frequency, hierarchical themes, and sentiment interpretation of leadership and digital competencies.

Figure B1: NVivo Auto-Coding Output of Initial Competency References.

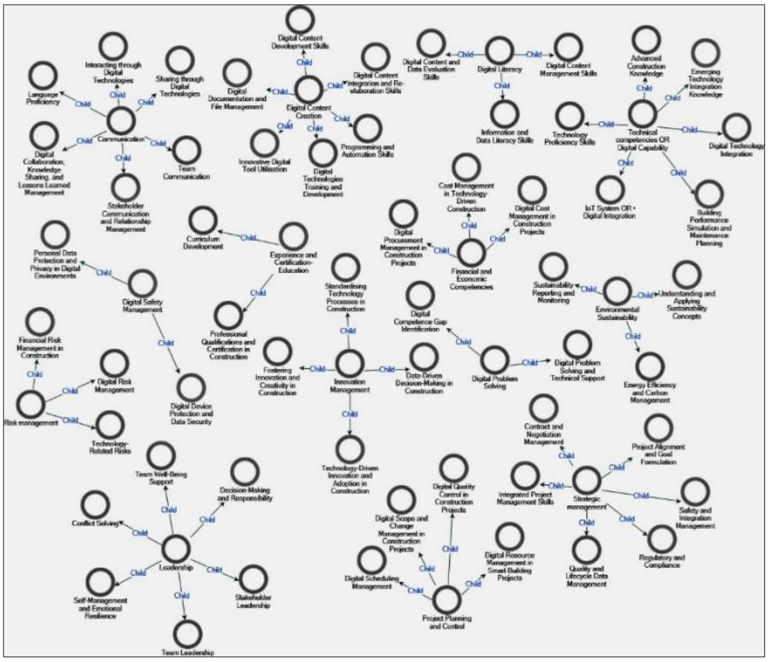

Figure B2: NVivo Thematic Mapping Showing Relationships Between Competency Codes and Emergent Themes.

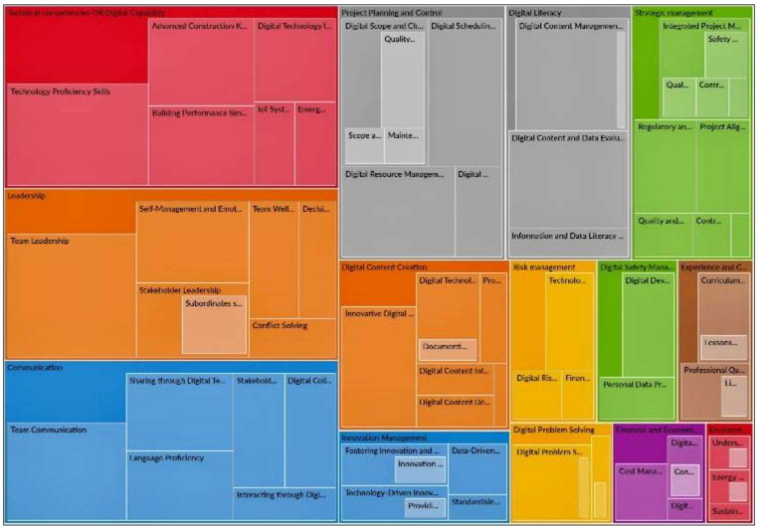

Figure B3: Hierarchical Node Structure in NVivo Representing Competency Classification.

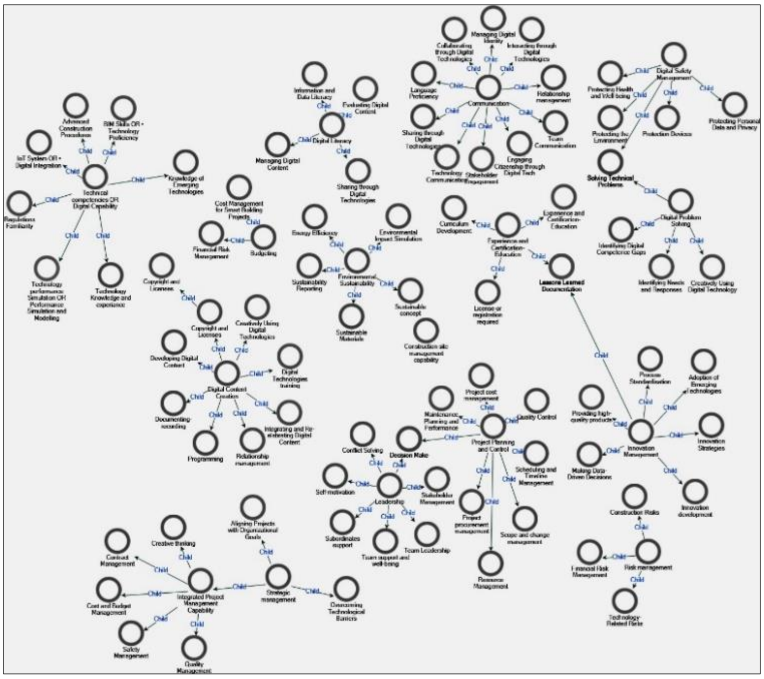

Figure B4: Visual Thematic Map of Digital Competencies Generated in NVivo.

Word	Length	Count	Weighted Percentage (%)
digital	7	1997	1.36
project	7	1659	1.13
construction	12	1592	1.09
management	10	1020	0.70
skills	6	816	0.56
information	11	790	0.54
level	5	734	0.50
knowledge	9	667	0.46
competencies	12	662	0.45
based	5	521	0.36
projects	8	513	0.35
competence	10	493	0.34
building	8	492	0.34
technologies	12	460	0.31
research	8	442	0.30
content	7	427	0.29
using	5	378	0.26
analysis	8	365	0.25

Figure B5: Coding Frequency Analysis of Digital Skill Competencies in NVivo.

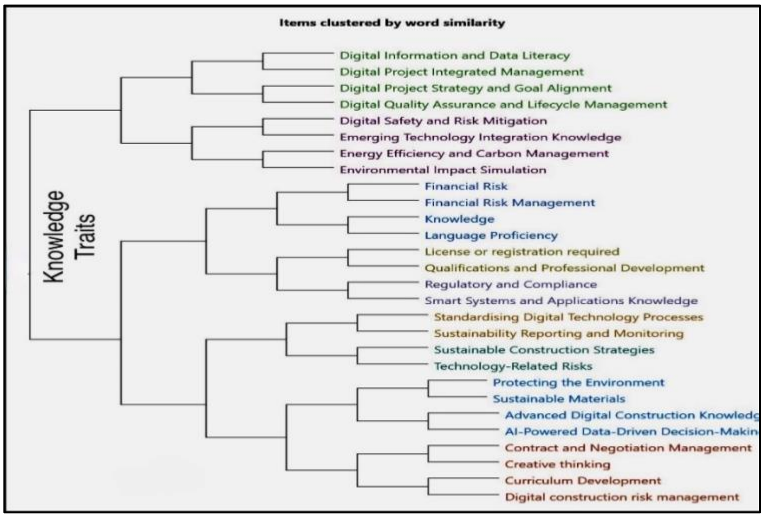

Figure B6: NVivo Cluster Analysis of Digital Knowledge Competencies.

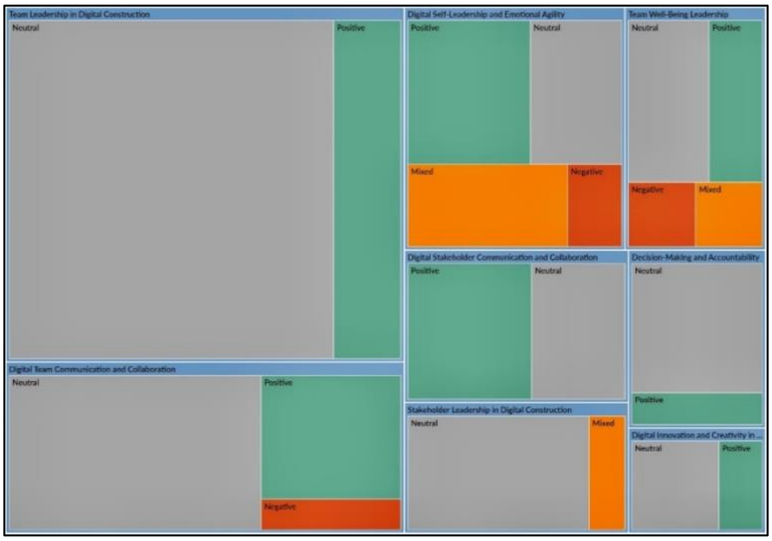

Figure B7: NVivo Sentiment Analysis of Leadership and Digital Competency Narratives.

APPENDIX C: FULL DEFINITIONS OF THE 55 NEXT-GEN DIGITAL PM COMPETENCIES

This appendix presents the full validated list of digital competencies developed in this study, organised under three domains.

- **Skills (S1–S26):**
  - **S1. Advanced Digital Technology Proficiency:** *The expertise required to effectively use digital tools and technologies in construction project management. This includes BIM systems, project software, and design tools like AutoCAD and Navisworks, along with managing BIM libraries, object attributes, and coordinating digital workflows. These skills enable seamless integration of technology into smart building practices and efficient project delivery.*
  - **S2. Digital Technology Integration:** *The ability to effectively integrate and utilise digital tools, systems, and resources in construction projects to enhance efficiency and innovation. This includes operating IoT systems, collaborating with technology providers for data capture and management, and leading digital teams through complex systems of digital innovation. It also involves proficiency in BIM model viewing, analysis, and integration software to optimise project workflows and ensure seamless collaboration in technology-driven environments.*
  - **S3. Digital Building Performance Optimisation:** *The use of digital technologies like BIM to simulate, monitor, and improve building systems throughout their lifecycle. This includes assessing energy performance, managing maintenance schedules, identifying repair needs, and ensuring sustainability. By leveraging digital tools to optimise long-term performance, this competency helps enhance durability, operational efficiency, and the overall resilience of buildings and infrastructure across project phases.*
  - **S4. Digital Communication and Interaction Strategies:** *The ability to engage effectively with stakeholders, teams, and non-technical audiences through various digital platforms and technologies. This competency involves adapting communication methods and tools to suit different contexts, clearly explaining the functionalities and benefits of advanced technologies, and fostering collaboration in virtual, hybrid, and in-person environments. It emphasises bridging the gap between technical and non-technical perspectives to ensure efficient and meaningful interactions.*
  - **S5. Real-Time Digital Information Exchange:** *The ability to facilitate live data sharing and coordination across teams using digital platforms such as BIM and DTs. It includes managing documentation, references, and knowledge transfer to enable collaborative problem-solving and improved project tracking. This competency ensures platform interoperability, timely updates, and collective decision-making, which enhance responsiveness and streamline communication in complex, multi-stakeholder environments.*
  - **S6. Digital Collaboration and Knowledge Retention:** *The use of digital tools and platforms to document, share, and apply insights, challenges, and solutions encountered during construction projects. This competency fosters effective collaboration by preserving institutional knowledge, encouraging team learning, and driving continuous improvement. By integrating lessons learned into digital collaboration processes, teams can make informed decisions, avoid repeated mistakes, and enhance overall project outcomes.*
  - **S7. Digital Data Evaluation and Analytics:** *The ability to assess the quality, accuracy, and relevance of digital data for informed project decisions. This includes analysing and validating datasets, updating digital models to reflect changes, and applying data visualisation tools for insight generation. These competencies ensure that project teams operate with reliable, current data and improve outcomes through evidence-based decision-making and efficient data lifecycle management.*
  - **S8. Cloud-Based Digital Content Management:** *The ability to organise, store, and access digital content using cloud technologies. It includes maintaining electronic databases, applying data processing guidelines, and ensuring responsible data handling. This competency also covers copyright*

adherence, digital identity management, and secure content sharing, enabling efficient reporting and collaboration across project teams.

- **S9. Digital Content Development Skills:** *The ability to create, edit, and manage digital content across various formats using modern tools and technologies. This competency enables individuals to effectively express ideas, communicate, and contribute to projects through innovative and original digital outputs. Proficiency in digital content development ensures clear communication, creative problem-solving, and the capacity to adapt content for diverse audiences and platforms, thereby enhancing collaboration and overall project success.*
- **S10. Advanced Digital Content Management:** *The ability to refine, modify, and adapt existing digital content to create new, original resources tailored to specific project requirements. These skills enhance creativity and efficiency by integrating and leveraging available digital assets to produce innovative outputs. Proficiency in this area ensures the effective reuse of resources, optimising workflows and fostering originality in content development while meeting project objectives.*
- **S11. AI-Assisted Programming and Automation:** *The ability to create, understand, and utilise programs or automated systems to enhance project workflows and efficiency. This includes proficiency in coding languages for interacting with digital tools, analysing project data, and developing customised solutions to address specific challenges. These skills enable the automation of repetitive tasks, the optimisation of processes, and the development of innovative approaches to improve construction and project management outcomes.*
- **S12. Smart Construction Digital Tool Utilisation:** *The creative and effective application of digital technologies, including CAD/BIM software, cloud platforms, and simulation tools, to achieve project objectives. This competency encompasses designing, modelling, rendering, and drafting accurate project documentation while ensuring compliance with technical standards. It also involves leveraging advanced software for visual design, energy modelling, and sustainable construction practices, as well as supporting the implementation of digital tools across projects. Proficiency in utilising these tools fosters efficient project management, enhances collaboration, and promotes innovation to optimise project outcomes.*
- **S13. Digital Technologies Training and Development:** *The process of equipping construction professionals with the skills and knowledge to effectively use digital tools and technologies, such as BIM, for data capture, analysis, and project management. This competency includes developing and delivering training materials, conducting instructional sessions, and providing ongoing education to ensure alignment with industry standards. It also involves fostering continuous professional development and supporting team members in managing electronic construction information, thereby enhancing overall project execution and collaboration.*
- **S14. Smart Digital Documentation and Archiving:** *The process of organising, maintaining, and updating electronic project files, including CAD and BIM data, throughout the project lifecycle. This competency involves defining file structures, creating and implementing documentation strategies, and ensuring that all drawings, data files, and project-related documents are accurately recorded, electronically filed, and readily accessible. It also includes managing version control, maintaining a CAD library and file system, and strategising document production to support efficient project workflows and seamless collaboration.*
- **S15. Digital Problem Solving and Technical Support:** *The ability to identify, assess, and resolve technical challenges in digital environments. It includes troubleshooting software or modelling issues, applying research-driven solutions, and advising teams on technology use. This competency also involves auditing digital models, supporting innovation, and ensuring sustainable, repeatable problem resolution, all of which contribute to smooth project execution and stronger digital capacity.*
- **S16. Digital Skills Gap Analysis and Development:** *The ability to assess and identify areas where an individual's or team's digital skills require improvement to enhance performance and adapt to the evolving digital landscape. This competency involves understanding current digital proficiency levels, recognising skill gaps that impact project success, and actively pursuing opportunities for self-development and team growth. It also encompasses fostering digital citizenship by engaging with public and private digital services to promote continuous learning and organisational improvement.*

- **S17. Cybersecurity and Digital Device Protection:** *The strategies and practices employed to safeguard personal and organisational devices and data from digital threats, ensuring integrity, confidentiality, and availability throughout the project lifecycle. This competency encompasses protecting devices against cyber risks, implementing robust security systems and risk mitigation protocols, and utilising advanced analytics to monitor, predict, and address potential vulnerabilities. Additionally, it involves promoting digital well-being by managing screen time, content exposure, and online interactions, thereby supporting a secure and balanced use of digital resources.*

- **S18. Digital Privacy and Data Protection Compliance:** *The practices and strategies to ensure the security, confidentiality, and integrity of personal and professional data within digital platforms. This includes safeguarding sensitive information by complying with data protection regulations and implementing measures to prevent unauthorised access, breaches, and misuse of data. These efforts aim to protect the privacy of individuals and organisations while maintaining secure and efficient workflows throughout digital processes and project lifecycles.*

- **S19. Emerging Technologies Cost Management:** *The ability to budget, monitor, and control the increased costs associated with implementing new technologies, materials, equipment, and training in smart building projects. This competency involves the strategic allocation of financial resources to ensure that advancements such as BIM and IoT are integrated efficiently without exceeding financial limits and is further supported by government and industry-led initiatives, such as workshops and training programs, aimed at enhancing cost management practices and fostering digital transformation in construction.*

- **S20. Real-Time Cost Optimisation and Digital Budgeting:** *The ability to effectively manage project costs and budgets using digital tools like BIM, particularly through the integration of 5D models. This enables precise cost estimation, automated quantity take-offs, real-time feedback on design changes, and efficient cost planning and reviews. It enhances budget tracking, productivity, and financial planning while requiring adjustments to traditional workflows. This approach empowers project teams to balance costs with project objectives, ensuring alignment with financial goals throughout the project lifecycle.*

- **S21. Automated Digital Procurement Management:** *The use of BIM and related digital tools to improve procurement accuracy and efficiency. This includes generating bills of quantity, managing 5D cost simulations, and integrating procurement data into broader scheduling and budgeting workflows. The competency enables digital planning of resources, supports transparency, and reduces errors in material estimation and vendor coordination, resulting in cost-effective, timely procurement operations.*

- **S22. Digital Scheduling Management:** *The ability to synchronise project timelines with digital models using tools such as 4D BIM. This competency involves linking schedule data with design and construction activities, visualising workflow impacts, and optimising task allocation. It also includes adjusting schedules in response to design changes and ensuring team coordination for timely, efficient project delivery through digital tracking systems.*

- **S23. Digital Resource Management:** *The ability to allocate and optimise project resources using digital platforms. This includes forecasting labour and materials, managing interdisciplinary coordination, and integrating resource planning with digital scheduling and budgeting. It also involves the use of BIM and related tools to minimise waste, improve sustainability, and ensure strategic utilisation of both physical and human assets across all construction phases.*

- **S24. Digital Quality Control:** *The process of integrating quality management practices throughout the project lifecycle using digital tools such as BIM, DT, and AI. This competency involves real-time monitoring and detailed audits of structural, electrical, and mechanical elements, leveraging features like clash detection and comprehensive documentation of defects to support quality assurance. It ensures adherence to standards and tolerances, facilitates continuous improvement and conflict resolution, and enhances overall project efficiency by reducing waste and ensuring high-quality outcomes.*

- **S25. Digital Scope and Change Management:** *The ability to manage evolving project scope and changes using digital tools like BIM and DTs. It includes visualising project alterations, coordinating* *stakeholder communication, and preventing scope creep. This competency ensures all updates are accurately represented and communicated in real time, maintaining alignment across disciplines and facilitating responsive project delivery in dynamic environments.*

- **S26. Innovation Management in Digital Construction:** *The ability to lead the adoption and integration of emerging technologies, including AI, automation, and big data tools. This competency supports the development of innovative solutions, enhances team capacity for digital transformation, and aligns project goals with evolving industry standards. It also includes overcoming adoption barriers and promoting a strategic culture of digital innovation across construction teams.*

➢ **Knowledge (K1–K21):**

- **K1. Advanced Digital Construction Knowledge:** *The expertise required to manage complex construction processes, integrate technical data into actionable project deliverables, and apply advanced skills across various engineering and construction domains. This includes mastery of digital tools, such as BIM and DT techniques, comprehensive knowledge of building materials and systems such as HVAC, plumbing, and electrical, and familiarity with structural drawings and installation procedures. It also involves understanding the complexity of construction projects, including the interaction of various elements, and leveraging technology-driven workflows to evaluate, select, and apply advanced construction procedures for efficient and innovative project execution.*
- **K2. Emerging Technology Integration Knowledge:** *The understanding and application of cutting-edge technologies, such as IoT, AI, VR, drones, and time-lapse cameras, to enhance construction processes. This competency involves ensuring the availability and effective use of these technologies within construction firms, leveraging them for tasks in digital technologies like BIM model viewing, analysis, and integration. It emphasises practical knowledge of their applications to improve efficiency, drive innovation, and optimise project outcomes in technology-driven environments.*
- **K3. Smart Systems and Applications Knowledge:** *The expertise and experience required to effectively utilise digital software and related technologies in construction. This includes proficiency in advanced digital technologies, such as BIM and DT systems, understanding their core functions, and managing libraries and classification systems for structured data usage. It also involves accurately inputting attribute values to maintain data integrity and leveraging digital technologies to collect and analyse information about building components, materials, and systems for future developments. Additionally, this competency encompasses technical knowledge of advanced materials, modern construction methods, and innovative applications, ensuring efficient project planning, development, and execution.*
- **K4. Digital Project Strategy and Goal Alignment:** *The ability to ensure that project objectives are aligned with the broader strategic goals of the organisation. This competency involves collaborating with top management and various departments to integrate projects with organisational strategy, engaging in regular data strategy discussions to guide team efforts, and establishing clear, actionable goals that direct project activities. By aligning project efforts with organisational expectations and fostering strategic collaboration, this competency drives successful project delivery and contributes to overall organisational success.*
- **K5. Digital Project Integrated Management:** *The ability to unify and manage multidisciplinary aspects of a project to ensure efficient planning, execution, and delivery. This competency involves integrating various components, such as systems, teams, and processes, through collaborative technologies like BIM, which enhances project planning, analysis, communication, and documentation. By fostering collaboration and leveraging interdisciplinary concepts, these skills enable the seamless combination of expertise from diverse fields, ensuring cohesive and efficient project execution.*
- **K6. Digital Safety and Risk Mitigation:** *The ability to manage safety throughout the entire lifecycle of a project, from design to construction and handover. This includes integrating safety standards with digital tools such as BIM to enhance hazard identification and mitigation. By leveraging automated safety checks, simulations, and early hazard detection during the preconstruction phase, this competency ensures a proactive and systematic approach to safety. It also involves streamlining safety*

processes, improving communication, and ensuring compliance with safety regulations, thereby reducing risks and fostering a safe and efficient project environment.

- **K7. Digital Quality Assurance and Lifecycle Management:** *The ability to oversee and manage quality control across all phases of a project, from initiation to completion. This competency ensures that project standards and specifications are consistently met by leveraging digital tools like BIM to gather, track, and analyse data throughout the building process. By integrating lifecycle data management, these skills enable continuous quality monitoring, facilitate informed decision-making, and support the long-term performance and sustainability of the built environment.*
- **K8. Contract and Negotiation Management:** *The capability to manage all aspects of contract negotiations and administration throughout the project lifecycle. This includes negotiating favourable terms, ensuring compliance with contractual obligations, and addressing any necessary adjustments. These skills involve resolving disputes, mitigating risks, and fostering strong relationships with all parties to support successful project delivery. Effective contract management also ensures adherence to legal and regulatory standards, contributing to project efficiency and stakeholder satisfaction.*
- **K9. Regulatory and Compliance:** *The knowledge and skills required to understand, apply, and adhere to industry laws, regulations, and standards throughout the project lifecycle. This includes familiarity with building codes, design regulations, and technical standards, as well as proficiency in creating and managing licensing documents to ensure regulatory adherence. It involves leveraging technologies to facilitate compliance, resolve conflicts, and align with national and international standards. Additionally, it encompasses mastery of design workflows, production cycles, and code procedures to ensure legal, safety, and quality standards are met, thereby supporting effective project execution within an evolving regulatory framework.*
- **K10. Language Proficiency:** *The ability to use language skills effectively, both spoken and written, to facilitate clear and efficient communication in project settings. This includes proficiency in common project languages such as English, as well as foreign languages such as Mandarin, Cantonese, Japanese, and German to support collaboration across diverse teams and cultures. It encompasses strong verbal communication, presentation, and writing abilities to ensure clarity in reports, speeches, and interpersonal exchanges, thereby fostering successful communication in both small and large group settings.*
- **K11. Digital Information and Data Literacy:** *The foundational knowledge required to navigate, evaluate, and manage digital information effectively. This includes understanding methodologies for browsing, searching, and filtering data to ensure accurate access to relevant resources. By developing this knowledge, construction professionals can enhance digital collaboration, improve project outcomes, and make well-informed decisions within digital environments.*
- **K12. Digital Construction Risk Management:** *The strategic use of digital tools to identify, assess, and mitigate risks throughout the construction project lifecycle. This competency involves leveraging technologies such as BIM and AI to provide a comprehensive view of potential risks, including safety hazards, cost overruns, and schedule disruptions. By integrating advanced risk forecasting, supporting real-time project updates, and enhancing stakeholder communication, it ensures a proactive approach to risk control, reduces rework, and improves overall project efficiency and safety.*
- **K13. Digital Technology Adoption Risk Mitigation:** *The process of identifying, evaluating, and mitigating challenges associated with adopting and integrating new technologies, such as BIM and IoT, in construction projects. This includes assessing the financial feasibility of technology adoption through cost modelling, enforcing the use of digital tools, and leveraging standardisation to reduce errors, delays, and cost overruns. By addressing these risks, this competency ensures that technological integration enhances project outcomes while minimising uncertainties and potential disruptions.*
- **K14. Financial Risk Management:** *The process of evaluating and managing financial risks related to the implementation of digital technologies in construction projects. This competency includes assessing the financial feasibility of adopting digital tools, forecasting cost implications, and developing strategies to mitigate unexpected financial demands. By ensuring thorough cost control and addressing potential budget uncertainties, it supports project viability and enables the effective allocation of financial resources in digital construction environments.*

- **K15. AI-Powered Data-Driven Decision-Making:** *The ability to leverage digital insights, industrial performance databases, and analytical tools to inform and optimise project decisions. This competency involves effectively evaluating and utilising data to make precise, evidence-based choices that enhance project efficiency, outcomes, and overall performance. By integrating data-driven approaches, construction professionals can improve resource allocation, minimise risks, and ensure informed decision-making at every project stage.*
- **K16. Standardising Digital Technology Processes:** *The creation and implementation of uniform procedures and guidelines within digital environments to enhance collaboration, minimise errors, and streamline workflows. This competency ensures that standards are consistently applied across all project stages and documentation, facilitating clear communication among teams and reducing miscommunications. By standardising technology-driven processes, construction projects achieve greater efficiency, reliability, and alignment with industry best practices.*
- **K17. Energy Efficiency and Carbon Management:** *The implementation of energy-efficient systems, such as smart HVAC and energy monitoring tools, to optimise energy consumption and promote sustainability in construction projects. This competency leverages digital technologies like BIM and DTs to quantify and reduce the embodied energy and carbon footprint of buildings. By simulating multiple scenarios and evaluating design alternatives, it supports informed decisions on materials, systems, and components to minimise environmental impact. These practices ensure that construction projects align with sustainability goals while enhancing efficiency and reducing carbon emissions.*
- **K18. Sustainability Reporting and Monitoring:** *The process of tracking, analysing, and documenting the environmental performance of smart building projects to ensure transparency and alignment with sustainability goals. This competency includes assessing and reporting on the environmental impact of digital technologies and their use, as well as identifying opportunities to enhance sustainable practices. By fostering awareness of a project's ecological footprint, it supports informed decision-making and continuous improvement in achieving environmental and sustainability objectives.*
- **K19. Sustainable Construction Strategies:** *The ability to promote environmentally responsible practices and achieve long-term ecological balance in construction projects. This competency includes awareness of sustainability principles and the selection of environmentally friendly materials to minimise environmental impact. By integrating sustainable practices into design and construction processes, this competency supports the creation of smart buildings that align with ecological and sustainability goals.*
- **K20. Qualifications and Professional Development:** *The education, certifications, and professional licensing required to effectively manage construction projects. It includes formal academic degrees (bachelor's, master's, or doctoral qualifications), industry credentials such as BIM management, LEED AP, or RIBA certifications, and adherence to construction standards and regulatory frameworks. Furthermore, it emphasises the importance of practical project experience, ensuring that professionals meet industry standards and maintain competency throughout their careers while adapting to evolving construction practices.*
- **K21. Curriculum Development:** *The process of collaborating with academic institutions to create and refine curricula tailored to the construction industry, with a focus on data management and technical skills. This involves designing courses that integrate industry best practices, hands-on training, and technical knowledge in disciplines such as architecture, civil engineering, mechanical, electrical, and plumbing systems, as well as HVAC and drainage. The goal is to equip students with the competencies needed to address modern construction challenges, fostering a workforce that is prepared for the evolving demands of the industry.*

➢ **Core Personality (CP1–CP8):**

- **CP1. Team Leadership in Digital Construction:** *The ability to lead, motivate, and manage multidisciplinary teams in collaborative digital environments. This includes building trust, organising tasks equitably, resolving conflicts constructively, mentoring team members, and aligning contributions with project goals to foster inclusive participation, strengthen teamwork, and enhance* *overall project delivery.*

- **CP2. Stakeholder Leadership in Digital Construction:** *The ability to manage diverse relationships with clients, government authorities, and end users in digitally enabled environments. It involves leveraging tools like BIM to facilitate open communication, align expectations, resolve conflicts, and build collaborative stakeholder engagement that enhances project transparency, efficiency, and satisfaction.*
- **CP3. Digital Self-Leadership and Emotional Agility:** *The ability to self-regulate, maintain focus under pressure, and adapt emotionally in complex digital settings. This includes managing stress, building resilience, sustaining motivation, and applying emotional intelligence to lead by example and maintain well-being while supporting effective team performance in dynamic project environments.*
- **CP4. Decision-Making and Accountability:** *The ability to make timely, informed decisions and take ownership of project outcomes. This involves assuming responsibility, guiding teams through uncertainty, and fostering a culture of accountability, where each member is empowered to contribute responsibly to achieving successful digital project delivery.*
- **CP5. Team Well-Being Leadership:** *The ability to create and maintain a psychologically safe, healthy, and positive work environment. This includes addressing team morale, supporting emotional and physical well-being, enabling open dialogue, and proactively managing stress factors to ensure long-term engagement and productivity across digital construction teams.*
- **CP6. Digital Team Communication and Collaboration:** *The ability to coordinate effective communication among team members through digital tools such as BIM, cloud platforms, or shared dashboards. This involves structuring information flows, facilitating virtual coordination, resolving misunderstandings, and promoting clear, data-driven collaboration throughout the project lifecycle.*
- **CP7. Digital Stakeholder Communication and Collaboration:** *The ability to foster and maintain professional, technology-supported relationships with internal and external stakeholders. This includes using digital platforms to support information exchange, facilitate joint decision-making, and ensure consistent alignment of objectives across diverse project actors in construction delivery.*
- **CP8. Digital Innovation and Creativity in Smart Construction:** *The ability to champion innovation and creative problem-solving through the strategic use of digital tools and emerging technologies. This includes designing new workflows, promoting experimentation, and embedding a culture of continuous improvement and digital advancement within smart construction environments.*