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Construction 4.0 Digital Maturity Model Development

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Construction 4.0 Maturity Model Development

Dissertation

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DISSERTATION DECLARATION

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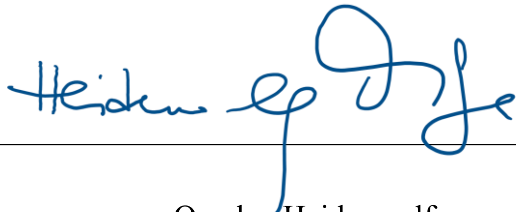

Orsolya Heidenwolf

Abstract

The construction industry faces growing pressure to adopt efficient tools and processes to meet the demands of providing solutions for labour shortages, rising global population, sustainability goals and technological backlog. These challenges manifest a significant economic impact on construction companies, resulting in only a one per cent productivity increase until 2020. A growing body of literature has been published focusing on Construction 4.0, which offers promising solutions. This phenomenon encompasses integrating advanced technologies, including Artificial Intelligence, Building Information Modelling, the Internet of Things, and Construction Robotics, to address productivity and sustainability challenges. Despite technological advancements, a significant research gap exists in developing a systematic approach to integrate diverse technologies effectively. This indicates a need to understand the various pillars of construction companies' digital maturity that can further drive the industry’s productivity.

The present dissertation aims to address the identified gap by developing a Construction 4.0 Digital Maturity Model. The purpose of the Construction 4.0 Maturity Model is to provide a robust framework for evaluating digital transformation in construction companies. The C4MM has been demonstrated to offer distinct advantages in addressing integration challenges, identifying areas for improvement, solving problems resulting from Construction 4.0, and implementing targeted strategies to enhance productivity and innovation. By applying Design Science methodology, this dissertation aims to create a C4MM that addresses these gaps and provides a robust framework for evaluating digital transformation in the construction sector. The dissertation follows an iterative process during model development through literature review, qualitative research, ontology development, and case studies.

The results of the final iteration evaluate the following six key dimensions: Culture and Knowledge Management, Digital Synchronisation, IT Management, Organisation and Structure, Process Management, and Technology for Construction 4.0. Applying ontology engineering ensured precise model verification and provided a machine-readable format to be the foundation of an AI-based maturity assessment system development.

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ABBREVIATIONS

AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
BPMN	Business Process Management
CDE	Common Data Environment –
C4	Construction 4.0
CI	Construction industry
C4MM	Construction 4.0 Maturity Model
CI	Construction Industry
DMM	Digital Maturity Model
DS	Design Science
DSR	Design Science Research
DT	Digital Transformation
FOL	First Order Logic
GIS	Geographic Information System
I4	Industry 4.0
IoT	Internet of Things
IFC	Industry Foundation Class
MM	Maturity model
OWL	Web Ontology Language
RDF	Resource Description Framework
RM	Readiness model
RQ	Research question
SME	Small and Medium Enterprise
SnePS	Semantic Network Processing System
SDG	Sustainable Development Goal
SWRL	Semantic Web Rule Language
URI	Universal Resource Identifier
VDC	Virtual Design Construction
VR	Virtual Reality
XR	Extended Reality

1. INTRODUCTION

The Construction industry (CI) contributes 13% of the world's GDP. In the last two decades, productivity has increased by only 1%, which has macro-level consequences. In 2020, the United Nations report showed that the CI is responsible for 37% of energy-related carbon emissions (Alliance for Buildings and Construction 2020) due to its inefficiency and high-emission supply chain.

In 2023, the recent construction productivity report from RICS still shows that global construction productivity has significantly declined. The last published research revealed that only 9% of respondents expected productivity growth in the next 12 months compared to 21% in the past year, reflecting a broader slowdown in construction activity (RICS 2023). Furthermore, the sector continues to confront obstacles in reducing its carbon footprint. The Global Alliance for Buildings and Construction, an organisation dedicated to zero-emission construction, has published a report that suggests the industry is unlikely to achieve this goal by 2050 (Global Alliance for Buildings and Construction 2023).[1]

With the pressure of a growing population and sustainability requirements, the CI needs the most efficient tools and processes to quickly catch up with this technological backlog, for the CI to be able to take advantage of the steps related to climate change as soon as possible, so that as many companies as possible must operate efficiently in the whole supply chain. Two Sustainable Development Goals (SDGs) have been identified as key factors in enhancing CI's sustainability: industry, innovation and infrastructure (SDG9) and sustainable cities and communities (SDG11). Several studies have focused on assisting the CI in achieving these goals.

SDG9 can be achieved through sustainable construction procurement (Joensuu et al. 2020) and stakeholder management (Rwelamila et al. 2000) or newly developed construction materials (Omer and Noguchi 2020). Lean project management, on-site industrialisation, standardisation, prefabrication, and modularisation (Li et al. 2020),

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[1] This paragraph was published in (Heidenwolf et al. 2024)

combined with digital twin (Khahro et al. 2021) and machine learning, can contribute to building our environment more sustainably, while I4 technologies and nanotechnology emerging are tools to create new construction materials (Kor et al. 2023).

Data generated during the CI can be particularly utilised by SDG11 and support better energy consumption analysis (Wei et al. 2018). The sustainable design of buildings and the construction of a sustainable city are supported by technologies such as generative design, 3D printing, AI and Augmented Reality (AR). The circular economy concept provides new solutions for achieving SDG11 (Joensuu et al. 2020). Sustainable city construction has already been supported by several technology giants, such as Google's Environmental Insight Explorer or Microsoft and Bentley to Develop Digital Twins for Sustainable Urban Planning.

Nevertheless, the rate of technological advancement is relatively slow, which could potentially impact the attainment of the desired objectives and the emergence of several challenges associated with implementing and effectively utilising these solutions. The future of CI is subject to influence from several industries (Bock 2015). The I4 concept has recently emerged in the context of CI; however, the CI is experiencing difficulties in adapting this concept, particularly in low-income countries (Maskuriy et al. 2019), which can only be operationalised if all organisations in the value chain adopt a digitalisation approach (Newman et al. 2020). The CI must align with the concept through technological support (Klinc and Turk 2019) and the support of higher education (Rivera et al. 2020) to understand and successfully implement digital transformation efforts. The continuously growing number of new technologies brings additional risk for organisations and projects (Davila Delgado et al. 2019). The traditional organisational structures represent a significant obstacle to implementing these technological solutions (Joensuu et al. 2020). The advent of blockchain technology has necessitated the development of novel business models, the acquisition of skilled human capital, and a rethinking of traditional procurement methods (Tezel et al. 2020; Turner et al. 2021). Furthermore, integrating new technologies necessitates applying data-driven approaches (Wei et al. 2018), where data generation and transmission can be key processes in this highly fragmented industry (Turner et al. 2021). However, data, in turn, raises further security concerns (Li et al. 2019), including data theft (Maskuriy et al. 2019). As the collaboration of technologies further complicates this evolving status, dominant technologies impacts are increasing

(Ernstsen et al. 2021).

In recent years, a growing body of literature has focused on C4 technologies and methodologies. C4 represents the CI's digital transformation (DT), drawing upon the principles of Industry 4.0 (I4). It encompasses integrating advanced technologies, such as BIM, IoT, AI, robotics, and big data analytics, to enhance productivity, efficiency, and sustainability in construction projects (Jaafar et al. 2024). Alongside the concept of C4, many innovations have emerged to drive the sector towards a more efficient, sustainable vision (Schönbeck et al. 2020) and solve labour shortage problems (Sadeh et al. 2024). Furthermore, integrating diverse technologies and methods can significantly influence the future of the built environment, potentially addressing environmental challenges (Haghighat and Sadeh 2023). However, despite the potential benefits, construction organisations face several unexpected challenges in systematically implementing these technologies (Osunsanmi et al. 2020; Nagy et al. 2021). These challenges are primarily due to a lack of digital maturity, which prevents organisations from fully leveraging the advantages of these advanced technologies. In order to address these challenges, this dissertation aims to outline and provide solutions to the problems of middle and senior management in the CI resulting from innovation and DT challenges with the Construction 4.0 Maturity Model (C4MM).

Several digital maturity and readiness models have been developed to assess how companies have embraced digitalisation and facilitated their seamless adoption of I4 technologies. These models employ a variety of evaluation criteria, which are shaped by the perspectives of the creators. These include factors such as the technological focus of the model, the availability of specific functional data, and data-driven methodologies. I use these models as a benchmark to create the C4MM. While these models have identified connections between technologies and company characteristics, including processes, human resources, and financial assets, the formalisation of these relationships has been limited. Ontologies eliminate ambiguity and enable consistent knowledge representation, supporting automated reasoning, reuse, and interoperability in intelligent systems. Ontologies are not merely hierarchical taxonomies; they are graph-based, logic-driven models capable of semantic reasoning, interoperability, and reuse across intelligent systems. Ontology development methods provide a structured approach to explicitly achieve this formalisation, which was applied to the developed C4MM to formalise these relationships.

Following the introductory chapter, the dissertation comprises seven chapters. Chapter 2 outlines the research background, beginning with the problem statement (2.1) and continuing with the research objective and framework (2.2), including the integration of various strategies within the Design Science Research Framework (2.2.1). The research questions and methodology are addressed in Section 2.3, with subsections detailing the approaches used for each research question (2.3.1–2.3.2), the maturity model building process (2.3.3), its validation using ontology (2.3.4), case study (2.3.5), qualitative interviews (2.3.6), and a summary of methodologies (2.3.7). Sections 2.4 and 2.5 articulate the motivation and relevance of the study.

Chapter 3 presents the theoretical foundation, introducing key concepts of Industry 4.0 (3.1), Construction 4.0 (3.2), and the challenges related to Construction 4.0 (3.2.2). Section 3.3 highlights the significance of digital maturity models in the construction industry context.

Chapter 4 explains the six-step artefact design and development process, detailing inputs, outputs, methodologies, and knowledge sources. Section 4.1 justifies the development of C4MM, exploring technological changes and their implications for CI’s organisations. Section 4.2 introduces the developed maturity model requirements. Section 4.3 introduces the C4MM version 1 design through literature review (4.3.1) and development with a case study (4.3.2). Section 4.4 explains the second design phase with systematic literature review (4.4.1-4.4.2) and the development of this model with ontology building (4.4.3), and qualitative findings (4.4.4). Sections 4.5–4.6 discuss the developed artefact's future demonstration and evaluation phase.

Chapter 5 discusses research findings, including key findings (5.1), the integration with existing literature (5.2), the role of ontology in this research (5.3), the unexpected results (5.4), the limitations and practical implications (5.5-5.6).

Chapter 6 concludes with key insights and directions for future research.

2. RESEARCH BACKGROUND [2]

Digital transformation describes integrating information, storage, communication, and networking technologies to revolutionise services, which involves replacing manual processes with digital solutions or updating outdated digital technologies to the latest versions (Maki et al. 2022). [3]

The European Parliament has released the 2030 Digital Compass, which identifies the construction sector as one of the five key ecosystems in the DT process. The report emphasises that the CI had the lowest productivity of all major sectors in the last 20 years. Executives believe new production technologies and digitalisation can drive change (European Commission 2021).

Digital transformation has demonstrated significant benefits in the CI, including improved productivity, enhanced stakeholder collaboration, and better integration of people, processes, and contexts (Klinc and Turk 2019). However, the industry faces challenges such as high initial investments, technological complexity, and the need for appropriate policies and infrastructure to support adopting new technologies (Statsenko et al. 2023).[4]

The phenomenon of C4, which has emerged as a consequence of DT in the CI, represents a novel industrial transformation in this field. An emerging number of studies have recently been published on C4 phenomena. In this dissertation, C4 is defined as a new construction ecosystem that incorporates (1) integrated technologies and cyber-physical systems (Anil Sawhney et al. 2020; Karmakar and Delhi 2021), (2) methods and processes (Schönbeck et al. 2020; Yang et al. 2022), and (3) human resource competencies (Yang et al. 2022). These three pillars are supported by automation and data analytics. In this ecosystem, achieving sustainability is a crucial objective for industry players, and it can be attained by improving the efficiency and productivity of construction processes. However, only a few studies have addressed the systematic integration of C4 into the construction organisations' life cycle and tools that can support

[2] This section was partly published in (Heidenwolf and Szabó 2024a)
[3] This paragraph was published in (Heidenwolf et al. 2024)
[4] This paragraph was published in (Heidenwolf et al. 2024)

companies in this endeavour (van der Heijden 2023).

The strategic implementation of C4 requires a shift in management mindset towards digitalisation (Maskuriy et al. 2019) and the effective use of a toolset that supports DT. One such tool is a maturity model (MM), which helps assess a company's evolution stage-by-stage in a specific area (Gökalp and Martinez 2022). Building Information Modelling (BIM) can also contribute to digitalisation endeavours, but researchers studied the BIM Maturity Matrix from the designers' perspective rather than general contractors or subcontractors (Jason and Umit 2010; Ferraz et al. 2020). Furthermore, these matrices often lack important domains from the contractor's perspective, such as technology management, business applications, innovation, or business processes. Contractors play a crucial role in the built environment as they are responsible for creating the physical product, such as buildings.

Digital maturity models (DMM) facilitate a smooth transition to a digital-first approach that enhances organisational performance and competitiveness (Peerally et al. 2022). These models are tools for top management to set strategic goals for organisations (Bellantuono et al. 2021), including procedures to achieve success (Basulo Ribeiro et al. 2023). A desired level of digital maturity can be the objective of the MM assessment, which can then be used to identify and prioritise specific actions that will facilitate progress (Thordsen and Bick 2023). Mapping the current maturity stage of a company with ontology can serve as a guideline for industry practitioners (Mora-Alvarez et al. 2023). [5]

In this era, the following two definitions can be distinguished: the readiness and maturity models. "*While maturity models aim to portray the current maturity level of the organization, readiness models look to understand if organizations are ready to begin the adoption process*" (P. Senna et al. 2023, pp. 9).

A readiness assessment is *" the systemic analysis of an organisation's ability to cope with and undertake a transformational process or change is defined as measuring or assessing readiness "* (Pirola et al. 2020, pp. 1047). The assessment serves as a guideline for organisations to understand whether they are prepared to start the DT process

[5] This paragraph was published in (Heidenwolf et al. 2024)

(Chirumalla 2021; Saad et al. 2021; Haryanti et al. 2023), and helps to understand the weak points of the organisation (Pirola et al. 2020).

On the other hand, digital maturity represents the current state of the organisation's DT journey (Chirumalla 2021; Zaoui and Souissi 2022; Thordsen and Bick 2023; Haryanti et al. 2024) that includes technological and social aspects (Schumacher and Sihn 2020). It has three goals: (1) analyse and understand the adapted technologies in terms of DT (Zaoui and Souissi 2022; P. Senna et al. 2023; Thordsen and Bick 2023), (2) provide guidance for the digital strategy and its objectives (Zaoui and Souissi 2022; P. Senna et al. 2023), and (3) help companies to explore their current state compared to other market players (P. Senna et al. 2023) to remain competitive in the market. " *on the assumptions of predictable patterns and represent theories about how organizational capacities evolve gradually, according to an anticipated, desired, or a logical maturation approach* " (Ferraz et al. 2020, pp. 507) . These models are tools to help organisations analyse their current state in the evolution of DT (Colli et al. 2019; Amaral and Peças 2021; Thomson et al. 2022; Thordsen and Bick 2023) from different aspects (Santos and Martinho 2020), and maturity stages or levels (Hortovanyi et al. 2023). Thus, MMs serve as strategic diagnostic tools to overcome the challenges and understand the priority development fields of the organisation in the DT journey (Kırmızı and Kocaoglu 2022).

Maturity and readiness models are both valuable tools for assessing an organisation's capacity for change and development in the DT journey, although they differ in scope and application. MMs assess long-term organisational development by analysing organisations' current state in the evolution of DT. In contrast, RMs provide a picture of the current state and are focused on short-term development. While both models provide a guideline for organisational assessment, I believe MMs offer greater value by using them as a diagnostic tool to support companies' long-term strategic development and success. MMs provide a roadmap for building capability across the organisation, supporting more significant changes in culture and processes over time. RMs are more useful for making immediate decisions about whether the organisation is ready to begin the DT journey and lacks this ongoing development focus. Hence, I have chosen to focus on the MM rather than the RM in my dissertation.

2.1. Problem Statement

Construction companies lag significantly behind other industries, which manifests itself in inefficiency and has a significant economic impact on companies (Barbosa et al. 2017). This inefficiency resulted from outdated technologies and processes, the lack of an educated workforce, labour shortage and unskilled labourers. The implementation of technology has the potential to significantly improve the efficiency of this transforming industry and drive the sector towards a more efficient and sustainable vision (Schönbeck et al. 2020). Using innovative technologies can lead to substantial reductions in costs, address environmental challenges (Haghighat and Sadeh 2023), provide solutions for labour shortages (Sadeh et al. 2024) and help the sector to increase productivity. Despite advancements in C4, most construction firms face significant challenges in integrating these tools and technologies effectively (Oesterreich & Teuteberg, 2016). Qualitative research revealed three key factors that hinder industry transformation: (1) management rejects technology due to a lack of experience, (2) the implementation of technology in the absence of process innovation fails, and (3) the lack of skills and competencies in new technologies (Nagy et al. 2021).

The lack of a comprehensive and systematic approach to assessing DT maturity hinders strategic alignment and continuous improvement (Chen et al. 2023). Several digital maturity and readiness models have been developed to assess how companies have embraced digitalisation and facilitated their seamless adoption of C4 technologies. Existing MMs frequently fail to adequately address the inherent complexity and multifaceted nature of C4, which ultimately leaves organisations without clear guidance in their digital journeys. These models adopt different approaches, with some focusing on general technology (Ribeiro et al. 2022; Chen et al. 2023) and others addressing specific technologies in greater depth, such as BIM (Joblot et al. 2019; Ferraz et al. 2020; Yilmaz et al. 2023; Chen et al. 2024) or AR/VR (Monla et al. 2023). Some models adopt a narrow focus, concentrating solely on the project's maturity in specific areas, such as site maturity (Wernicke et al. 2023), health and safety (Oswald and Lingard 2019; Asah-Kissiedu et al. 2023), or project management (Lin et al. 2022). Offsite construction MMs focus on production (Bendi et al. 2021), whereas industrialised construction MMs measure the different technological applications by use cases (Razkenari and Kibert 2022). Recently, researchers have focused on developing general MMs for CI organisations (Bou Hatoum et al. 2022; Das et al. 2022; Perera et al. 2023; Han et al. 2024; Zhu et al. 2024). However, these models apply various evaluation criteria, which are shaped by the perspectives of the creators involved.

Although these studies have identified connections between technologies and company characteristics, including strategy, processes, human resources, or innovations, the formalisation of these relationships has been limited. The ontology development method provides an explicit, structured approach to achieving this formalisation.

A developed C4MM enables managers to guide their company through the DT journey, identify areas for improvement, solve problems resulting from C4, and implement targeted strategies to enhance productivity and innovation. By applying DS methodology, this dissertation aims to create a C4MM that addresses these gaps and provides a robust framework for evaluating DT in the construction sector. Applying ontology engineering within the C4MM ensures precise model verification and provides a machine-readable format to be the foundation of an AI-based maturity assessment system development.

2.2. Research Objective and Research Framework

Construction companies lag significantly behind other industries in digitalisation, which manifests itself in inefficiency and has a significant economic impact on companies. Therefore, I believe the first challenge of CI is that companies and managers are unaware of what digitalisation means in CI, which could be clarified by the concept of C4. Second, the CI is becoming less and less attractive to the new generation, generating persistent labour shortages and becoming an ageing industry. A DT can be a tool which could help make the CI more appealing to the new generation. Third, I see it as a problem to identify the digital maturity of each construction company. An industry-specific digital maturity model (DMM) would guide companies in developing a more efficient operating model that would bring new technologies into the lives of companies and entirely new processes and knowledge.

Design Science (DS) produces an artefact in the form of a model (Hevner et al. 2004). This methodology is widely used for DMM building. For instance, this methodology has been applied by Thordsen and Bick (2023) and Haryanti et al. (2024). In Design Science Research (DS), the design *" focuses on the use of scientific principles, technical information and imagination in the definition of a structure "* (van der Merwe et al. 2020, pp. 1). It aims to formulate cutting-edge developments to characterise the theoretical frameworks, operational methodologies, technological competencies, and tools (Hevner et al. 2004).

The DS framework serves as a guideline for the dissertation. It structures the study around developing and evaluating a Construction 4.0 maturity model. The C4 environment business needs and the applied knowledge base support the information science research. Anchored in real-world organisational and technological contexts, the framework addresses business needs and contributes applied knowledge to the academic knowledge base during the research process. It follows an iterative approach during the Develop/Build phase, where the maturity model is designed, and a Justify/Evaluate phase, where the artefact is empirically assessed and refined. This process is methodologically supported by foundational inputs such as literature and insights from industry experts. It draws on qualitative and mixed-methods techniques, including Grounded Theory, case studies, ontology engineering, expert interviews, and thematic content analysis. (Fig. 1).

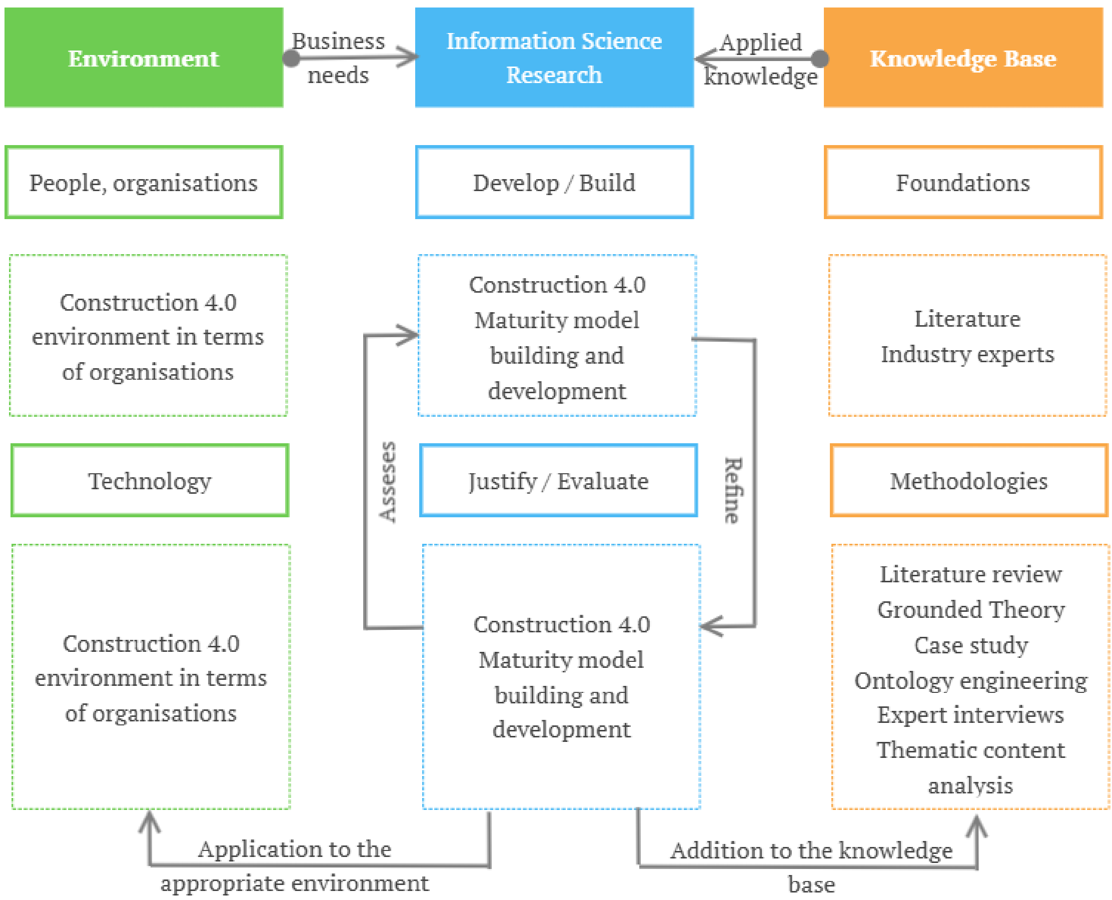

Figure 1 Design Science Research framework based on Hevner et. al. (2004)

2.2.1. *Application of DSR in Maturity Model Building*

In addition to describing the research framework, the presentation of the methodological requirements and the application of the MM in the DSR context, along with the methodologies associated with these steps, play an important role in supporting the final research goal.

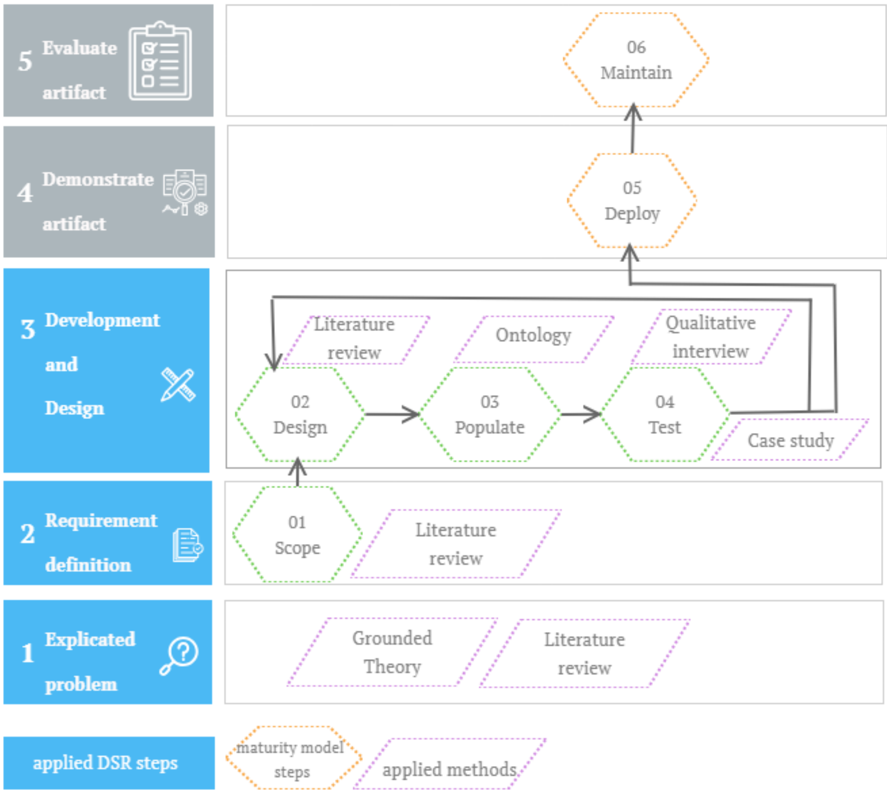

Figure 2 Research strategies application in the DSR framework

Figure 2 illustrates the research strategies' application in the DSR framework. DSR applies the following five steps: (1) The Explicate Problem activity involves identifying and justifying a significant practical problem for both local and global contexts, (2) requirement definition involves outlining a solution as an artefact and transforming the explicated problem into specific demands research, (3) design and develop artefact activity involves creating an artefact that addresses the explicated problem and meets the defined requirements, (4) the demonstration involves using the developed artefact in a real-life or illustrative case to prove its feasibility and show that it can solve an instance of the problem, and finally (5) evaluation assesses how effectively the artefact meets the requirements and addresses the practical problem that motivated the research (Johannesson and Perjons 2014). This dissertation applies the first three steps in DSR.

In this research context, I have identified key steps (illustrated by hexagons in Fig. 3) of the MM building proposed by de Bruin et al., 2005. These stages are as follows: (1) scope, (2) design, (3) populate, (4) test, (5) deploy, and (6) maintain. The figure illustrates the iterative process of model building, which is repeated multiple times throughout the research project to refine and adapt the continuously evolving model. The supplementary research methods and strategies employed at each stage are indicated in purple. These include literature review, grounded theory, ontology development, qualitative interviews and case study. The following paragraphs will introduce these research strategies in detail.

2.2.2. Research Questions and Relevance

This dissertation aims to develop a digital maturity model tailored to the construction industry, serving as the foundation for an AI-based assessment tool designed to address challenges arising from innovation and digital transformation initiatives. It outlines and provides solutions to the problems of middle and senior management in the CI resulting from innovation and DT challenges with the C4MM.

Table 1 outlines the summary of the research questions (RQ). RQ1 examines the C4 environment by investigating the C4 paradigm in the organisational context, its definition, challenges and solutions through qualitative Grounded Theory research. Following an understanding of the phenomenon, a more profound comprehension of the industry was obtained by examining the value chain and emerging technologies. Through a literature review, RQ2 examines the C4 environment from a technological perspective across the value chain. These technologies will be part of the final developed MM. After clarification and a deeper understanding of the environment, RQ3 supports creating the MM by answering questions about the factors that influence the C4MM in the CI using mixed methods, including ontology development and case studies. RQ3.1 seeks to validate the model through ontology, and RQ3.2 through a case study. Finally, RQ4 focuses on the correlations and characterisation of the C4MM and how they can be explored on the basis of input from industrial experts. This structured approach aims to understand and validate C4MM and its implications for the CI.

Table 1 Summary of the Research Questions

No.	Research Question	Methodology	Method
RQ1	*What is C4, and what are its challenges and solutions?*	Qualitative Research	Grounded Theory
RQ2	*What solutions do innovations bring through the CI value chain?*	Mixed methods	Literature Review
RQ3	*What factors influence the C4MM in the CI? How to characterise and formalise construction companies' technology adaptation maturity?*		Systematic literature review
RQ3.1	*How can the C4MM be validated by ontology?*	Design Science Research / Ontology Engineering	Ontology development
RQ3.2	*How can the C4MM be validated by a case study?*	Qualitative Research	Case study
RQ4	*What correlations and characterisation of the C4MM can be explored on the basis of input from industrial experts?*	Qualitative Research	Expert Interviews / Thematic Analysis

The following paragraphs will introduce the research process and applied methods for each RQ.

2.3. Research Methodology

2.3.1. RQ1 - What is C4, and what are its challenges and solutions?[6]

Grounded Theory is a methodology-based strategy that was chosen to explain what C4 is and the challenges and opportunities C4 can bring. Grounded Theory is a systematic method to explain a particular phenomenon with the increasing information obtained during the research (Glaser and Strauss 1967). The systematic discovery of the theory included data collection and analysis, process analysis, constant comparison between the data and the emerging theory, theoretical sampling to confirm the originally formulated categories with the new data and theoretical coding (Bryant 2017). During the research, constant iteration was applied to identify the final theory (Nagy et al. 2021).

Figure 3 illustrates the research process, method, IT tools, and timing. The research process included the following tasks: data collection, transcription, data management, data analysis, drawing conclusions, and concept verification.

6 Note: a part of this paragraph was published in (Nagy et al. 2021)

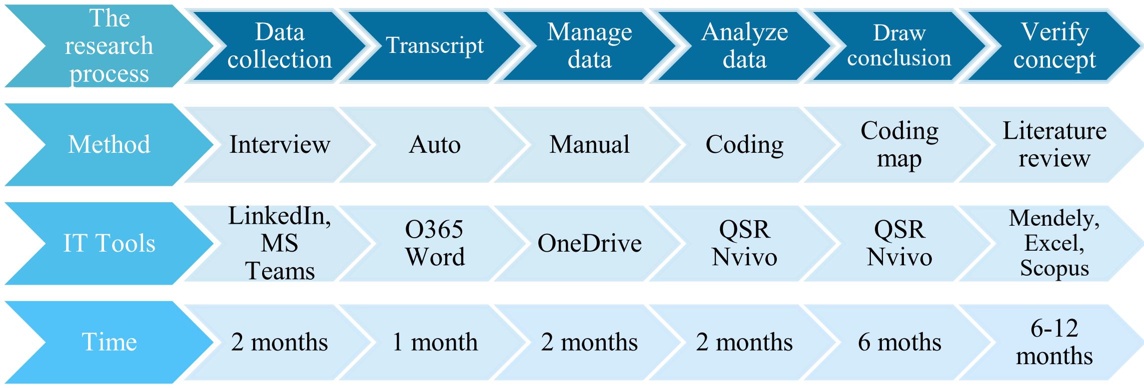

Figure 3 The Grounded Theory research process

The data collection method included semi-structured interviews with CI experts. The interviews were recorded with Microsoft Teams, while Microsoft Office 365 Word was used for automatic transcription. Experts were selected based on their experience from their LinkedIn profiles. The snowball technique was also applied to find further experts in the field (Biernacki and Waldorf 1981). The expert selection considered the following aspects: company size (multinational enterprises, large domestic companies and small and medium enterprises), business field, and experience. The selection considered six dominant industries: CI, electronic automotive industry, IT, manufacturing, government, and real estate. C4 represented a complete paradigm shift within the market during the research (October 2020 – January 2021). In selecting the relevant actors, it was hypothesised that numerous new industries would enter the construction market. Therefore, in addition to the construction sector, the IT area and emerging construction software vendors were considered. In addition, construction manufacturers, including those specialising in prefabrication, public actors involved in construction policy, the real estate development sector closely linked to the BIM field, and the electric car industry, which has entered into large-scale investment in the construction sector, were also considered. These stakeholders were chosen, and anonymity and confidentiality were assured for the interviewees.

An interview guideline was formulated to navigate the research. Kvale's (1996) recommendations were applied during the development of qualitative research. Data management included the audio files and the transcribed document management in OneDrive. QSR NVivo software supports coding and in-depth text analysis to apply grounded theory during the data analysis. Coding was divided into three phases: open, axial, and selective coding (Miles Matthew and Hubermann A. Michael 1984). The next phase of the research included the creation of concept maps using QSR NVivo software. These concept maps have supported the creation of the theories and further research directions. During this research, constant iteration was applied to identify the final theory. This part is called theoretical sampling or concept verification. At this stage, a literature review was applied, as introduced by Bandara et al. (2011).

By answering RQ1, we can understand the C4 environment and its challenges and solutions and see where we would like to integrate our MM.

2.3.2. RQ2 - What solutions do innovations bring through the CI value chain?

During the pre-empirical stage of the research, **a literature review was conducted** in the field of innovations through the CI value chain. A systematic literature review is a structured approach to identify, evaluate and synthesise research (vom Brocke et al. 2015). Figure 4 Research Process for RQ1 illustrates the main process, method and IT tools in this phase.

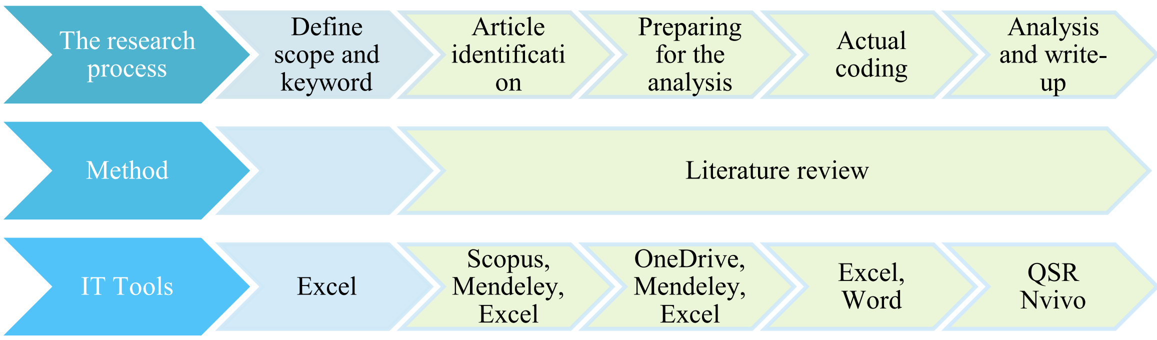

Figure 4 Research Process for RQ1

During the literature review process, vom Brocke et. al's (2015) recommendations were applied to define the scope of the search and the keywords. The scope of this research was to understand what solutions innovation has brought through the CI value chain. As a first step, Year One Report Towards a Digital Built Britain (2018) was used as an initial point of the research. This report provided a complex summary of the construction industry project-life cycle digital transformation and was used to define keywords that guided the research literature review (Fig. 5).

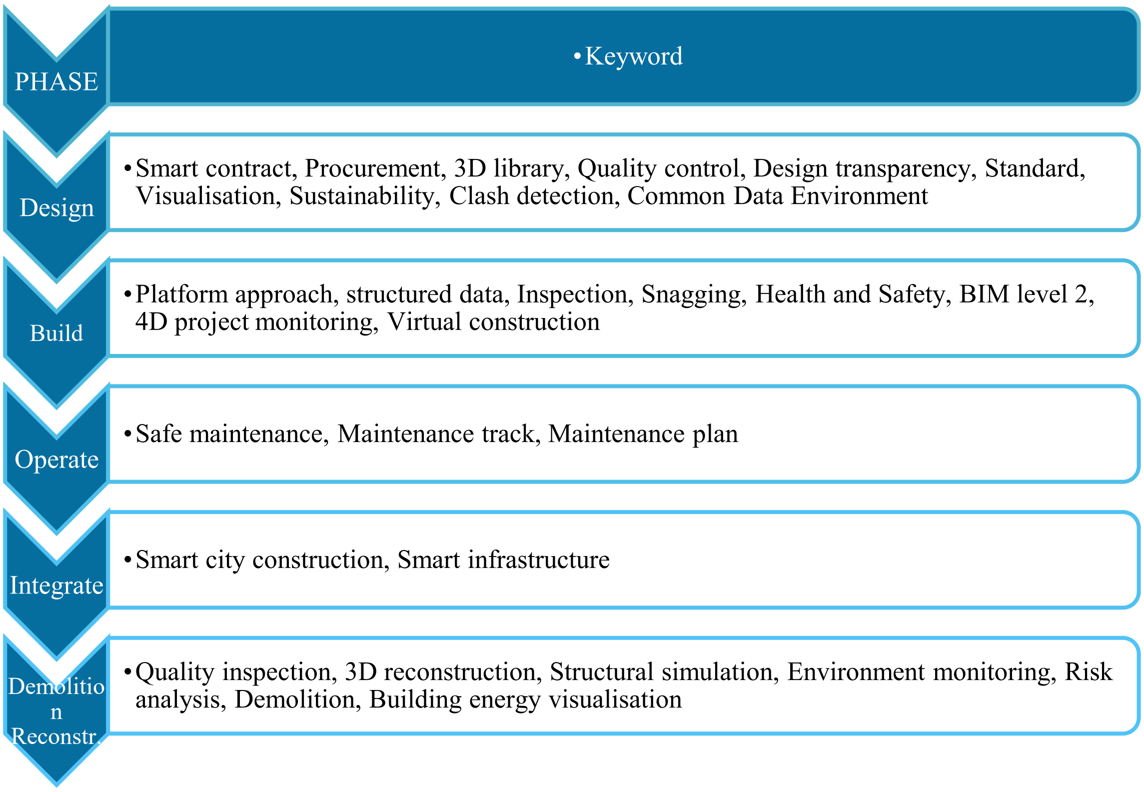

Figure 5 Defined search keywords for RQ2

The literature review for the research was conducted in 2021 in four phases (Bandara et al. 2011). Phase I involved the identification and extraction of articles. The domain of interest considered in this step included the year of publication from 2019 to 2021, the publication type, which should be an article or case study in leading journals in the CI field (Q1 or Q2). The defined keywords were applied to search for those in the article's abstract or title for the search strategy. After pre-screening the articles, forward and backwards searches were applied based on the citations identified. Phase 2 involved preparing an analysis by reviewing each paper based on the initial scope and keywords. Webster and Watson (2002) proposed a concept matrix during the literature review process that should include the article titles and retrieved concepts in a matrix structure that supports summarising similar topics. In phase 3, this concept matrix was developed to support summarising similar concepts by filtering them in Excel (Table 2). Table 2 Concept matrix for RQ1 based on (Webster and Watson 2002).

Table 2 Concept matrix for RQ1

Article title		Article 1		Article 2	
Journal		Journal name 1		Journal name 2	
Document type		Case study / Research paper		Case study / Research paper	
Technology		Technology description1		Technology description2	
Construction phase	**Search term**	**Value proposition/ opportunity**	**Challenges, barriers, hindering factors, and obstacles**	**Value proposition/opportunity**	**Challenges, barriers, hindering factors, and obstacles**
Design/Build/Operate/integrate/Demolition	ex.: Snagging	Details from papers	Details from papers	Details from papers	Details from papers

The final phase of the literature review included analysis and writing up the findings. The answer to the RQ indicates that the emerging technologies, innovations, and processes in the context of C4 represent a fundamental point of origin for subsequent model construction. Section 4.1.2 will introduce this research in detail.

2.3.3. RQ3: What factors influence the C4MM in the CI? How to characterise and formalise construction companies' technology adaptation readiness?

The first two research questions(RQ) provided a framework for the third research question. RQ1 explored the barriers organisations face in terms of people and processes in Construction 4.0 (C4), and the second research question answered the question of what technologies appear in this phenomenon to solve challenges during the project life-cycle. Thus, the RQ3 goal was to solve the explored challenges with a new tool, the C4MM.

RQ3 provides the framework for developing the C4MM (Figure 6).Construction 4.0 Maturity Model (Figure 6). In the first development phase, a draft version of the model (C4MM v0) was created, followed by C4MM v1, which was informed by a comprehensive literature review. This version was subsequently tested through a case study (RQ3.2).

The second development phase involved a more complex and iterative workflow. C4MM v2 was developed based on a systematic literature review. In the first stage of this phase, the model's categories and elements were defined, followed by the development of the maturity levels. The categories and elements also served as the foundation for constructing the C4MM v2 ontology (RQ3.1). These components and the maturity levels were subsequently used to guide the coding process in the qualitative data analysis (RQ4).

Finally, the third version of the model (C4MM v3) was developed. This version represents a more refined conceptual framework, which will be further developed in future research beyond the scope of this dissertation.

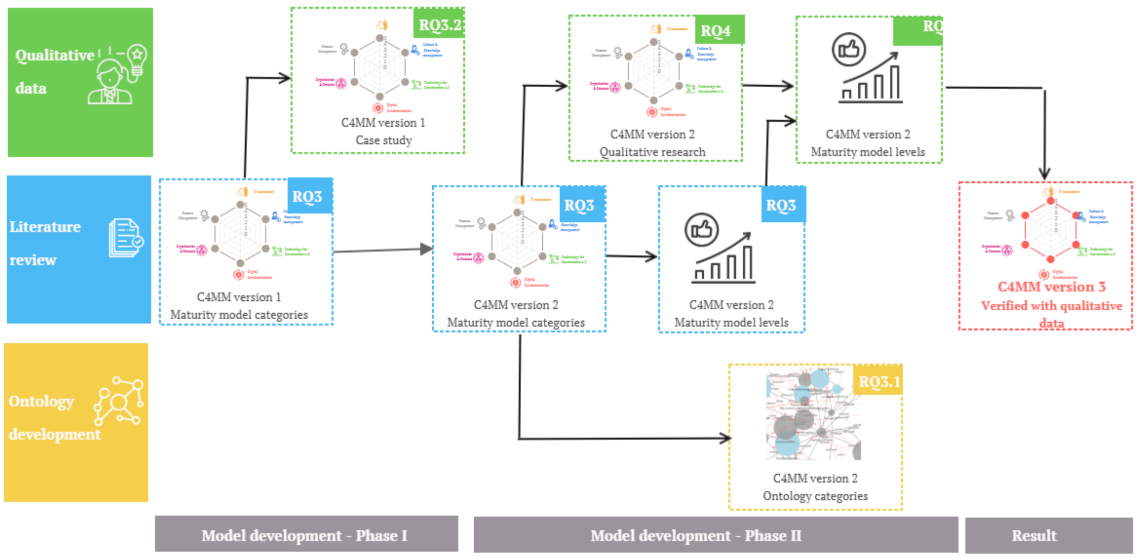

Figure 6 Model development phases and research questions

2.3.3.1. Literature review – Phase I

In developing the initial model, relatively limited literature was available. Therefore, to construct the zeroth version of the model, I relied on the three most frequently cited I4 maturity models, which I supplemented with the definition of C4. This zeroth version served as a preliminary conceptual framework and guided the subsequent literature review that informed the development of the first model version.

A literature review was conducted in 2022 during the development process using the following keywords to identify relevant literature: 'Industry 4.0 maturity model", "Industry 4.0 readiness", "Construction maturity model", "Construction 4.0 readiness", and "Construction 4.0 business model". The literature review identified 22 relevant articles in the field of I4 and only three in the CI. A matrix was created during the review to establish the main categories of the C4MM. These categories supported the next development phase, where further literature was identified using the following keywords:

category name (technology, culture, change management, innovation, IT), and/or maturity model/readiness model, and construction (Heidenwolf and Szabó, 2024a).

2.3.3.2. Systematic literature review – Phase II

In the second phase, a comprehensive literature review was conducted to delineate the specifics of each model element. The second iterative round was further substantiated by the observation that numerous elements of the model constructed in the first iterative round were only partially defined by the limited available literature on digital maturity in the construction field.

A systematic literature review was conducted to elucidate and delineate the components of Digital Maturity Models and Readiness Models within the contexts of I4 and C4. The process followed the PRISMA method (Page et al. 2021). During this process, we integrated various research databases, pre-screening tools, manual searches, and coding techniques to ensure a comprehensive and refined set of relevant literature. This systematic approach culminated in developing a robust maturity model verified through ontology classification. Figure 7 represents the systematic literature review process.

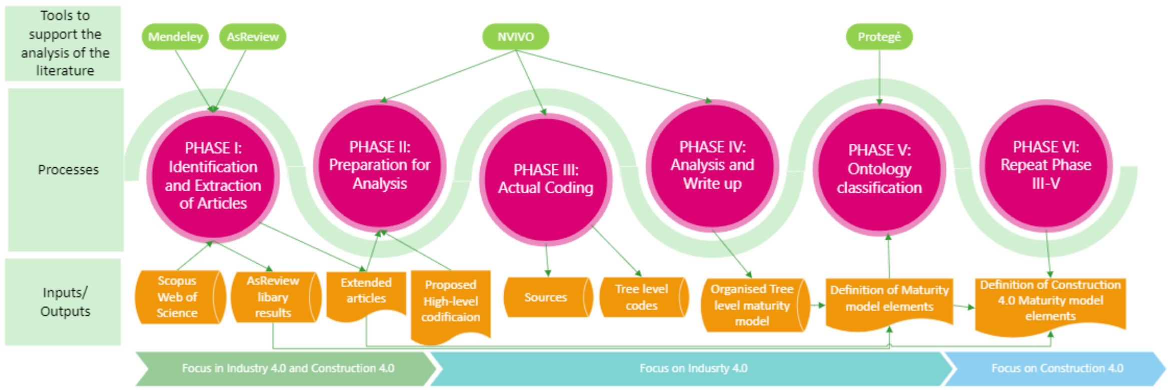

Figure 7 Overview of the literature review approach based on (Bandara et al. 2011)

I divided the process into three main parts (Fig. 11). In the first part, we focused on both I4 and C4MMs. After finding relevant literature, I first created two groups, and we processed and analysed I4-related maturity models. I then used those results as a benchmark and repeated the steps with C4MM articles.

The first phase of the literature review process commenced with keyword searches, which yielded 500 results from Scopus and 444 from Web of Science research databases. These were then reduced to 564 unique articles after the removal of duplicates. Next, the articles were subjected to a preliminary screening where I applied asReview, an open-source machine learning application (van de Schoot et al. 2021), to identify relevant papers. This step reduced the number to 230 by evaluating the abstracts and summaries. A subsequent manual screening further reduced the number to 84 articles. I prioritised Q1-Q2 journals in the Computer Science and Management fields and reduced the number of relevant articles to 51. Then, I applied a backwards and forward search on citations, resulting in 28 extra articles and three industry reports, for a total of 85.

While preparing the analysis, I categorised the results into topics about I4 (52 articles) and C4 (33 articles). A high-level codification tree was developed to identify relevant topics for model building, adhering to the recommendations provided by Gökalp et al. (2017).

During the in-depth literature review, NVivo was applied to the high-level coding of these articles, and multiple codes under the predefined high-level codes were created that supported our model building. In this step, we primarily focused on coding model elements and their definitions to see the similarities between different models.

As a first step in the literature review, the initial version of the maturity model (C4MM version 1) was used to construct a coding structure. This coding structure was then used to examine the maturity models from the literature and ascertain whether the model elements occurred or were new model elements. During this process, I was responsible for 60% of the literature review, while two other researchers conducted 40% of the literature review.

After we coded the relevant articles, we organised the results into a new tree-level maturity model. Each maturity model element was defined at three levels during this phase (category, subcategory and element). In the next phase, the ontology was used to classify and verify the model based on the developed definitions.

The results of this comprehensive review process were twofold. First, an I4 maturity model was developed, comprising elements defined from 52 articles. Second, this model was subsequently refined and adapted for C4, leveraging insights from 33 construction-specific articles and reports. We used our I4-developed model as a new high-level coding to review the C4MMs and repeated phases III-V. The results of this RQ will be introduced in Section 4.4.

2.3.4. RQ3.1: How can the C4MM be validated by ontology?

Ontology development was employed in this study as a formal method to validate the conceptual integrity and structural coherence of C4MM version 2.

2.3.4.1. Ontology definition

The term "ontology" was introduced in 1613 in Rudolf Göckel’s Lexicon philosophicum and Jacob Lorhard’s Theatrum philosophicum. However, its conceptual origins are often attributed to Aristotle by later philosophers (Smith, 2002, in Borbásné Szabó, 2013).

In the context of knowledge representation, ontology is a *"formal and explicit specification of a shared conceptualization"* (Thomas R.Gruber 1993, pp. 199). Ontologies are pivotal in enabling digital transformation (DT) across industries by providing a shared vocabulary and semantic interoperability in knowledge management (Spoladore and Pessot 2022). Ontology was chosen as the formal modelling tool because it provides a machine-interpretable, logically precise representation of theoretical constructs (Thomas R.Gruber 1993). The objective was to use ontology to conceptualise the model and ensure internal consistency, completeness, and reasoning capability across the framework's components.

The ontology consists of defined classes (concepts), properties that describe the different features of the classes (relationships), and their individuals (instances) and logical constraints (axioms or restrictions) that together constitute a semantic model interpretable by both humans and machines. These together form a knowledge base in a specific domain (Noy and McGuinness 2001).

Ontologies eliminate ambiguity and enable consistent knowledge representation, supporting automated reasoning, reuse, and interoperability in intelligent systems. Ontologies are not merely hierarchical taxonomies; they are graph-based, logic-driven models capable of semantic reasoning, interoperability, and reuse across intelligent systems (Vas, 2007).

The five core concepts in ontology are classes, attributes, instances, relationships, and axioms. Classes represent the groups or categories of entities within a domain. For instance, in construction, classes can be a "Building," "Material", or a "Worker".

Subclasses describe the main class properties more precisely and inherit the properties of the main class(es). For instance, the subclass of the “Building” can be “Residential Building”, “Commercial Building”, or another alternative for the subclass of the “Building” can be “Wooden Building” or “Brick Building”. Instances are specific examples of the classes, such as the John Hancock Tower in Chicago. Attributes help to define the characteristics of the classes. For example, the “Material” class can have properties like "Strength" or "Cost". Relationships specify the entity's relationship to other entities, such as "isPartOf" or "isConstructedBy". Finally, axioms define the constraints for the logical coherence within the ontology.

2.3.4.2. Ontology structure and methodologies

Constructing an ontology is one of the most pivotal stages in its lifecycle, and its success is fundamentally shaped by the methodology chosen. When building an ontology for a maturity model, it is crucial to articulate both the development process and the methodological framework that will guide it, considering the future use case of the ontology during model development. Ontology development can be structured in a top-down approach, a bottom-up method and a middle-out strategy depending on the intended application and context. Due to the limitations of this dissertation, I will only briefly introduce one example from each approach.

The **top-down approach** begins with broad and abstract concepts, establishing a consistent high-level framework across domains. For instance, the CommonKADS methodology, initially designed for developing knowledge-based systems, emphasises that ontology construction should be driven by the requirements of specific applications, as adopted in the **KACTUS** (Bernaras et al, 1996 in Vas, 2007), where ontologies are built through specification, content development, and structural refinement, and may later be unified if multiple application-specific ontologies exist. (Vas, 2007)

In contrast, the **bottom-up method** starts from specific and detailed elements, often derived from existing data or practical examples, allowing detailed components to emerge early in the process. For instance, the **On-To-Knowledge** methodology focuses on application-driven ontology development for enterprise knowledge management, following a structured process that includes feasibility analysis, requirement specification, iterative refinement and evaluation, and long-term maintenance to ensure the ontology remains effective and adaptable within evolving organisational contexts (Staab et al., 2001). (Vas, 2007)

Finally, the **middle-out strategy** (e.g., used by TOVE, Uschold and King, Methontology) blends both methods by identifying key core concepts first, then expanding toward more general categories and specific details, making it a flexible and balanced option for many real-world applications. For instance, **Methontology** offers a comprehensive framework for ontology development that not only defines each stage of the ontology lifecycle but also details management, development (detailed steps of ontology building including specification, concept creation, formalisation, and maintenance), and support activities, ranging from specification and conceptual modelling to implementation, evaluation, and maintenance, supported by structured documentation, configuration management, and continuous quality assurance (Corcho et al., 2003) (Vas, 2007).

Among the approaches presented above, one of the most widely adopted is the middle-out strategy, which is also applied in this dissertation. Given the nature of the maturity model, the research necessitated the development of precise domain concepts, thereby justifying the choice of this methodology. Throughout the development, the guidelines proposed by Noy and McGuinness (2001) were followed, which are discussed in detail in Section 2.3.4.4.

2.3.4.3. Ontology languages

Ontologies can be expressed in different knowledge-representation paradigms, each with a logical basis and modelling style. Thus, the choice of ontology languages fundamentally determines the formal structure of a knowledge model, its inferencing capabilities, and computational requirements. These languages are based on different logical foundations, each offering distinct advantages for representing ontological knowledge (Vas, 2007).

The four major categories of ontology languages are first-order logic-based (e.g. Cycl), frame-based (e.g. SnePS, Ontolingua, OCML, Knowledge Machine, EPILOG and Flogic), description logic-based (e.g. LOOM and PowerLoom), and web-oriented languages (Vas, 2007). Due to the limitations of this dissertation, I will only briefly introduce the two most popular web-oriented languages, namely RDF and OWL, in this dissertation.

Web-oriented languages, such as *RDF* (Resource Description Framework) and OWL (Web Ontology Language, with sublanguages: OWL Lite, OWL DL, OWL Full), focus on structuring data and exposing semantics through URIs and triples. These are well-suited for the Semantic Web, recognising the importance of interoperability and automation. (Vas, 2007)

The meaning of terms and their interrelations can be formally defined through **OWL**, a structure referred to as an ontology. OWL allows the explicit definition of classes, properties, individuals, and their logical relationships. In the OWL language, a class defines a set of individuals with shared properties, and these classes can be structured hierarchically by specifying subclasses. Properties represent either relationships between individuals or links from individuals to data values, and they can be constrained by a domain, which determines the type of subject they apply to, and a range, which specifies the type of permissible values or objects. Individuals are instances of classes and may be connected through properties, which can be characterised as inverse, transitive, symmetric, functional, or inverse functional. (McGuinness, 2003)

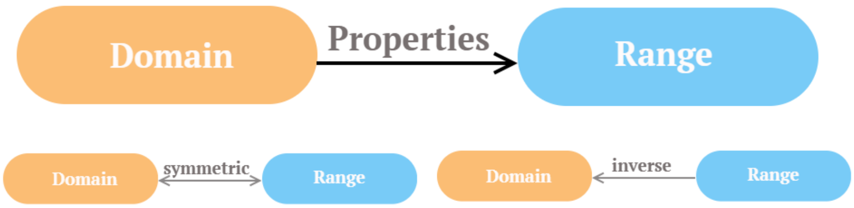

Figure 8 OWL and some property type

RDF is particularly suitable as a foundation for inference systems because it represents data using a clear triple structure (subject, predicate, object), which provides a well-structured, machine-interpretable format. This format enables the explicit definition of relationships between entities, a fundamental requirement for automated reasoning. RDF formalises the connections between objects and supports the derivation of new relationships or knowledge from existing data. Its flexibility - using URIs and the ability to specify domain and range constraints on properties - facilitates the uncovering of semantic relationships. (Champin and Lindström, 2025)

Figure 9 An RDF graph with two nodes, source: Cyganiak, R. et. al (2014)

The use of the RDF format is further justified by the Open (Linked) Data initiative supported by the European Commission.“*Linked Data is about publishing and connecting structured data on the Web, using standard Web technologies to make the connections readable by computers, enabling data from different sources to be connected and queried, allowing for better interpretation and analysis.*” (Open Data Support, 2025). Tim Berners-Lee, the creator of the Web, set out the Linked Data Principles in 2006. These state that data entities should be identified with URIs (Uniform Resource Identifier), made accessible on the Web through HTTP, provide meaningful information when accessed, and be interconnected by linking to existing URIs (Open Data Support, 2025). Using open standards such as RDF, linked data establishes connections between different datasets by referencing them with URIs (European Commission, 2014, pp. 11).

During the formalisation process of this research, the OWL language was used; however, its full expressive capabilities were not utilised. The ontology was later exported into RDF format, which, as described earlier, reduces expressive power, such as property constraints, compared to OWL. By encoding the C4MM in RDF, the maturity model becomes subject to logical validation via reasoners. This development is introduced in the following section.

2.3.4.4. The applied methodology

Ontology was selected to provide an unambiguous vocabulary and logical framework to define and connect core elements of the C4MM. It also enables consistency checks, completeness evaluations, and simulation of theoretical logic through automated reasoning (e.g., Pellet, Hermit).

The ontology was developed iteratively using Protégé and conformed to the steps outlined in ontology engineering methodologies (Noy and McGuinness 2001), adapted to Construction 4.0 maturity modelling needs.

Figure 10 The Ontology building steps by (Noy and McGuiness 2001)

During ontology development, the first step is to define the scope and domain. This step includes clearly identifying the domain, objectives, and intended applications of the ontology (Noy and McGuinness 2001). The domain of the systematic literature review provided the foundation for formulating definitions that were the foundation of the ontology.

The second step collects existing ontologies. While more and more ontologies were born in the Construction industry, I did not find any ontology in the Construction 4.0 maturity model domain. Due to the lack of existing ontologies, a new one was developed.

Then, we identified classes, subclasses, and object properties based on the definitions developed by the C4MM v2. Concepts were organised into a taxonomy to ensure logical groupings and avoid category overlap. For example, "BusinessProcess" was defined as a subclass of "Process". The definition of the class properties follows this phase. Relationships were formalised as object properties (e.g., "hasSubcategory", "influences") with defined domains and ranges. Logical constraints, such as dependency rules between knowledge management and collaboration, were added to reflect theoretical assumptions.

The final step in this process is the instance definition. In this research, instances were not created, as they will be part of further research.

The ontology building was followed by a consistency check with reasoners: any unsatisfiable classes or unmet competency questions led to model refinement.

This ontology-driven approach enabled rigorous validation of the C4MM v2 by ensuring consistency (no internal contradictions among model elements), evaluating completeness (ability to represent all relevant maturity aspects), and confirming semantic integrity through logical axioms and dependency rules.

These steps can be done in a unified system using the Protégé software with the OWL2 Web Ontology Language, which has been developed by Stanford University for ontology machine processing (Musen 2015). This process includes the iterative fine-tuning of the definitions created through literature review and supported by ontology development.

In the context of the maturity model, ontologies are particularly valuable because they enable formal representation of domain-specific categories such as the maturity model categories, including their subdimensions and interdependencies.

2.3.5. RQ3.2 How can the C4MM be validated by a case study?[7]

A qualitative case study was conducted in four steps based on Winston M. Tellis (1997) to justify the integrity and applicability of the model to the environment as follows: (1) designing the case study protocol, (2) conducting the case study, (3) analysing the evidence, and (4) developing the conclusion. The data was collected through interviews. During the case study protocol phase, we developed a sampling strategy to select a business that covers all areas of our model, including planning and design, construction, and production. We prioritised selecting a company that demonstrated a high level of maturity in digitalisation compared to other market players. (Heidenwolf and Szabó, 2024a)

During the second phase of the case study, two interviews were conducted. The company's CEO first explained the main steps taken in their DT journey. Secondly, the C4M elements were discussed in detail to assess the importance of each model element on a scale of 0 to 5. The Chief Technology Officer (CTO) was interviewed in the subsequent round of the case study. During the analysis phase, we prepared the interview transcripts and created a matrix in Microsoft Excel to justify the model. The matrix rows represented categories, sub-categories and elements (C4MM elements), and the two columns (CEO and CTO) were filled with the data collected from the transcripts (Heidenwolf and Szabó, 2024a). During this phase, our main objective was to identify correlations between different model elements and determine the drivers of digital transformation (DT). In this process, the responses to each element of the maturity model were examined, including the steps in the DT process. As a result, a schematic process diagram was created to illustrate the company's C4 DT steps. This draft process diagram was used to create the BPMN 2.0 model of the company's C4 transformation process. The goal was to understand the key steps in DT in terms of the C4MM. The BPMN 2.0 model

[7] This section was published in (Heidenwolf and Szabó 2024a)

was constructed using the Aris Express software. During the model building, we applied the Aris method manual (Software AG 2022).

2.3.6. RQ4 - What correlations and characterisation of the C4MM can be explored on the basis of input from industrial experts?

My final work focused on answering the question of what correlations and characterisation of the C4MM can be explored on the basis of input from industrial experts.

The **qualitative** research followed the Virginia Tech Institutional Research Protocol (IRB #24-984) that ensures my research complied with the U.S. research standards and regulations to conduct human subject research under the supervision of Assistant Professor Kereshmeh Afsari. This section describes the most important details of the IRB #24-984 related to the dissertation from Section 5.1 to Section 5.3.

The empirical research aim was to refine and evaluate the practical relevance and applicability of the C4MM version 2, developed from the literature review to assess the digital maturity of construction companies, to facilitate successful DT. The research focused on the C4MM elements, especially related to technologies for C4 and how to measure the successful technology implementation. Thus, the research objective was to explore the best practices for short- and long-term technology implementation and how to measure the successful implementation of those technologies for the C4MM. The second objective was to explore interrelationships between technology implementation and different aspects of the C4MM developed from the literature review.

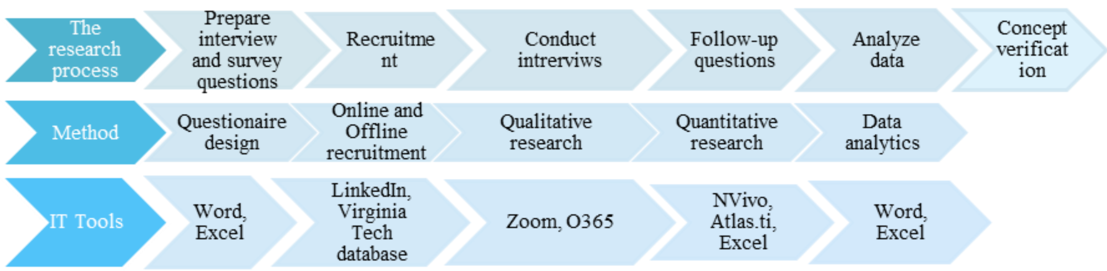

Figure 11 Expert interview research process

I conducted technology interviews with 33 participants to explore the best practices for implementing short—and long-term technology and how to measure successful technology implementation. (Figure 11)

The semi-structured interview questions focused on the latest technology integration process and its challenges, enabling the identification of which company aspects were affected by the technology implementation process. I also asked the participants to define Construction 4.0 maturity levels on a scale of one to five and to put their organisation on this scale. The answers provided empirical insights into which company aspects were affected by the implementation process, validated and refined the definition of the maturity model elements, and supported the maturity level development. This approach can help to explore use cases to refine the Technology for Construction 4.0 category and connect the use cases to different maturity model levels. In the third interview phase, I asked how to define the digital maturity levels in the construction sector. The answers helped me to align the research's goal to define the levels of the digital maturity model. After the interview, I collected quantitative data and sent a follow-up online questionnaire (see Annexe VII) to the participants to answer the questions about the different aspects of the organisation that are related to the specific technology that they are using.

The sampling process involved selecting participants from various construction organisations, including general contractors, subcontractors, construction technology companies, construction software providers, and construction consultants. In this process, active and passive recruitment were applied. However, only active recruitment resulted in interviews. Active recruitment means direct interaction with a potential participant (Gelinas et al. 2017). This process occurred in person and on LinkedIn. The in-person recruitment occurred at the Virginia Tech Career Fair at Virginia Tech HITT Hall and the Chicago Built Expo in Chicago, Illinois. During this process, the candidates were asked about their positions and responsibilities related to technologies to ascertain relevant experience. After identifying the relevant participant, I collected data to contact the candidate by e-mail, which contained relevant information about the study. During the active recruitment on LinkedIn, participants were recruited through direct messages on LinkedIn for first-level contacts. Snowball sampling was also applied to recruit further research participants. The research was solely conducted in the U.S.

During the interview, I informed the participant that the meeting would be recorded on the Zoom platform for transcription. Later, I gave the participant the consent information sheet (Annexe IV - Consent form) to review and ask questions before agreeing to participate. After consenting verbally to participate in the research and agreeing to record the meeting, participants were asked to answer the pool of questions (Annexe V - Demographic survey and Annexe VI - Interview Questions). At the end of the interview, I asked each participant to fill out an online questionnaire (Annexe VII – Follow-up questions). The interview took 30-60 minutes to complete. As the sole interviewer, I guided each session based on research questions aligned with the study's aims. One research participant withdrew from the study. Upon a participant's request, all data related to his participation was deleted from databases and other storage locations.

The first phase of the data analysis was to ensure that the data was managed properly and secured according to the IRB. I assigned a master code to each participant, stored in a separate folder from the data obtained from the research. The company and participant names were removed from the data. Based on the IRB, these data will never be shared outside of the research, only de-identified data (e.g. "Company-1", "Participant-1"). The data generated from transcriptions was stored in Microsoft Word .docx format on Microsoft OneDrive to ensure the validity of the collected data. This cloud-based platform allowed me to track any changes and revert files to previous versions. After manually revising all transcribed files, I also saved all transcriptions to .pdf format. Given the scope and limitations of this dissertation, quantitative data were not utilised. Instead, they will be incorporated during the subsequent model development phase following the completion of this dissertation.

The Zoom platform was used to record the interviews. Microsoft 365 Word's online transcribe function was used to generate automatic transcription from the recording. The automatically generated transcriptions were then manually checked to address any potential issues within the transcript file, ensuring the reliability of the transcripts. Memos were also created, which were used to understand the initial coding. Qualitative data analysis software was used to process and thematically analyse the results.

2.3.7. Summary of Research Methodologies

DS comprises the framework for this research, which employs various research strategies. In the initial research phase, Grounded Theory was applied (RQ1, Section 2.3.1) and a comprehensive literature review (RQ2) to gain insight into the C4 environment (Section 2.3.2). During the model-building phase, the core stages of the maturity model building within the DS framework were integrated and refined through the iterative integration of multiple research strategies. An initial model, followed by two further models, was developed based on the findings of the literature review (RQ3, Section 2.3.3).

During the first development phase, we investigated the potential for utilising a case study to examine the effectiveness of the model's components in assessing the digital maturity of a company (RQ3.2, Section 2.3.5). The research findings indicated that the initial model required refinement, as the CI maturity models upon which it was based did not encompass several areas that rapid technological advancements had anticipated.

Consequently, a second iterative phase was undertaken, comprising a systematic literature review in the field of I4 (Section 2.3.3.1). This model was validated by ontology (RQ3.1, Section 2.3.4). Finally, qualitative research refined the results (Section 2.3.6). The details of the research will be introduced in Chapter 4.

2.4. Research Motivation

As a CI professional, I have personally experienced the lack of an appropriate working environment, the insufficiency of collaboration, the limitation of IT skills and the absence of career paths. These factors make the CI less and less attractive to the next generation, resulting in a labour shortage. I am eager to bring change to the CI through my research to transform the CI into the C4 cyber-physical ecosystem. This ecosystem redirects the industry to build cities sustainably for societies and makes construction companies much more effective, which can attract new generation workers and professionals. To elevate CI DT, I am developing a Construction 4.0 Maturity Model (C4MM) tool, which can provide a comprehensive picture for organisations whose complex context will be supported by ontology development. This model will be suitable for the basis of an IT system to show the current state of the digital maturity of a company and recommend steps that need to be taken to reach the next level of maturity, considering the resources, processes and potential risks of a company.

2.5. Research relevance and opportunities

The emergence of digital technologies and the concept of I4 has catalysed the DT within the CI. The DT affects the entire industry value chain, resulting in significantly more efficient and effective corporate operations than those currently observed. This phenomenon is evidenced by a reduction in costs and lead times, as well as a decrease in environmental impact. Nevertheless, the DT is progressing slowly in the CI, which calls for a comprehensive scientific investigation.

The number of studies in this field is increasing rapidly, although the quantity of available research remains limited. According to the Scopus database, fewer than 10 publications were published annually on "Construction 4.0" keywords (AUTHKEY (construction 4.0) OR TITLE (construction 4.0)) until 2017 (Figure 12). Since 2017, there has been a notable surge in interest in the subject, with the number of publications rising to over 150 in 2025.

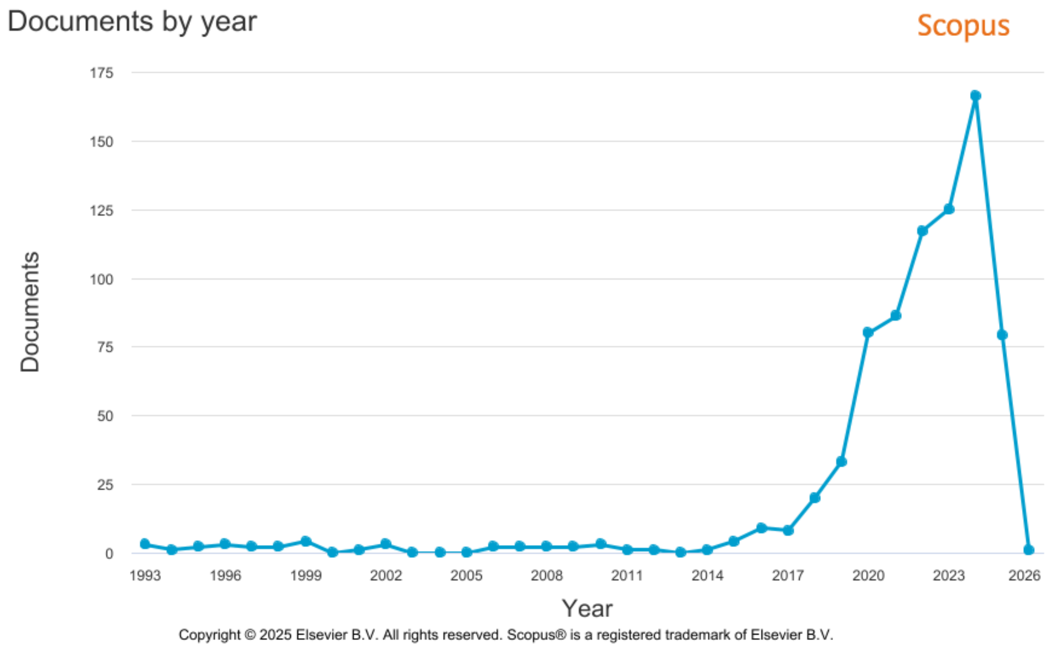

Figure 12 Scopus "Construction 4.0" keyword and title results[8]

The preliminary findings of the research indicate that organisations within the construction sector require a compass to facilitate effective and expeditious DT. This process has been the subject of a relatively limited number of studies. According to the Scopus database, there were fewer than 20 publications with the title or keyword "Construction Digital Maturity" until 2019, when this research started (Figure 13). This number increased to 58 in 2023 and reached 71 in 2024.

[8] based on 27.08.2025 data

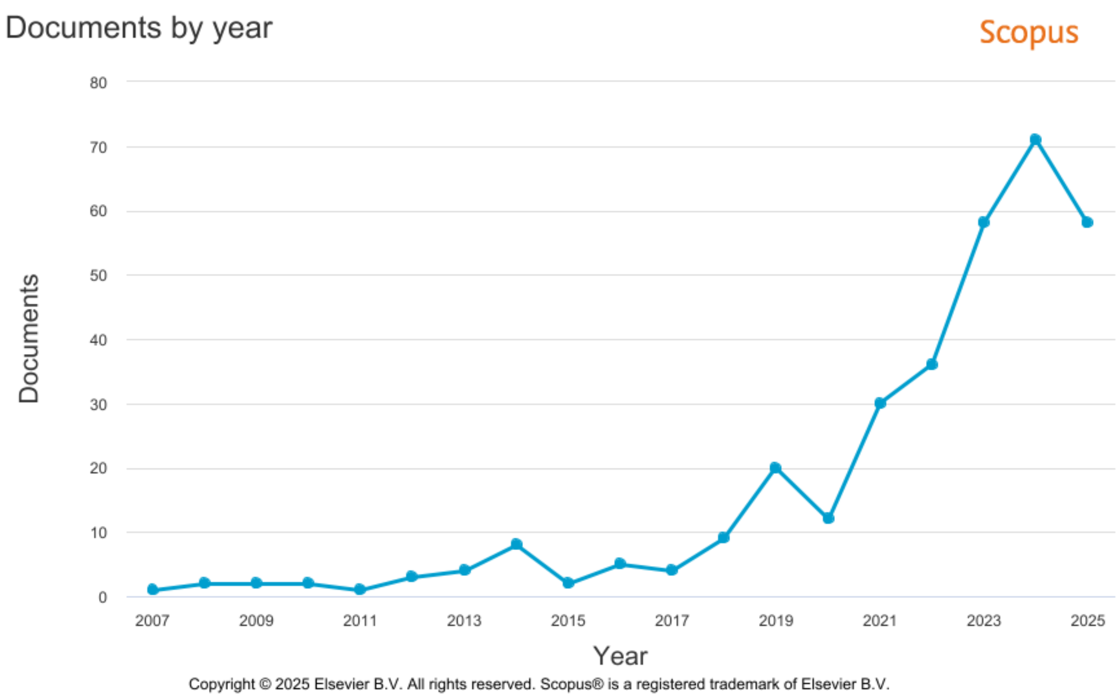

Figure 13 Scopus "Construction Digital Maturity" abstract and title results, source: Scopus[9]

This dissertation addresses this gap by developing a comprehensive C4MM that can be a practical tool for construction companies to assess and enhance their digital maturity. By providing a structured approach to DT, this model will assist companies in reducing costs, improving efficiency, and minimising environmental impact, thereby contributing to the sustainable development of the CI. The findings and tools developed through this research have the potential to significantly impact both academic research and industry practices, offering solutions to the challenges faced by construction companies in their DT journey.

My research touches on several issues. Currently, construction companies lag significantly behind other industries, which manifests itself in inefficiency and has a significant economic impact on companies. Therefore, I see that the first problem of the industry is that companies and managers are not aware of what digitalisation means in the CI, which could be clarified with the concept of C4. Second, the CI is becoming less and less attractive to the new generation, generating persistent labour shortages and becoming an ageing industry. DT could help make the CI more appealing to the new generation.

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[9] based on 27.08.2025 data

Third, I see it as a problem to identify the digital maturity of each construction company. An industry-specific digital maturity model could guide companies in developing a more efficient operating model that would bring new technologies into the lives of companies with entirely new processes and knowledge.

3. THEORETICAL BACKGROUND

This paragraph introduces the concepts of Industry 4.0 and Construction 4.0 and explains the difference between the readiness and maturity models. The end of this paragraph gives examples of recent research in C4 maturity models.

3.1.Industry 4.0[10]

Technological advancement due to I4 had a substantial influence on social and economic structures, thereby affecting corporate competitiveness and social welfare. In 2011, I4 was first mentioned (Buhr 2015), as a term that refers to the integration of information and communication technologies (ICT) within an industrial environment (Schuh et al. 2014). In the I4 era, the five key elements were defined as follows (Roblek et al. 2016): digitisation, optimisation and personalisation of production; automation and adaptation; human-machine collaboration; value-added services and warehousing; and automatic data exchange and communication. Zezulka et al (2016) proposed three additional elements to the I4 framework: digitisation and network integration, new market models, and digitisation of products and services. The digitalisation process impacts the entirvalue chain, extending from business models to management systems (Bleicher and Stanley, 2016). The principal driving forces and obstacles associated with I4 have been identified as human resources, organisation, management, market conditions and competition, financial resources and profitability, productivity and efficiency, customer satisfaction and technological and process integration (Horváth and Szabó, 2019; Szabo et al., 2020) (Nagy et al. 2021).

I4 focuses on innovating smart products, smart production systems, smart factories, and smart logistics, working in a decentralised and dynamic manner (Ávila-Bohórquez and Gil-Herrera, 2022). The aforementioned eight concepts have been incorporated into the definitions of numerous studies examining the maturity of I4 (Nagy et al. 2021).

3.2.Construction 4.0

The competitive structure of the CI is undergoing a fundamental transformation due to the fourth industrial revolution, which is also bringing about significant technological

[10] A part of this paragraph was published in (Nagy et al. 2021)

advances. However, these developments present several challenges for all players in the industry. In this novel competitive context, the paradigm of C4 is emerging. It is important to note that the term 'Construction 4.0' has been introduced by analogy with 'Industry 4.0'. The key achievements of the first industrial revolution were the introduction of the loom, water and steam power. The second was the advent of the first assembly lines, mass production, and electricity. At the same time, the third was the first programmable logic controller, which used electronics and IT for further automation. C4, emerging in the fourth industrial revolution, is a new digital ecosystem that integrates digital (physical and virtual) technologies, methods and processes, and prioritises sustainability. It will continuously transform the competitive structure of the industry. The actors involved in this transformation include public organisations, research institutes, educational institutions, companies and other actors in the construction supply chain (Heidenwolf and Szabó, 2024b).

3.2.1. Construction 4.0 Definition [11]

There has been a growing body of literature on C4 recently. Some literature has defined C4 as applying I4 in construction (Brito et al. 2022; Kor et al. 2023). Other researchers have defined it as the application of digital technologies in construction (Karmakar and Delhi, 2021) or the application of I4 technologies (Begić and Galić, 2021; Osunsanmi et al., 2022) to enhance the efficiency of the supply chain (Temidayo. O. Osunsanmi et al. 2018). Additionally, other literature highlights the advancement of novel technologies (Anil Sawhney et al. 2020), processes (Schönbeck et al. 2020), and operational methodologies (Yang et al. 2022), as well as the evolution and automation of data management (Farzad Pour Rahimian et al. 2022). A summary of the various definitions is provided in Table 5.

[11] this paragraph was published in (Orsolya and Roland Zs., 2024)

Table 3 Definitions of Construction 4.0 (Heidenwolf and Szabó, 2024b)

Definition	Source
"Construction 4.0 is the digitalisation of the construction industry"	(Ammar and Nassereddine 2022, pp. 1)
"Construction 4.0 is the application of Industry 4.0 or the Fourth Industrial Revolution in Construction"	(Brito et al. 2022, pp. 1; Kor et al. 2023, pp. 463)
"construction 4.0 as the process of implementing modern technology to encourage the digitization of the construction industry as well as the supply chain."	(Temidayo. O. Osunsanmi et al. 2018, pp. 152)
Construction 4.0 is the application of digital technologies in the construction industry	(Karmakar and Delhi, 2021)
"Construction 4.0 is a framework that is a confluence and emergence of the following broad themes: industrial production, cyber-physical system, digital and computing technologies "	(Anil Sawhney et al. 2020, pp 5)
"Construction 4.0 represents the architecture, engineering, construction and operations industries exploration of new technologies, equivalent to Industry 4.0 for the manufacturing industry."	(Schönbeck et al. 2020, pp. 1)
Construction 4.0 is the partial application of Industry 4.0 technologies in the construction industry	(Begić and Galić, 2021)
Construction 4.0 includes methods and applications that are changing as a result of software and hardware technologies.	(Yang et al. 2022)
Construction Industry 4.0 is *"advancements in technology and data management, new manufacturing techniques, and advanced digitalisation and automation, new manufacturing techniques, and advanced digitalisation and automation."*	(Farzad Pour Rahimian et al. 2022, pp. 53)

Following the conduct of expert interviews and the analysis of relevant literature, the results were synthesised, resulting in the following definition. The concept of C4 in this dissertation is defined as follows: C4 paradigm represents a novel construction ecosystem encompassing three fundamental pillars: (1) integrated technologies and cyber-electronic systems, (2) methods and processes, and (3) human resource competencies. These three pillars are supported by automation and data analytics. In this ecosystem, sustainability represents a significant goal which industry players can achieve by enhancing the efficiency and productivity of construction processes (Heidenwolf and Szabó, 2024b).

3.2.2. Construction 4.0 Organisational level challenges and solutions [12]

While the CI lacks human resources and labour (Forcael et al. 2020), new skills are significant challenge to implementing C4 (Al-Saeed et al., 2020; Lavikka et al., 2018; Li et al., 2019; Maskuriy et al., 2019; Muñoz-La Rivera et al., 2020). In this demanding environment, the COVID-19 pandemic brought further mental health and burnout problems to the industry (Lingard et al. 2021). Social and mindset change is crucial to prepare workers for the future human-robot collaboration (Klinc and Turk, 2019; Maskuriy et al., 2019) that creates new roles and tasks (Davila Delgado et al. 2019;

12 a part of this subchapter was published in (Nagy et al. 2021)

Muñoz-La Rivera et al. 2020). Furthermore, the growing number of implemented robots brings ethical questions and can lead to an increased unemployment rate (Forcael et al. 2020).

Organisations face new challenges with new workflows (Maskuriy et al. 2019; Muñoz-La Rivera et al. 2020) and organisational change (Maskuriy et al. 2019; Newman et al. 2020) that technology demands, but old business models (Lavikka et al. 2018) and hierarchical organisations (Bonanomi et al. 2019) hinder the transformation. The low innovation culture (Klinc and Turk, 2019) and the low speed of technology implementation (Maskuriy et al. 2019) can be accelerated through well-defined digital partnering agreements (Aghimien et al. 2020). However, some research believes SMEs have little value in applying I4 principles (Newman et al. 2020).

Management faces knowledge and decision-making problems. The growing number of innovations demands extra technological knowledge (Klinc and Turk, 2019) and external support (Al-Saeed et al. 2020). However, in the absence of data on technology investment, decision-making becomes increasingly complex (Kim and Kim, 2011). Furthermore, these professionals might not value technological innovation (Osunsanmi et al. 2020).

The high initial cost hinders technological adaptation (Davila Delgado et al. 2019; Maskuriy et al. 2019; Rane et al. 2019). Meanwhile, technologies that provide expensive training (Newman et al. 2020 usuallyack a cost-benefit study (Davila Delgado et al. 2019).

Table 4 Challenges behind C4 identified from the literature (Nagy et al. 2021)

Challenge	Sources
New skills for human labour	(Al-Saeed et al., 2020; Lavikka et al., 2018; Li et al., 2019; Maskuriy et al., 2019; Muñoz-La Rivera et al., 2020)
Organisational and workflow changes	(Maskuriy et al. 2019; Muñoz-La Rivera et al. 2020; Newman et al. 2020)
Management knowledge of technologies	(Osunsanmi et al. 2020)
The high initial cost of new technologies	(Davila Delgado et al. 2019; Maskuriy et al. 2019; Rane et al. 2019)

Table 4 summarises the main challenges for C4 identified in the literature. The table shows that in the C4 environment, Maskuriy et al. (2019) and Muñoz-La Rivera et al. (2020) identified most of these challenges. Five articles identified that new skills are necessary in this transformative industry. Furthermore, three articles highlighted the need for organisational and work processes change. Finally, the initial high costs were also mentioned in three studies.

C4 is reshaping the CI, making it more attractive (García de Soto et al. 2019; Maskuriy et al. 2019; Alaloul et al. 2020). The recent pandemic proved the value of human resource efforts: well-being and occupational health in the sector (Lingard et al. 2021). Despite technologies demanding new skills, they also create new roles (Lavikka et al. 2018) to support knowledge transfer to robots (García de Soto et al. 2019). Social network analysis can help increase workers' skills and transfer knowledge inside the organisation (Bonanomi et al. 2019).

Contrary to Newman et al. (2020), Lekan et al. (2020b) discuss SMEs as the beneficiaries of the technologies. Furthermore, digital partnering is a new solution for businesses to gain experience from collaboration and successfully implement new technologies (Aghimien et al. 2020), where group construction is achieved in a new collaborative resource-sharing way (Lavikka et al. 2018). Organisations can solve the innovation challenges by involving research and development institutions (Lavikka et al. 2018; Davila Delgado et al. 2019; Maskuriy et al. 2019), by applying cross-functional teams in hierarchical organisations (Bonanomi et al. 2019), and by implementing innovations to the organisational strategy (Barata and da Cunha, 2019).

Managers can apply new methodologies. For instance, situational leadership can solve innovation challenges (Zhang et al. 2018), and scenario planning is a new tool for managers and researchers (Lavikka et al. 2018)**.** Technologies can increase competitiveness in the global market by allowing local companies to step out internationally or increase local competitive advantages through a new business model, such as digital partnering (Aghimien et al. 2020).

From a financial point of view, Kim and Kim (2011) suggested activity-based costing to use as a tool to (1) identify the inspection activities, (2) compute the cost driver rate, and (3) enable the performance of the scenario analysis by manipulating the volume of cost drivers under different scenarios. Sacks et al. (2020) emphasised that technologies can reduce the cost of workers and materials. Furthermore, the platform business model can solve complex management problems, supply chain, material and equipment issues, leading to cost savings (Centre for Digital Built Britain, 2018).

Table 5 Solutions behind C4 identified from the literature

Solution	Sources
Make CI more attractive.	(García de Soto et al. 2019; Maskuriy et al. 2019; Alaloul et al. 2020)
New roles and skills	(Lavikka et al. 2018; García de Soto et al. 2019)
Social network analysis	(Bonanomi et al. 2019)
Digital partnering and group construction	(Lavikka et al. 2018; Aghimien et al. 2020)
Involve research and development, innovation	(Forcael et al. 2020; Muñoz-La Rivera et al. 2020; Zabidin et al. 2020)
Situational leadership	(Zhang et al. 2018)
Early technology involvement	(García de Soto et al. 2019; Turner et al. 2021)
Sustainable solutions	(Lavikka et al. 2018; Alaloul et al. 2020)
Increase competitiveness	(Aghimien et al., 2020; Kim and Kim, 2011).

Source: (Nagy et al. 2021)

Table 5 summarises the solutions behind C4 identified in the literature. Most articles highlighted the importance of involving research and development and making the industry more attractive. Lavikka et al. (2018) and Garcia de Soto et al. (2019) focused on most of the solutions behind C4.

3.3.Digital Maturity Models

The impact of I4 caused the emergence of the technologies. Researchers found that I4 strategic guidance can enable companies to effectively transform their business processes by considering risks and recognising opportunities (Ganzarain and Errasti, 2016). Maturity models are commonly used as an initial tool for DT to explore the "as-is" state of businesses (Bellantuono et al. 2021; Czvetkó et al. 2022). These models serve as guidance and a starting point in the DT journey (Peerally et al. 2022) to develop organisational goals and strategies, and understand the company's weaknesses (Carvalho and Teixeira, 2021).

In the CI, the C4 transformation is happening very slowly due to a lack of education, a skilled workforce, and the right tools and technologies. Therefore, companies need strong external support that guides them in the DT world to ensure the highest level of readiness (Ghobakhloo and Iranmanesh, 2021).

Several MMs and RMs have been developed to assess how companies have embraced digitalisation and facilitated their seamless adoption of C4 technologies. Existing maturity models frequently fail to adequately address the inherent complexity and multifaceted nature of C4, which ultimately leaves organisations without clear guidance in their digital journeys. These models adopt different approaches, with some focusing on general technology (Chen et al., 2023; Ribeiro et al., 2022) and others addressing specific technologies in greater depth, such as BIM (Chen et al., 2024; Ferraz et al., 2020; Jason and Umit, 2010; Joblot et al., 2019; Kassem and Succar, 2017; Succar et al., 2012; Yilmaz et al., 2023) or AR/VR (Monla et al. 2023). Some models adopt a narrow focus, concentrating solely on the project's maturity in specific areas, such as site maturity (Wernicke et al. 2023), health and safety (Asah-Kissiedu et al., 2023; Oswald and Lingard, 2019), or project management (Lin et al. 2022). Offsite construction maturity models focus on production (Bendi et al. 2021), whereas industrialised construction maturity models measure the different technological applications by use cases (Razkenari and Kibert, 2022). Recently, researchers have focused on developing general maturity models for CI organisations (Bou Hatoum et al. 2022; Das et al. 2022; Perera et al. 2023; Han et al. 2024; Zhu et al. 2024). However, these models apply various evaluation criteria, which are shaped by the perspectives of the creators involved. Furthermore, my research findings so far support the view that such a model is not suitable for promoting industry transformation, as my research has shown that first, the project-centric mindset hinders C4 (see Section 4.1.1), as it requires a process-centric mindset. Second, the maturity model of projects does not support the readiness and technological capability of companies. Third, the project is determined by the competence level of the actors involved, which does not necessarily mean that the same company in two different projects will show similar maturity.

4. RESULTS - ARTEFACT DESIGN AND DEVELOPMENT

The following chapter presents the details of the research and how each RQ was answered, following the steps of DS. The IDEF0 diagram is also presented in each step of the following paragraphs. For each activity, the IDEF0 diagram shows the inputs and outputs and the knowledge base supporting the implementation of the activity. The control supports the methodological implementation of each activity through the appropriate applications (Johannesson and Perjons, 2014).

4.1.Explicated problem

The Explicate Problem activity identifies and justifies a significant practical problem for local and global contexts (Johannesson and Perjons, 2014).

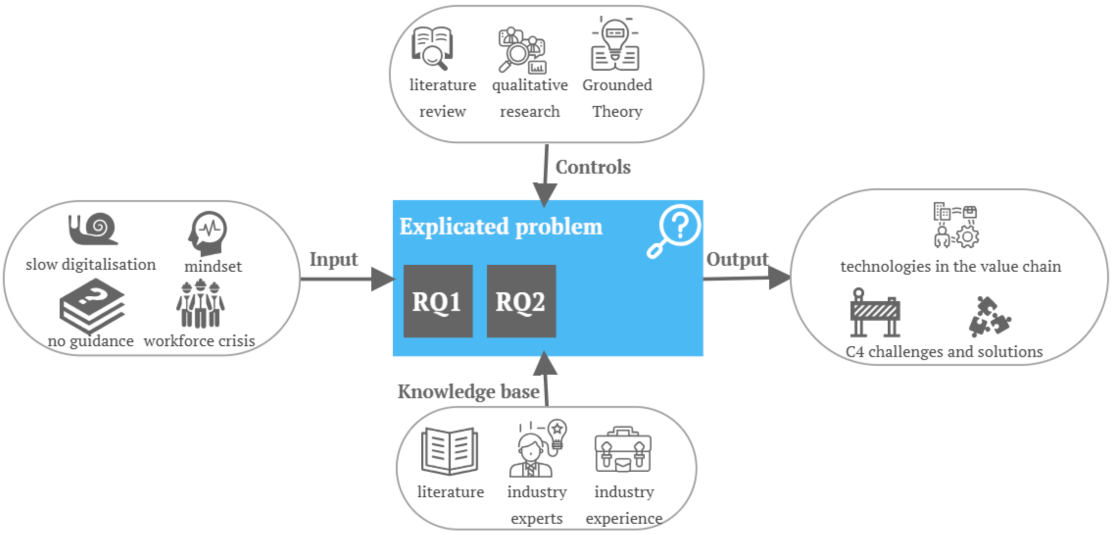


Figure 14 Explicated problem IDEF0 diagram

The Explicated problem presented in Figure 14 inputs are the following: Construction companies lag significantly behind other industries in terms of digitalisation, which results in inefficiency and a significant economic impact on a global scale. The United Nations report shows that the CI is responsible for 37% of carbon emissions due to its inefficiency and high-emission supply chain. Furthermore, this industry has a 17% direct and 27% indirect contribution to the SDGs ("On the Role of Construction in Achieving the SDGs", 2019). Therefore, the fundamental issue is that senior management frequently lacks awareness of the potential benefits of digitalisation and the strategies required to implement it. Moreover, they often fail to recognise the necessity for a shift in mindset. Additionally, the CI faces a growing workforce crisis, characterised by an ageing population and declining appeal for the younger generation. A DT could make the CI more appealing to the younger generation. Developing an industry-specific maturity model could prove an effective means of guiding companies towards more efficient operations. The integration of innovations resulting in a reduction in labour requirements and the creation of a more attractive industry could make the CI a more attractive proposition for the next generation of workers. Furthermore, the implementation of entirely new processes and the acquisition of new knowledge could lead to a decrease in the necessary labour required for construction.

RQ1 and RQ2 guided the exploration of the explicated problem, and the results of this research are the output of the explicated problem. The following two sections will introduce this research in detail.

4.1.1. C4 Organisational Level Challenges and Solutions explored from qualitative research[13]

This section will introduce the results from the qualitative research expert interviews (related methodology in Section 2.2.3). The research categorised C4 organisational-level challenges and solutions. In this dissertation, the following groups are introduced from the paper published by Nagy et al. (2021): human resources and society, organisational factors, management reality and expectation. The interview participants can be found in the Annexes in Table 9.

The first group is categorised as the "human resource and society". The research revealed that the CI will face increasing labour and skill shortages in the coming years, making it less attractive to younger generations. The lack of career paths, gender issues and generational problems inhibit the industry's attractiveness. The emergence of new technologies and methodologies requires all stakeholders to provide ongoing education

[13] This section was published in (Nagy et al. 2021)

for their workers and develop new computer skills, representing a significant challenge for the ageing generation. Furthermore, the advent of robotics on construction sites has introduced a new set of considerations. Cultivating a highly trusted environment and psychological safety is essential to facilitate human-machine collaboration. The application of robots has the potential to create new job opportunities while simultaneously increasing the unemployment rate in the sector (Nagy et al. 2021).

The interviews revealed that technological advancement has the potential to enhance the appeal of the industry. These technologies can support situational awareness and expand the scope of workers' responsibilities. A more social environment and new career paths can enhance workers' engagement. Knowledge transfer from other industries, such as automotive and manufacturing, can catalyse DT. Recruiting IT professionals, including coders and developers, is inevitable in this transformative environment. Their expertise can support the work of engineers and can be a source of value-added services (Nagy et al. 2021).

The second group is the organisational factors. The increasing volume of data necessitates the development of novel expertise and the facilitation of information sharing. Nevertheless, a prevailing atmosphere of distrust between and within the organisations hampers their collaboration capacity. The various disciplines have divergent preferences, and the exponential growth in technologies and platforms does not facilitate this collaboration. Furthermore, the existing approach to collaboration remains individualistic. The organisation's historical assumptions, lack of innovative mindsets, and long decision-making processes significantly hinder its growth and implementation of new technologies. It is essential that organisations prepare to understand how to choose and connect digital interfaces. Technological advancement remains a crucial factor, yet ensuring that the existing workflow is not disrupted is essential (Nagy et al. 2021).

Data collection can provide useful information for organisations, enabling them to maintain tools and equipment while supporting the development of more effective contracts. For instance, data handling can be incorporated into the contractual agreement, fostering collaboration and transparency between the parties involved. Furthermore, the investment in research and development can facilitate the acceleration of organisational transformations and the implementation of technological solutions. The evolving industry landscape presents opportunities for small and medium-sized enterprises (SMEs), such as the ability to accelerate innovation due to their size and flexibility.

Top management is unwilling to acknowledge the reality of the CI transformation, as they lack an understanding of the technologies and methodologies that exert considerable pressure on them. A significant gap in knowledge and training has resulted in a lack of clarity regarding the benefits of technology and the financial and social value of innovation to management. The management of these businesses is of the opinion that their operations are efficient and constantly evolving, and that the continued profitability of older working methods is evidence of this. The potential risks posed by innovations are a barrier to progress, as they could reveal organisational policy issues and long-term problems. A tendency of management to rejective behaviour can result in the loss of enthusiasm among ambitious employees. The result is often a delay or absence of transformation when management lacks the knowledge required to facilitate the transformation of internal processes following a technology investment, which can give rise to further issues and tensions within the organisation. Implementing new technology requires knowledge acquisition, and it is therefore essential that management accept the necessity of education. Innovation and decision-making depend on top management's actions; however, change management also requires the active engagement of lower management levels.

The infusion of research and development can facilitate a shift in mindset and enable the identification of current issues and future challenges, such as thinking of collaboration as a profit for the organisation. By leveraging new business models, organisations can become part of the solution. Technologies can support the development of new business models, including those that view construction as a product, a service, or a space as a service. Management can also inform decision-making and strategic thinking by considering collaboration as a potential source of profit. Furthermore, technology implementation can enhance the quality and delivery of services while influencing an organisation's market position.

Table 6 Organisational level challenges and solutions behind Construction 4.0

Challenge	Category		Solution
Attractive industry Education Skill and labour shortage Human feeling Generational issues Human-machine collaboration	Human Resources and Society		Situational awareness Young generation Reform the industry brand Knowledge transfer More social industry
Information and data Innovative mindset Historical assumptions Procurement and bidding Collaboration Technology and process	Organisational factors		Faster adaptation for SMEs Data handling in the contract Data collection Data Sharing R&D investment
Technology pressure To see the transformative industry Understand the value of innovation Believe technology without process Mindset change Lack of training	Management reality	Management expectation	Think of collaboration as a profit Change the decision-making process Strategic thinking New business model

source: (Nagy et al. 2021)

4.1.2. Technologies across the Construction industry value chain[14]

The stages of construction, from initial planning to the incorporation of new technologies into the infrastructure of smart cities, demonstrate the capacity of emerging technologies, such as BIM, VR, AR, and blockchain, to effect transformative change. These technologies have brought various new use cases with several benefits for the CI value chain.

In the construction planning and design phase, integrating technologies such as BIM presents several challenges for smaller firms, primarily due to the limited availability of internal expertise and established processes (Owen et al. 2010). Integrating BIM as a contractual foundation can streamline supply chains (Dowsett and Harty, 2019) and improve project coordination (Ghaffarianhoseini et al. 2017). By early phase integration of BIM, companies can utilise the historical data and enhance quality control processes (Bassanino et al., 2014; Whyte, 2019). The use of visual technologies connected to BIM, such as VR, has the potential to enhance design transparency (Whyte, 2019),

[14] This paragraph was partly published in (Nagy & Szabó Zs., 2021b)

collaboration (Li et al., 2003; Sacks et al., 2015), and safety (Ghaffarianhoseini et al. 2017). Another potential technological solution to enhance efficacy is integrating the Common Data Environment (CDE), which can facilitate improved organisation and project-level collaboration (Gerbert et al. 2016), enhance accountability for project stakeholders (Bryden Wood et al. 2018), increase overall project performance and process, and reduce costs (Bryden Wood et al. 2018).

Various recently developed technologies and methodologies have emerged to make the construction phase more effective. Firstly, platform construction and advanced fabrication methods address supply chain challenges (Agustí-Juan et al. 2017; Perera et al. 2020), enabling complex design through algorithm-driven robotics. Secondly, integrated camera technologies support lean construction by improving resource planning, scheduling, and quality control, thereby benefiting unskilled workers and reducing the necessity for rework (Ahmed, 2019). Thirdly, autonomous technologies and robotics can potentially eliminate the need for workers on-site (Behzadan et al. 2015). Fourthly, mobile and cloud-based solutions facilitate real-time management and snagging issues (Bohn and Teizer, 2010; Conlin and Retik, 1997; Park and Brilakis, 2012; Soman and Whyte, 2017; Zaher et al., 2018). Fifth, XR enhances site safety and productivity (Bohn and Teizer, 2010). Finally, 4D BIM facilitates proactive monitoring and scenario testing (Zaher et al. 2018), optimising risk management (Whyte and Lobo, 2010) and decision-making (Gao and Pishdad-Bozorgi, 2019).

DT brings several benefits to the operational and maintenance phases. To optimise the advantages, asset owners should implement a BIM strategy that aligns with their organisational objectives (Delgado et al. 2017), which can facilitate contractors' exploration of Building as a Service (BaaS) models and guarantee continuous revenue generation (van den Berg et al. 2021). Using real-time monitoring, real-time asset information and visual problem alerts can enhance safety by supporting on-demand decision-making (Bryde et al. 2013; GhaffarianHoseini et al. 2017). Nevertheless, enhanced communication between the construction and operational phases is essential for fully utilising higher-dimensional BIM in maintenance planning and monitoring (Woodhead et al. 2018). The implementation of 6D BIM in the planning and monitoring of maintenance activities provides substantial support for the sustainability of buildings, as it enables the analysis of as-built conditions, energy consumption (Munir et al. 2020), and life-cycle assessments (Woodhead et al., 2018a).

The deconstruction phase of our built environment can benefit even faster than the construction phase. Technologies can help in real-time structural monitoring, simulation, and quality inspection (Franz et al. 2018). Scan-to-BIM solutions can create as-built 3D BIM models from a built structure, which can be automated by collaborative technologies (Sedláková et al. 2020). BIM-based life-cycle environment on deconstruction and support fast decision-making between demolition and renovation (Engin et al. 2019). 3D existing condition analysis, reusable element labelling, and a 4D deconstruction simulation (Feng et al. 2020) further help to rebuild our environment. For the demolition phase, the circular construction concept can bring new solutions for demolition waste to synchronise the building and our living environment (Engin et al. 2019).

Technologies can create value by establishing connections between their technology, from the initial planning and design stages to the implementation of smart infrastructure. It is imperative that technology generates real-time data that is accessible and transparent to enhance the lifespan of intelligent cities (Heaton and Parlikad, 2019). Technologies can create value in connection with local information, predictions derived from people's habits, healthcare information, emergency solutions, maintenance solutions and solutions that connect the public and private sectors (Kocaturk, 2016). The application of emerging technologies can facilitate value creation by implementing human-centred infrastructure solutions during the integration phase. Connecting the functions of assets to city services can facilitate the creation of a data analysis platform, thereby enhancing the ability to meet citizens' requirements (Whyte and Lobo, 2010), which can be achieved through the utilisation of validated scenarios (Snijders et al. 2010). The societal and environmental factors contributing to delivering a life-cycle valuable asset to the economy are important. The fostering of supply chain collaboration can facilitate the delivery of superior asset information by utilising linked data of their function and connection with smart infrastructure (van den Berg et al. 2021), which enables the asset information to be delivered effectively across project phases.

Table 8 shows that most of the emerging technologies focused on design transparency and visualisation during the research (in 2021) in the planning and design phase. During the build phase, lean construction and structured data were the focus of research and software development. Inspection and scan-to-BIM solutions emerged in the reconstruction phase, while most smart city integration solutions focused on digitalising the existing assets. Despite the technological boundaries blurred due to the connected technologies, six categories were formed to support the development of the C4MM (Section 4.3.6). Namely, BIM and Digital Twin, IoT and sensors, Robotics and Automation, and Data analytics methods. These categories will help to understand the different use cases and connect those to different maturity levels later.

Table 7 The Construction value chain and emerging technologies

	Technology	3D libaries	Quality control	Cost estimation	Design transparency	Visualisation	Clash detection	Sustainability	Common data environment	New supply chain solution	Innovative manufacturing	New fabrication methods	Structured data	Integrated BIM on site	Onsite mobile application	Lean construction	Snagging	Health and safety	4(n)D BIM	Safe maintenance	Planning and tracting maintenance	Ispection	Life-cycle environmental impact	Scan-to-BIM	Demolition and recycling	Smart infrastructure	Human-centered infrastructure	Digitalisation of exsisting assets	Life-cycle value assesment	Total
Digital Twin and BIM	BIM methood	3	6	3	8	8	5	4	3				5	6	3	9	3	3	1		2	2		2		1		1		78
	3D scanning/ projecting		1		1	1		1					1	3	1	3	1	1			1	1		1				1		18
ERP and PMP	Software and cloud	2	2	2	2	3	2	3	2			1	1	1	1	1	1	1			1					1				27
	PWA/Website/Applications and cloud	1	5	1	8	7	4	3	2	2			17	4	13	20	4	8	1		1	3		2	2			1		109
IoT and Sensors	360 camera												4	2	3	5	1	4												19
	Sensors and smart tags (RFID, BLE)									1			5	1	3	7		4												21
	Smart devices				1	1	1		1					1		1		1												7
Robotics and Automation	3D printing											1																		1
	Drones		1		1	1							1		1	2						1		1						9
	Robots and automous machines											2				2		1												5
AI/ML/Big Data	Big data	1	2	1	4	3	2					1	7	1	4	8	1	4	1			2		1						43
	AI and Machine learning	1	2	1	4	2	2	2	2			12	4		3	4	1	2				1			1					44
	Blockchain and supply chan									1			1		1	1														4
Extended reality	AR and VR				1	1	1		1					1		1		1												7
	Total	8	19	8	30	27	17	13	11	4	0	17	46	20	33	64	12	30	3	0	5	10	0	7	3	2	0	3	0	392
		Planning and Design Phase								Build										Operate		Reconstruction				Integration				

x	relevant cases from observation
x	number of cases
	relevant from articles

Despite these technologies' benefits, several challenges emerge in successfully implementing them into the CI organisation's life cycle.

Firstly, the CI presents many challenges in terms of collaboration and communication. The lack of collaboration (Dowsett and Harty, 2019), organisational-level change management, and process change (Ghaffarianhoseini et al. 2017) can impede the integration of these technologies, which can, in turn, give rise to project-level misunderstanding (Sacks et al. 2015), resulting in an additional cost for designers. In order to facilitate the integration of smart standards, it is essential to address the challenges associated with change management (van den Berg et al. 2021). Change management can ensure consistent and valuable asset information delivery across project phases, with the appropriate size, version, and data structure (Sacks et al. 2020). Furthermore, the CI must prioritise resolving the 'network mindset' issue (Whyte and Lobo, 2010).

Secondly, technological adaptation's success depends on change management to deliver valuable life-cycle asset information across project phases with the right size, version, and data structure (Sacks et al. 2020). The effective implementation of BIM and AR necessitates substantial organisational change management and investment, particularly in lean construction practices (Carvajal-Arango et al. 2019). However, the first and most important step before change management is the management's understanding of the benefits of technological development(Bohn and Teizer, 2010; Conlin and Retik, 1997; Oesterreich and Teuteberg, 2016).

Thirdly, data management and security are new fields in CI. While using the CDE approach may reduce design time (Perera et al. 2020), it is only effective when accompanied by clear data structures and defined roles (Alaloul et al., 2020; Carvajal-Arango et al., 2019; GhaffarianHoseini et al., 2017; Oesterreich and Teuteberg, 2016). Data security concerns hinder real-time data collection (Bohn and Teizer, 2010; Conlin and Retik, 1997; Oesterreich and Teuteberg, 2016), and internet access on-site (Conlin and Retik, 1997; Davies et al., 2014). Furthermore, robotic technology brings further safety questions for organisations (Bohn and Teizer, 2010).

Fourthly, cost, skills and workforce can hinder the technological advancement of the sector. The advanced use of these technologies requires skilled workers. However, a lack of skilled workforce brings additional challenges to the CI (Heaton and Parlikad, 2019). The high cost, the necessity for skilled labour, and complex technical requirements restrict the effective utilisation of 4D BIM for risk management and project monitoring (Gao and Pishdad-Bozorgi, 2019).

Finally, these technologies bring ethical, legal, and societal considerations to the surface. Implementing safety management systems is resisted due to the legal and GDPR implications of surveillance and autonomous technology (Ghaffarianhoseini et al. 2017), which should be considered in the project budget (Gerbert et al. 2016). With the emergence of innovative technologies, special education is necessary for public society (Engin et al. 2019) to generate the necessary data for smart cities. However, many questions need to be answered to develop a human-centred infrastructure. Firstly, what are the citizens' requirements? Secondly, how would data privacy legal questions be solved (Snijders et al. 2010). Thirdly, the ethical, cognitive, and economic considerations must be answered (Whyte and Lobo, 2010).

The technological landscape demonstrated that the systematic introduction of technologies into the life of construction companies is a considerably more complex issue. Consequently, prior to developing the C4MM model, I concentrated on mapping the enterprise-level challenges of C4 in the subsequent phase of my research. The mapped technologies provided a framework for identifying which technologies would emerge in C4, which I will discuss in depth later in the model-building process in section 4.3.3.6.

4.1.3. Explicated problem output

The first research question explored that the Construction 4.0 paradigm represents a novel construction ecosystem encompassing three fundamental pillars: (1) integrated technologies and cyber-electronic systems, (2) methods and processes, and (3) human resource competencies. These three pillars are supported by automation and data analytics. In this ecosystem, sustainability represents a significant goal which industry players can achieve by enhancing the efficiency and productivity of construction processes (Heidenwolf and Szabó, 2024b).

The emergence of C4 has already resulted in complex challenges for companies. The research explored multiple challenges and solutions in the C4 paradigm that could guide organisations. Regarding human resources, organisations should focus on the young generation by reforming the industry brand. Knowledge transfer plays a key role in this new environment. Emerging technologies require focused data collection and management processes, while management should change its mindset, be more open to new business models, and align business objectives with innovations. These findings provided input for the requirement definition of the model.

The answer to the second research question explored what innovations bring into the construction value chain. Technologies such as BIM and 3D libraries facilitate enhanced design efficiency, cost estimation and collaboration. During the construction, innovations such as mobile applications and robotics facilitate enhanced project management and safety. In the operation phase, real-time monitoring enables optimised maintenance, while demolition benefits from 3D modelling for sustainable practices. Integration into smart cities leverages real-time data and human-centred infrastructure, necessitating public education and addressing legal and ethical concerns (Nagy and Szabó Zs. 2021).

Six technology groups were identified based on the mentioned technologies as the explicated problem output that transformed the CI, namely BIM and Digital Twin, IoT and sensors, Robotics and Automation, Data analytics methods, and XR. These categories will guide the research in exploring different use cases and connecting those to different maturity levels. Furthermore, the challenges identified in the qualitative research will subsequently serve as critical components of the digital maturity framework, as they act as barriers to DT and influence the digital capability of companies.

4.2.Requirement definition

The requirement definition phase involves outlining a solution as an artefact and transforming the explicated problem into specific demand research (Johannesson and Perjons, 2014). Figure 15 represents the requirement IDEF0 diagram.

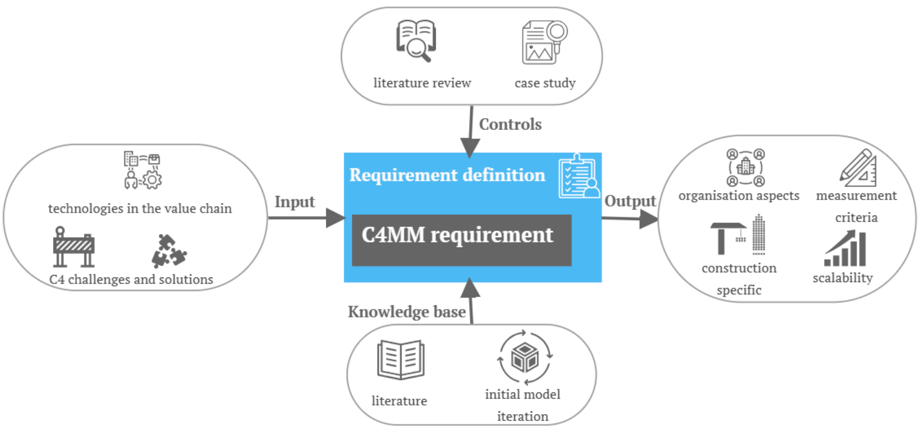


Figure 15 Requirement definition IDF0 diagram

In this process, the initial step in developing the C4MM involved defining its scope, a critical determinant of the model's applicability and overall design. As emphasised by De Bruin et al. (2005) scoping decisions shape all subsequent stages in the model development process, delineating the boundaries for application and ensuring focused relevance. This model is specifically designed for the construction industry (CI), where digital transformation necessitates strategic foresight and integrative planning.

This study identifies the factors influencing C4MM implementation within the CI (addressing RQ3), to provide structured strategic guidance to large general contractors. The model serves as a guideline for technological adoption, helping align innovation with business objectives, integrate new technologies with legacy systems, facilitate horizontal and vertical collaboration, and support cultural and behavioural change (Heidenwolf and Szabó, 2023). The CI involves various stakeholders—including clients, designers, contractors, and suppliers—each with distinct roles and requirements. Attempting to develop a universal model that serves all actors would introduce undue complexity and exceed the scope of this doctoral research. Accordingly, this model targets **large general contractors** because their tasks span the whole life of the project. While applicable to this group, the model may require further development to address the unique needs of small and medium-sized enterprises (SMEs) and other specialised contractor types in future research.

The Solution Artefact is a C4MM, designed to assess the maturity of C4 and the capacity for advanced technological integration. The model should seek to satisfy the following four key attributes that ensure its effectiveness and relevance to the CI. Firstly, the model should incorporate the principal domains of C4 and the interrelationships between its various domains. This approach ensures that the multifaceted nature of DT within the organisational framework is considered and that construction companies address all relevant aspects. The model must be described in a formalised manner that can be interpreted by a computer, on which an automatic or semi-automatic evaluation/advisory IT system can be developed. Secondly, the maturity level should be measured on a five-level scale, ranging from one to five. This scale will allow us to compare different results from various organisations. Thus, the results will be comparable.

Thirdly, the assessment parameters should be developed based on a literature review and expert opinions. Finally, the developed model will be applicable to general contractors in any country, ensuring its broad relevance and usability across different geographical regions and regulatory environments.

It is important to highlight that the current model does not provide a dynamic representation of the organisation but rather captures an "as-is" state. This snapshot serves as a starting point in digital transformation (Peerally et al., 2022), supporting the development of strategic goals and initiatives (Carvalho and Teixeira, 2021). In this context, the model is intended to evaluate the feasibility of introducing one or more technologies, typically framed within a well-defined digital transformation project. Unlike ongoing operational dynamics—such as changes in executive leadership, corporate acquisitions, or the persistent time constraints faced in rapidly evolving market environments—this model does not aim to reflect continuous fluctuations in daily business conditions.

4.3.Design and Develop Artefact – Phase I

Design and Develop Artefact activity involves creating an artefact that addresses the explicated problem and meets the defined requirements (Johannesson and Perjons, 2014). Figure 16 represents the IDF0 diagram of this activity.

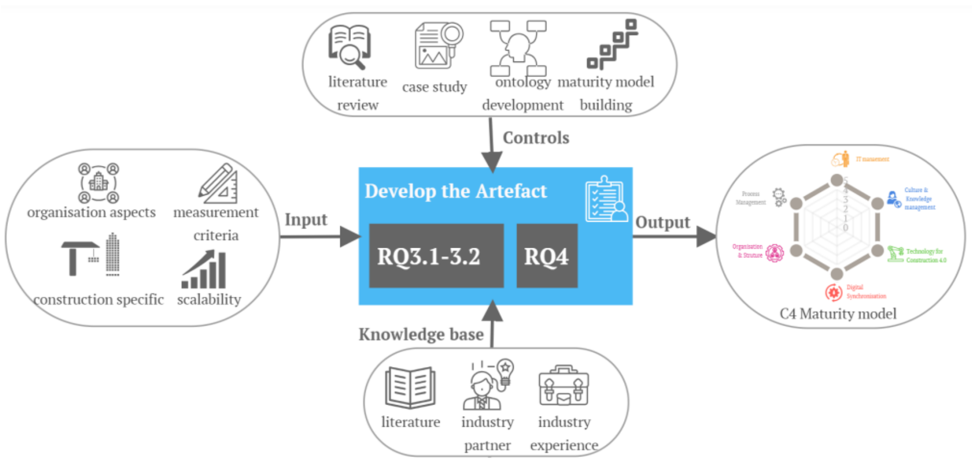


Figure 16 Design and Develop Artefact IDF0 diagram

4.3.1. Model design with literature review

Three models (Gökalp and Martinez, 2021a; Onur et al., 2022; Wernicke et al., 2023) and the definition of C4 (RQ1) were used to define the initial model's main dimensions. The subdomains consist of industry-specific elements identified from previous research (RQ1-RQ2).

Figure 13 shows that at the beginning of my research in 2019, there were still a few articles on the subject. Therefore, I selected the following five categories to create the first model: Manufacturing and Organisation, People Capability, Technology Driven Process, Digital support and Business Organisation strategy to evaluate SME's readiness for I4 (Chonsawat and Sopadang, 2019). In a subsequent study, 18 MMs were examined using nine criteria to enhance a comprehensive digital RM (Gökalp and Martinez, 2021b). Figure 17 Initial C4MM (version 0) represents the main dimensions of this model. Four models were used (De Bruin et al. 2005; Gökalp and Martinez 2021b; Onur et al. 2022; Wernicke et al. 2023), and the definition of C4 was used to define the model's main dimensions. These dimensions are the following: strategic governance, IT and innovative tools, digital process transformation and BIM, supply chain, workforce management, sustainability, and security. The six dimensions of the initial model emerged from the explicated problem output of the research, which conceptualised Construction 4.0 as a novel ecosystem of technologies, evolving processes, and human competencies.

The **strategic governance** dimension addresses structural challenges such as outdated decision-making frameworks, insufficient strategic foresight, and the need for innovative business models. **IT and innovative tools** reflect the technological pressures, R&D requirements, and the role of digital enablers such as BIM, IoT, and automation in reshaping industry processes. **Digital process transformation and BIM** dimensions reflect the CI's efforts to overcome systemic inefficiencies, particularly in data management, procurement protocols, and integrating digital innovation into operational workflows. The **supply chain** addresses the need for greater inter-firm coordination, transparency, and responsiveness, which are driven by digital platforms and collaborative procurement models that enable real-time data exchange and synchronised operations across stakeholders. The **workforce management** responds to labour market pressures, including skill shortages, intergenerational tensions, and the importance of knowledge transfer and rebranding the industry to attract talent. **Sustainability** is emerging in solutions such as creating a more socially responsive industry, investing in innovation, and fostering collaboration for long-term value creation. Finally, the **security** dimension underscores the growing importance of robust data governance—particularly concerning data collection, sharing, and storage—which underpins trust and resilience in increasingly digital construction environments. Collectively, these dimensions distil the key challenges of C4 into the initial digital maturity framework.

At this research stage, we still accepted that readiness and maturity are equivalent and used them as synonyms, but later, we emphasised the distinction between them. This initial model guided the subsequent literature review, which was further refined as additional publications emerged during the later stages of the research, contributing to the model's continued development (Figure 7).

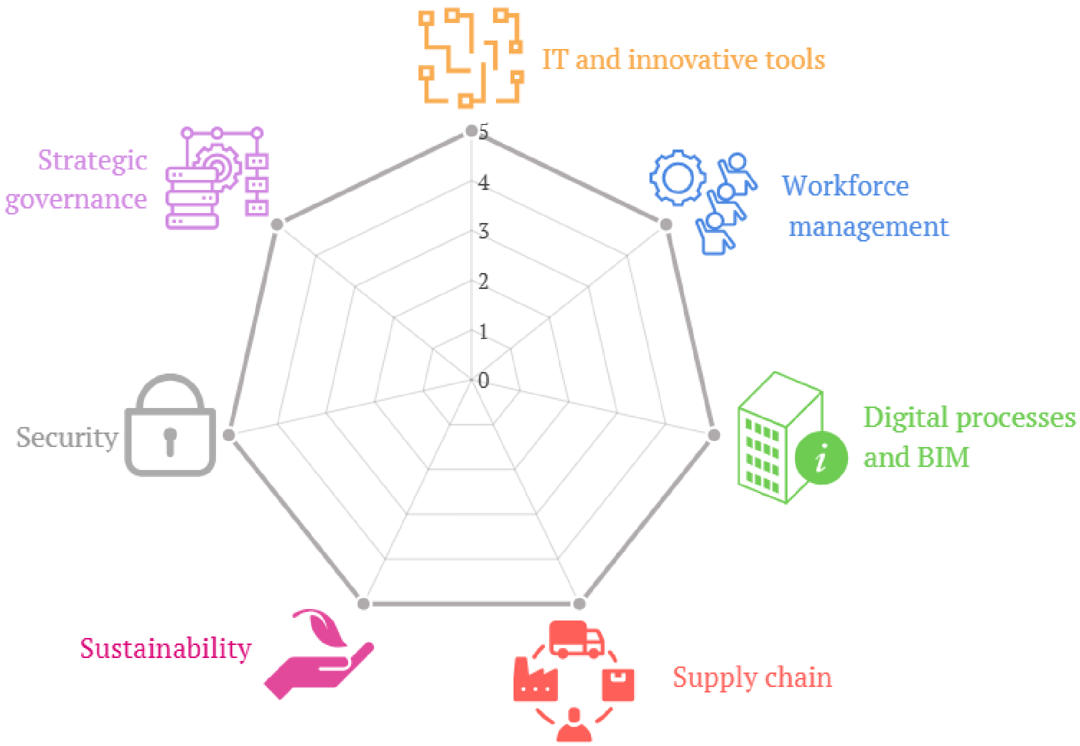


Figure 17 Initial C4MM (version 0)

During the development of the C4MM version 1, six categories were identified from the literature review that refined the C4MM version 0. These initial categories are the following. Technology Management and Business Applications (Gökalp and Martinez, 2022; Williams et al., 2019), Culture and People Management (Das et al., 2023; Gökalp and Martinez, 2022; Pirola et al., 2020; Wernicke et al., 2023; Williams et al., 2019), Collaboration and Communication (Das et al., 2022, 2023), Technology for Automation (Chonsawat and Sopadang, 2019; Das et al., 2022, 2023; Pirola et al., 2020; Succar et al., 2012; Turk, 2021), Innovation (Das et al., 2023), and Change Management and Processes Management (Bou Hatoum et al., 2022; Das et al., 2023; Gökalp and Martinez, 2022; Pirola et al., 2020; Wernicke et al., 2023; Williams et al., 2019). In this new model, Technology Management and Business Applications encapsulates elements from the earlier dimensions of IT and innovative tools, strategic governance, and security. Likewise, Culture and People Management reflects the core concerns of workforce management, and Collaboration and Communication incorporates the supply chain-related themes of inter-organisational integration and information sharing. Innovation in version 1 now spans technological advancement and sustainability considerations, while Change Management and Process integrates digital process transformation and BIM elements.

Technology Management and Business Applications refer to planning, organising, and controlling the use of technology within an organisation to achieve its strategic goals and objectives. It involves the IT management of technology-related resources, including hardware, software, data, networks, people, the IT investment strategy and Cybersecurity.

The Culture and People Management category pertains to overseeing the organisational framework, administering knowledge, and facilitating ongoing progress through digital leadership and persistent skills enhancement among organisational personnel.

Collaboration and Communication refer to the collaboration, communication and cooperation within the physical and digital environment of the organisation as well as throughout its supply chain. It also assesses the organisation regarding the effectiveness of jobsite culture and social media collaboration.

The Technology for Automation category includes the use of industry-specific automated devices, information modelling techniques, sensing systems and data infrastructure, AI and Machine learning, and Human-machine interfaces to streamline and improve the efficiency of construction projects.

The Innovation category evaluates the corporate culture, leadership approach, and innovation feasibility to foster the creation and implementation of novel concepts, products, services, technologies, or procedures that generate value, instigate beneficial transformations for the organisation, and set it apart in the construction sector.

The Change Management and Process category refers to the degree of alignment between organisational and digital processes that enable the company to promptly and efficiently address customer requirements and integrate or introduce new processes. This category also incorporates the organisational capability of change management.

The developed C4MM version 1 has six main categories listed above (Figure 18), ten subcategories, and fifty-seven elements, which can be seen in Annexe II.

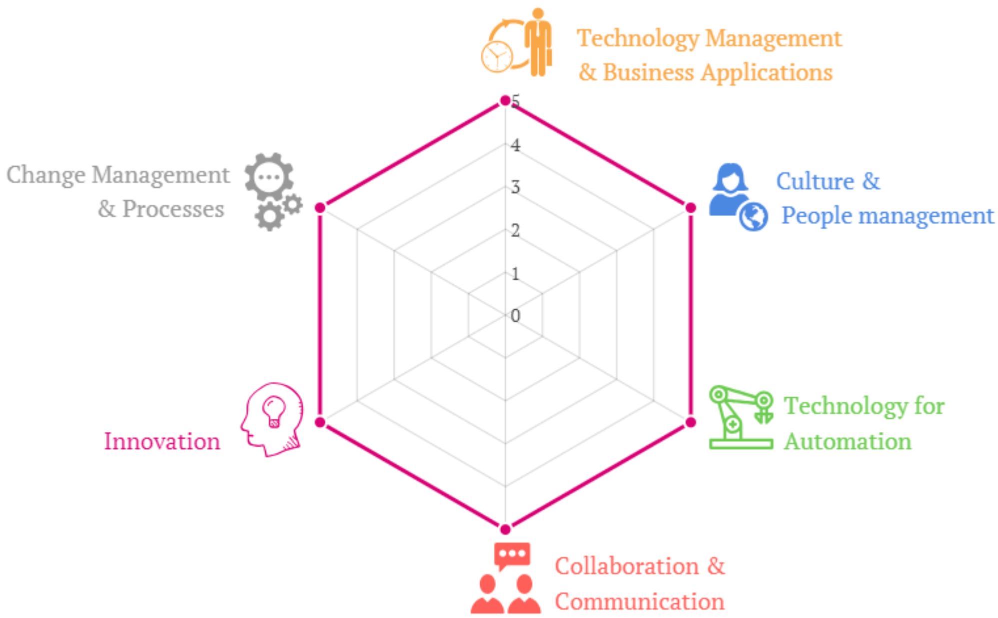


Figure 18 C4MM (version1)

4.3.2. Model development with case studies

The purpose of the case study was to validate and illustrate the applicability of C4MM version 1 by mapping its model categories onto real-world digital transformation (DT) activities within a data-driven façade company. A BPMN diagram was developed to visualise the company's transformation journey, highlighting the relevance of each C4MM category through concrete business activities. This approach shows how the model can assess a company's digital maturity as a static snapshot and analyse its ongoing DT processes in an "as-is" state. Two conference papers were published from this research. The first, titled *"Justification of Construction 4.0 maturity model with a case study of a data-driven façade company",* applied the C4MM to describe and evaluate the company's DT processes. The second, *"Applying BPMN and Ontology to Measure Digital Maturity in Construction 4.0: A Case Study",* presented a concrete example of how the digital transformation was conducted in this company and how the C4MM can contribute to assessing the maturity level attained. It has been demonstrated that the C4MM can assist in evaluating a company as a static outcome and outlining its current DT steps as an as-is state. The BPMN model can subsequently help the company to take further steps in its DT using process improvement methods.

In this case study, the company's digital transformation process unfolded over four interconnected phases, beginning with establishing a strategic and technological foundation. In Phase 1, leadership defined a data-driven business strategy, supported by IT governance, system integration planning, and cloud-based workflow design. Phase 2 shifted the focus to human capital and culture, fostering innovation, building internal expertise, and developing a digitally fluent workforce through targeted education and expert engagement. In Phase 3, the organisation moved into active transformation, emphasising customer-centric processes, BIM ecosystem development, internal and external training, and implementing KPIs and automation strategies to drive innovation and performance. Finally, Phase 4 ensured long-term sustainability through continuous development, robotic process advancement, supply chain integration, and data-driven decision-making powered by BI dashboards.

As illustrated in Table 8, the results of the case study are summarised as follows. The description column represents the C4MM version 1 category, subcategory and elements. The workflow column represents the defined process step from the case study. The verification column shows if the specific model element was verified based on the case study. Finally, the score column represents the importance on a scale of one to five based on the feedback from the company's CEO.

Table 8 Technology Management and Business Application Category Verification

Description	Workflow elements	Verification	Phase	Score
Technology management and business applications				4.27
IT management				5
Information management process	Define a data-driven business strategy. Plan cloud-based workflows	Verified	Phase I	5
IT policy and data governance	Define IT governance policy	Verified	Phase I	5
Technology investment strategy				4.8
User satisfaction	Develop IT skills	Verified with changes	Phase II	5
IT skill development		Verified with changes	Phase II	5
IT Infrastructure	Define system integration requirements	Verified with changes	Phase I	4
IT applications	Integrate into Operational processes	Verified with changes	Phase IV	5
System Integration	Define system integration requirements	Verified	Phase I	5
Cybersecurity				3
Data privacy	Not part of the workflow diagram	It cannot be verified	NA	3
Network security and intrusion detection	Not part of the workflow diagram	It cannot be verified	NA	3
Cybersecurity applications	Not part of the workflow diagram	It cannot be verified	NA	3

In the Technology Management and Business Application category, the case study verified that information management processes, IT policy and data governance, and system integration were the first steps, as well as the key elements of DT. User satisfaction and IT skill development elements resulted from the IT skill development element. The IT infrastructure resulted in the part of the system integration element that the CEO gave a score of 4 on a five-level importance scale, and the originally defined IT applications cannot be measured systematically, but rather by their use cases on operational processes.

Despite cybersecurity playing an important role in DT, this subcategory could not be verified, as detailed information about the company was missing. The CEO also gave a score of 3 to the elements of this category. Based on the case study, system integration was a pivotal element in this category as its requirements guided the development of the IT architecture, the choice of the proper software and later the hardware requirements.

In the Culture and People Management category, all elements except employee satisfaction were verified as important elements of the C4MM. Although the flowchart did not outline the organisational structure management, the interview confirmed that a matrix organisation supports integrating innovation processes and technologies. Digital leadership also played a pivotal role by speeding up education efforts with an internal knowledge base. KPI supported the continuous data-driven culture. The case study demonstrated that knowledge management and the development of a knowledge base played a pivotal role in the company's DT in this category, as it represented the foundation of continuous education, the designation of subject-matter experts, and later, the basis of the cloud-based collaboration workflow (Fig. 23). Table 9 represents these results.

Table 9 Culture and People Management Category Verification

Culture and people management				**4.3**
Organisational structure management	Not part of the workflow diagram	Verified	NA	5
Digital leadership	Define digital expertise fields	Verified	Phase II	5
Knowledge management	Develop a knowledge base	Verified	Phase II	5
HR skill development	Internal education	Verified	Phase III	5
~~Employee satisfaction~~	Not part of the workflow diagram	Disproven	NA	2
Continuous data-driven culture	Measure efficiency with KPI	Verified	Phase III	4

As a result of the case study, the workplace as a job site culture and social media usage elements were removed from the model as they were rated unimportant and could be hard to measure in terms of DT. Cloud-based collaboration and supply chain collaboration were rated as equally important elements of the C4MM. Table 10 represents the results.

Table 10 Collaboration and Communication Category Verification

Collaboration and communication				2.75
~~Workplace as a Jobsite Culture~~	Not part of the workflow diagram	Disproven	NA	0
Supply chain collaboration	Improve supply chain collaboration	Verified	Phase IV	5
Cloud-based collaboration	Develop a cloud-based communication culture	Verified	Phase II	5
~~Social media usage~~	Not part of the workflow diagram	Disproven	NA	1

The necessity for innovative leadership, as evidenced by the case study, was rated as high as five by the CEO. This rating aligns with the established criteria for innovation culture. Both of these elements were key terms during the second phase of DT. The innovation's realisability was also verified; however, its precise definition is crucial for effective measurement. Table 11 represents the results.

Table 11 Innovation category verification

Innovation				5
Innovative leadership	Dedicate an innovation leader	Verified	Phase II	5
Innovation culture	Maintain an innovation culture	Verified	Phase II	5
Innovation realisability	Realise innovation	Verified with changes	Phase III	5

In the initial subcategory of the Change Management and Process category, namely Business Processes, all elements were assigned a rating of 5 on the importance scale. However, the CEO noted that a separate business process strategy does not exist, as it is incorporated into the data-driven business process strategy. The automation process development played a pivotal role in the DT, as all efforts were undertaken to achieve an automated system. The second subcategory, Construction Management and Operational Processes, was recommended for complete removal from the model due to the difficulty in measuring the digital maturity of these elements. It is further recommended that the core and operational processes and the use cases applied by the company be focused on. The details of this model category can be found in Table 12.

Table 12 Change Management and Process Category Verification

Change Management and Processes				
Business processes				5
Technical leadership	Define digital expertise fields	Verified	Phase II	5
Process transformation	Develop automation processes	Verified	Phase III	5
Customer-centred processes	Focus on customer-centred processes	Verified	Phase III	5
Process integration	Develop process integration steps	Verified	Phase I	5
Business process strategy	Define a data-driven business strategy	Verified with changes	Phase I	NA
~~Construction management and Operation process~~				0
~~Design and Quantity Survey processes~~	Not part of the workflow diagram	Disproven	NA	0
~~Construction phase processes~~	Not part of the workflow diagram	Disproven	NA	0
~~Renovation and demolition processes~~	Not part of the workflow diagram	Disproven	NA	0
~~Operation and maintenance processes~~	Not part of the workflow diagram	Disproven	NA	0

The Technology for C4 category results are presented in Annexe II, including the subcategories from which they were derived. The majority of model elements were verified with changes, with the AI strategy and contractual policy scoring particularly low due to their irrelevance to the model. The Technology for Automation category results indicate the need for further modifications, particularly within this category.

In summary, the findings of this case study demonstrated that the developed main categories applied to the analysis of a construction company and that the majority of the model elements had been verified. However, it was also concluded that further refinement and precise definitions were required for the subcategories, elements and definitions. It was noted that some model elements from the C4MM version 1 could be understood by referencing the same concept without a proper definition, such as the development of IT skills or internal education. Furthermore, the case study demonstrated that the Technology for Automation category necessitated in-depth research. The current model is too broad and challenging to develop into a model that can be utilised by industry. Finally, the verification of the C4MM version 1 was strongly influenced by subjectivism, as the validation of the model relied solely on a simple case study, which can strongly influence the final outcome of the research (Peshkin, 1988). Thus, further validation and an in-depth systematic literature review are needed during the next phase of the model building.

4.4. Redesigning the Artefact – Phase II.

4.4.1. Model design from the literature review

The C4MM was subjected to continuous development and testing, which revealed the necessity for more precise definitions based on the existing literature. Consequently, the next development phase entailed a systematic literature review based on PRISMA (methodology in Section 2.3.3.1) and the creation of precise definitions for each model category.

The resulting model comprises six main categories: IT management, Culture and Knowledge management, Technology for C4, Digital synchronisation, Organisation and Structure, and Process Management (Figure 19). The following paragraphs will introduce these categories in detail.

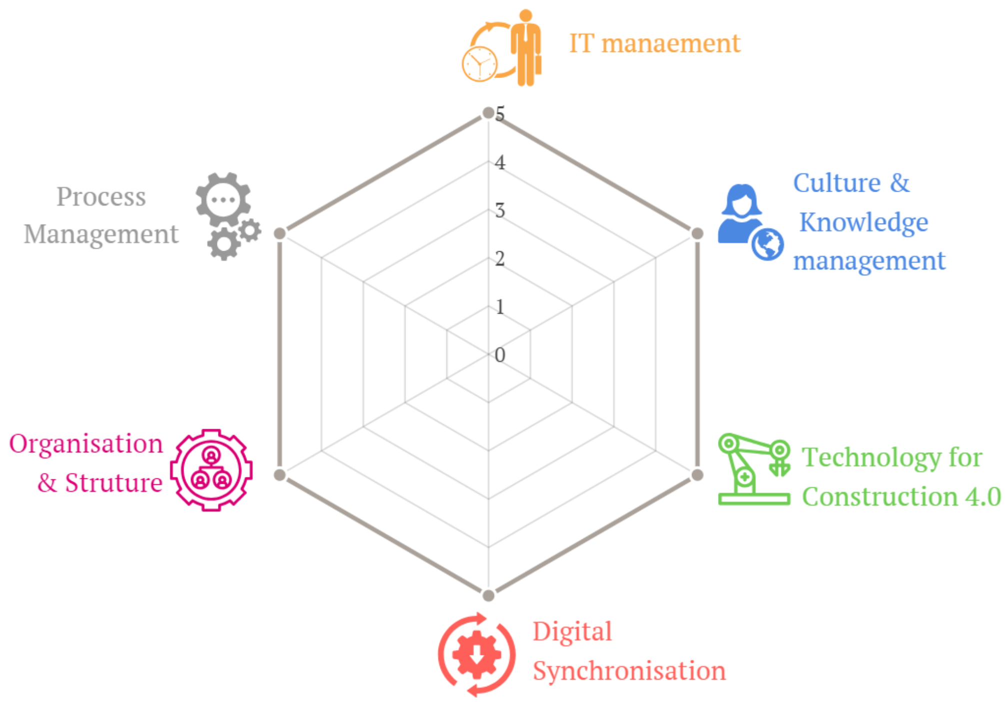


Figure 19 The developed C4MM (version 2)

Culture and knowledge management

The term knowledge management refers to the process of building and managing collective organisational knowledge. It plays a key role in DT and consequently received new attention due to the development of the I4 paradigm (de Bem Machado et al., 2022). Culture and knowledge management are influenced by collective intelligence, which refers to the organisation's internal knowledge. Knowledge management is the process that supports these activities. Its capabilities are influenced by corporate culture. Figure 20 illustrates these subcategories.

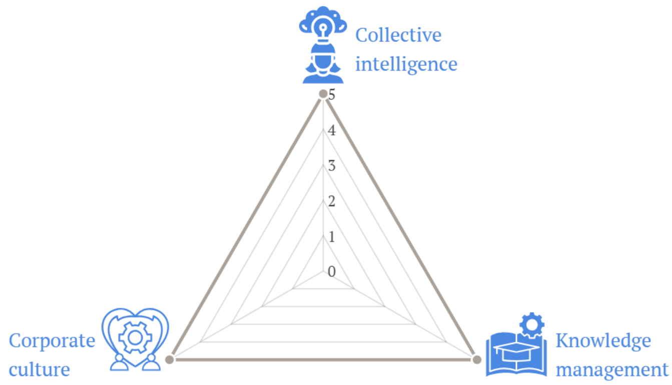


Figure 20 The subcategories of Culture and knowledge management

Collective Intelligence

Collective intelligence incorporates "*the pooling of skills, knowledge, creativity, thinking, and problem-solving abilities*" (McManus and Snyder, 2003). The synergic combination of these terms is facilitated by a collaborative culture and supported by digital tools (Gökalp and Martinez, 2021a; Kırmızı and Kocaoglu, 2022; Monshizadeh et al., 2023; Pirola et al., 2020; Schumacher et al., 2019; Zaoui and Souissi, 2022).

Key components include competencies, skill acquisition and employee autonomy, competency mapping, competency building (Das et al., 2022, 2023), and personnel training to enhance professional abilities and expertise in the C4 era (Chen et al., 2024). Health, safety and environmental protection are key elements of CI corporate intelligence (Asah-Kissiedu et al., 2023)

Knowledge Management

Knowledge management includes " *capturing, organising, filtering, sharing, and retaining key corporate knowledge as an asset* " (McManus and Snyder 2003, pp. 17). Knowledge management encompasses the creation of knowledge, the development of digital systems for its storage, and the implementation of knowledge-sharing processes, including continuous training (Amaral and Peças, 2021; Haryanti et al., 2023, 2024; Mo et al., 2023; Zaoui and Souissi, 2022).

The transformative CI requires continuously maintaining the expertise and education of emerging technologies (Chen et al., 2023) and identifying employees with advanced technological competencies to support effective knowledge transfer with critical thinking (Tuma Neto et al., 2022).

Corporate culture

Corporate culture assesses the organisation's flexibility for change (Santos and Martinho 2020; Wagire et al. 2021; Razkenari and Kibert 2022; Haryanti et al. 2023) through employees' mindset for innovations (Razkenari and Kibert, 2022) and collaboration, which is supported by continuous professional development, including management-level education, and mentoring (Das et al., 2023).

An organisational culture that values digital technology innovation and employees' mindset toward adopting those technologies is crucial for DT (Chen et al., 2023). The capacity for digital innovation is indicative of the organisation's research and development competence and thus influences transformation and overall efficiency (Zhu et al., 2024). Adapting organisational structures, work processes, and employee skills while promoting a digital culture is vital (Chen et al., 2023). Multidisciplinary approaches and collaboration reinforce these strategies (Tuma Neto et al., 2022).

Digital Synchronisation

Digital synchronisation refers to aligning and integrating various digital elements within an organisation to achieve seamless operation and transformation.

This involves establishing robust governance, adhering to legal and regulatory frameworks, and implementing comprehensive standards to guide digital activities and initiatives. Human-machine collaboration is another element of digital synchronisation that supports automated systems and humans seamlessly working together. (Figure 21)

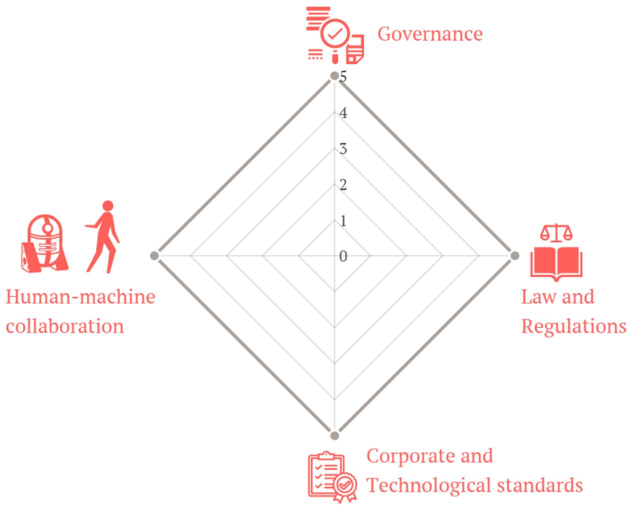


Figure 21 The subcategories of digital synchronisation

Governance

Governance encompasses the strategic oversight and management of digital resources and processes.

It provides a framework for decision-making and accountability, facilitating the alignment of digital initiatives with organisational goals (Gökalp and Martinez, 2022). It encompasses utilising management platforms for collaborative work to integrate and enhance the intelligence of finance and human resource management (Han et al., 2024). This includes data governance, which guides the availability, usability, integrity, and security of data used within an organisation. Furthermore, it incorporates waste management, ethics, and human rights (Tuma Neto and Araujo de Souza Junior 2022).

Law and Regulations

Law and Regulations refer to the regulatory environment and policies influencing a company's DT.

The economic and regulatory environment plays a significant role in shaping DT (Zaoui and Souissi 2022), especially in the regulations that govern the use of new digital technologies (Chen et al., 2023). The Law and Regulations category includes regulations related to technology, such as BIM and IoT (Han et al., 2024; Zhu et al., 2024), finance and taxation (Han et al., 2024; Zhu et al., 2024), labour rights (Kırmızı and Kocaoglu, 2022), and legal protection to safeguard intellectual property and data security (Schumacher et al., 2019).

Policy and Technological Standards

The Policy and Technological Standards subcategory is a comprehensive framework of principles and guidelines that govern organisational activities (Chen et al., 2024).

This framework encompasses documentation and modelling standards, procedures, and guidelines for strategic planning. It includes policies and standards related to BIM, IoT, technology research and development, and digital talent training (Han et al., 2024; Zhu et al., 2024). Additionally, it defines the division of responsibilities and rights among participants, such as data ownership and access rights (Chen et al., 2024). BIM policy plays crucial preparatory, regulatory, and contractual roles in the design, construction, and operational processes (Jason and Umit, 2010).

Human-machine collaboration

While several digital maturity models were analysed and mentioned multiple dimensions, none focused on the evolving nature of human-machine collaboration in the CI. This concept aims to describe a collaborative working environment between human cognitive skills to support real-time decision-making and robotic capabilities to perform complex or repetitive tasks in dynamic environments or site conditions (Brosque et al., 2020; Liang et al., 2021; Marinelli, 2022) to enhance productivity, efficiency, and safety (Maurtua et al., 2017).

IT Management

IT management is the strategic oversight and coordination of an organisation's IT resources to support and drive DT. IT management includes the following four fields: Cybersecurity, Data-centric IT management, Digital Infrastructure Management, and System Integration.

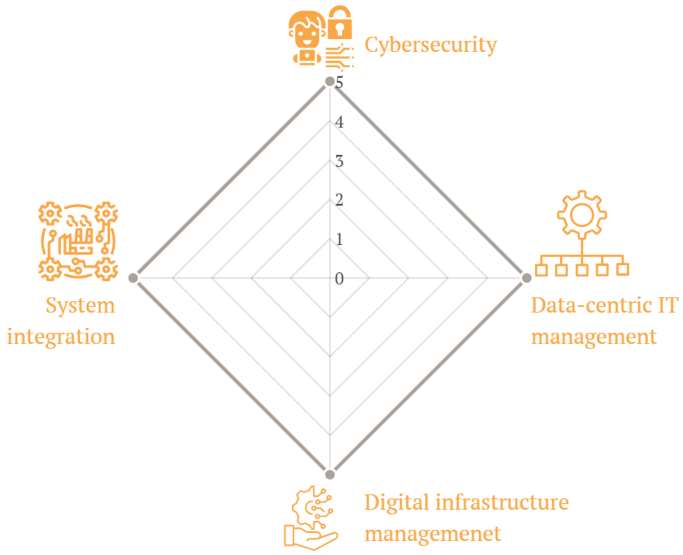


Figure 22 The subcategories of IT management

Cybersecurity

The emergence of internet-based technologies demands robust cybersecurity measures to protect systems from cyberattacks (Ribeiro et al., 2022; de Soto et al., 2022). Cybersecurity's focus is to prevent cyber-attacks and unauthorised access to the systems by preserving the confidentiality, integrity and connectivity of computer systems (Neil et al., 2023), which should be a priority for enterprises to safeguard data and systems (Han et al., 2024).

It involves data security and integrity, ensuring secure data storage, adhering to data security standards, and maintaining robust data security protocols (Das et al., 2023). Furthermore, it includes continuous security maintenance to protect data sources and compliance with legal requirements (Zhu et al., 2024).

Data-Centric IT management

The objective of Data-Centric IT management is real-time data processing and interoperability to develop and maintain data-driven automatic systems that support daily operations across the organisation with data analytics.

Automatic and real-time data processing requires context-based information and data collection (Das et al., 2023). Data collection includes determining the type and extent of data to be acquired for internal and external data integration (Das et al., 2023). Optimal data requires eliminating data duplication (Stich et al., 2018). The data collection requires system integration from multiple information systems across the organisation (Stich et al., 2018) to collect real-time data from cyber-physical systems, digital twins and IoT devices (Das et al., 2022). During data processing, enterprises should safeguard the systems and the data (Stich et al., 2018).

System Integration

System integration involves creating and managing multiple connected software and systems, providing a core ecosystem of DT for the organisation. This ecosystem unifies various technologies and tools, providing a single operating interface and a data interaction platform. This process can help companies share seamless information and enable collaborative work to enhance efficiency (Han et al., 2024), preventing the need for data reconstruction (Chen et al., 2024).

In the CI, the key obstacle to system integration is interoperability. Interoperability issues generate increased costs for organisations and all stakeholders in the building life-cycle (Robert E., 2005). Thus, BIM interoperability – as the core technology of CI digital transformation – influences organisations' digital maturity. It is shaped by multiple interrelated factors, including "legal, organisational, technical, and semantic interoperability" (Shehzad et al., 2021; Turk, 2020).

On the legal interoperability level, organisational policy, applied technological standards, and contractual structuresither support or limit BIM implementation (Shehzad et al., 2021; Turk, 2020).

Internally, an organisation's capacity to adopt BIM depends on its digital maturity and strategic leadership support (Shehzad et al., 2021). Additionally, integrating BIM with

XR demands technical compatibility and shift toward collaboration among internal and external stakeholders (Van et al., 2025).

Technical aspects involve managing diverse data formats, exchanging information effectively, especially with Industry Foundation Class (IFC), and maintaining in-house expertise capable of operating complex BIM systems. Additionally, the used platforms should meet cybersecurity requirements, especially regarding access rights. The applied technologies should be compatible to support continuous data flow. (Shehzad et al., 2021)

Semantic interoperability refers to the seamless exchange of information between different software tools, which requires consistent data standards and clear process definitions to enable meaningful system-to-system communication (Shehzad et al., 2021; Turk, 2020). This layer also includes syntactic interoperability, which refers to the basic ability of different systems to exchange information (Turk, 2020).

Organisation and Structure

The *Organisation and Structure* category focuses on structural agility and flexibility, strategic collaboration and coordination (digital transformation communication, horizontal collaboration and coordination, vertical collaboration and coordination), and the strategic leadership required to align the organisation's vision and goals (Stich et al., 2018).

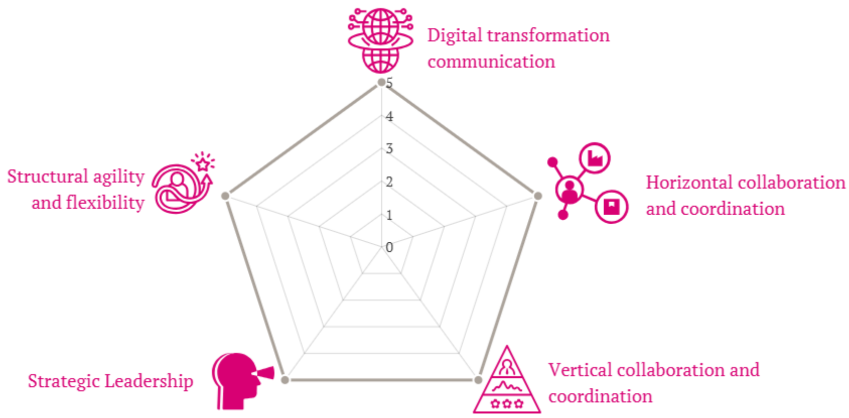


Figure 23 The subcategories of Organisation and Structure

Digital transformation communication

Digital Transformation Communication refers to systematically disseminating the vision, strategies, and processes essential to DT to enhance interactions and networks and support decision-makers (Haryanti et al., 2024; Schwer et al., 2018; Stich et al., 2018).

Effective communication ensures systematic information integration to support decision-makers (Stich et al., 2018). This approach facilitates C4 activities by setting clear employee objectives and involving all organisational levels (Schumacher et al., 2019) to increase employee engagement and commitment to DT (Zhu et al., 2024).

Horizontal Collaboration and Coordination

Horizontal Collaboration and Coordination examining customer integration into design, production and construction processes, enhancing value propositions, and increasing customer engagement and trust through tools and transparent information exchange (Das et al., 2023; Haryanti et al., 2023, 2024; Hortovanyi et al., 2023; Kırmızı and Kocaoglu, 2022; Monshizadeh et al., 2023; Schumacher et al., 2019; Schumacher and Sihn, 2020; Zaoui and Souissi, 2022).

The digital platform integration facilitates the seamless and transparent data and information exchange among teams and partners, providing transparent communication channels which promote a more profound connection towards common goals (Das et al., 2022; Haryanti et al., 2023; Schumacher et al., 2019). This integration permits customers to participate in the decision-making process, thereby enhancing the overall value proposition (Haryanti et al., 2023; Monshizadeh et al., 2023; Schumacher et al., 2019), which increases customer engagement (Haryanti et al., 2024; Kırmızı and Kocaoglu, 2022; Schumacher et al., 2019), and trust (Schumacher and Sihn, 2020; Zaoui and Souissi, 2022). Horizontal integration requires consolidated data usage by removing old processes and developing entirely new ones. These generate new organisational policies, positions (Dolla et al., 2023), and standards that require talent training (Han et al., 2024) to elevate DT inside the organisation. Additionally, this collaboration encompasses digital technology-related knowledge and information sharing across organisations (Chen et al.

2023; Han et al. 2024).

Vertical collaboration and coordination

Vertical collaboration and coordination refer to the systematic integration and alignment of various organisational levels and functions to achieve effective DT and operational efficiency.

This involves cooperation and collaboration between functional organisational units (Chen et al., 2023; Das et al., 2023; Oswald and Lingard, 2019), cooperation with networks and the centralised coordination of C4 activities across the organisation (Amaral and Peças, 2021; Schumacher et al., 2019), which is supported by IT-enabled resources to facilitate comprehensive digital integration across all functional areas (Hortovanyi et al., 2023). In this environment, established dedicated teams can drive digitalisation efforts, ensuring continuous progress and adaptation to new technologies (Wagire et al., 2021). Effective vertical collaboration also encompasses the organisation's capacity to coordinate digital initiatives and operations across different levels, promoting seamless integration and efficiency (Ávila-Bohórquez and Gil-Herrera, 2022; De Carolis et al., 2017).

Strategic Leadership

The Strategic Leadership category investigates the degree of alignment between the management mindset and the strategy with C4 objectives.

This involves the creation and execution of strategies (Chen et al. 2024), including governance, strategic planning, and resource allocation (Colli et al., 2019; Sukrat and Leeraphong, 2024; Thordsen and Bick, 2023) to embrace C4 and balance long-term and short-term goals (Chen et al., 2024). A strong vision and roadmap inspire the organisation and leverage technology for the future with shared value (Haryanti et al., 2023; Schumacher et al., 2019). Top management commitment has a significant impact on driving C4 maturity (Das et al., 2022), fostering a data-driven culture (Pirola et al., 2020; Schumacher and Sihn, 2020) and prioritising data-driven decision-making, goal-setting and continuous improvement (Ghobakhloo, 2018; Gökalp and Martinez, 2021a; Haryanti et al., 2024). Nevertheless, it is of the utmost importance that the CI undergoes a fundamental shift in its managerial approach, moving away from a project-centric mindset towards a process-oriented one (Bou Hatoum et al., 2022; Tuma Neto et al., 2022). Applying agile management, leaders can focus on forming flexible communities, promoting digital leaders to drive transformation (Amaral and Peças, 2021; Ávila-Bohórquez and Gil-Herrera, 2022; Han et al., 2023; Kırmızı and Kocaoglu, 2022; Mateo-Casalí et al., 2023; P. Senna et al., 2023), and foster dynamic and digital partnerships (Razkenari and Kibert, 2022). Furthermore, they should also follow the continuously changing digital environment, which brings legal, financial and regulatory developments (Gökalp and Martinez, 2022), and emphasise the importance of health, safety and environmental (HSE) management (Asah-Kissiedu et al., 2023).

Structural agility and flexibility

Structural agility and flexibility refer to the capacity of an organisational framework to adapt swiftly to market shifts by utilising comprehensive human resource planning, management systems (Wernicke et al., 2023), and aligning organisational processes with C4 goals to ensure continuous adaptation and innovation (Zhu et al., 2024). This can be done by eliminating rigid hierarchical structures (Kırmızı and Kocaoglu 2022), significantly impacting the development and execution of the enterprise processes (Ferraz et al., 2020). Human resources should also focus on increasing and maintaining workers' continuous engagement through frequent knowledge and skill development (Pornthepkasemsant and Charoenpornpattana, 2019). This can be achieved by empowering employees based on their expertise (Kırmızı and Kocaoglu, 2022) and dedication to subject matter or digital experts who can speed up the DT process inside the organisation (Zhu et al., 2024).

Process Management

"*The digitalisation of business processes and management is a core part of the digital transformation of construction companies*" (Han et al. 2024, pp. 14). The Process Management category is defined as follows: "*Processes can be defined as a set of interrelated or interacting activities that transform inputs into outputs for the purpose of* *enabling the digital transformation of the organisation*" (Gökalp and Martinez 2021, pp. 4). While maturity model key element is the processes category (Thomas and Saleeshya, 2023) that drives DT (Asah-Kissiedu et al., 2023; De Carolis et al., 2017; Gökalp and Martinez, 2022; Mateo-Casalí et al., 2023; Wagire et al., 2021) it facilitates the organisation's value proposition (Mo et al., 2023) by transforming workflows to digital work processes (Sukrat and Leeraphong, 2024) to increase organisational work efficiency (Lin et al., 2022), and by creating new processes to collect and share data (Pirola et al., 2020; Sukrat and Leeraphong, 2024). BPMN can significantly accelerate the DT in CI (Han et al., 2024), which is defined as the following: "*Business process management (BPM) is a discipline involving any combination of modelling, automation, execution, control, measurement, and optimization of business activity flows in applicable combination to support enterprise goals, spanning organizational and system boundaries, and involving employees, customers, and partners within and beyond the enterprise boundaries*" (Von Rosing et al., 2014).

Process Management includes four fields in the C4MM: organisational change management, process development, core and operational processes, and supporting processes.

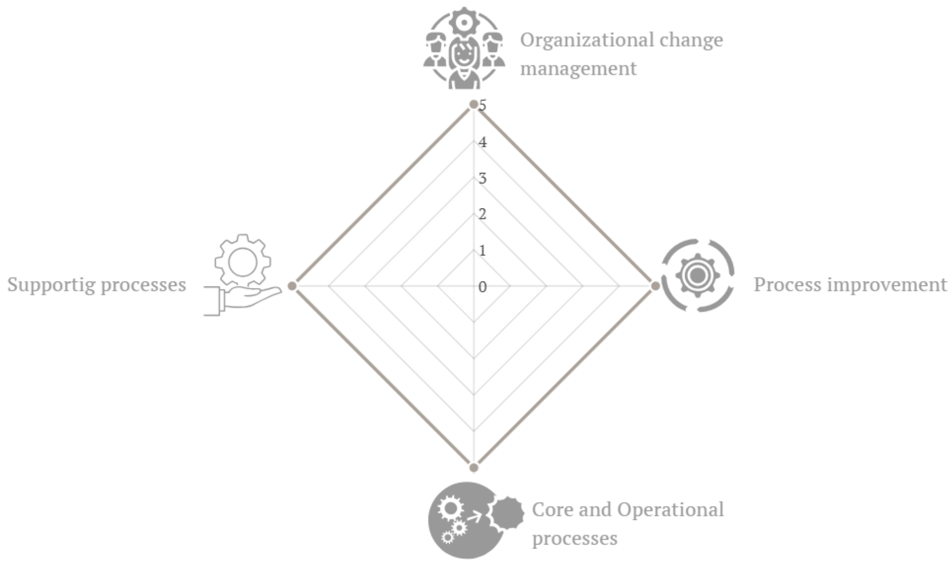


Figure 24 Process management category

Organisational Change Management

Organisational Change Management is a process that drives the transition from the current state of an organisation to a desired future state (Bellantuono et al., 2021). This approach emphasises renewing the organisation's direction, structure, and capabilities to meet evolving internal and external requirements (Amaral and Peças, 2021; P. Senna et al., 2023) through innovations.

Multiple business fields are connected through Organisational Change Management. Firstly, the strategies to manage individuals ensure alignment with the organisation's digital strategy, structure, and key performance indicators (Haryanti et al., 2023, 2024; Thordsen and Bick, 2023). Secondly, the development of digital competencies through the implementation of structured training programs and integrated digital skills within the organisational culture (Das et al., 2023; Haryanti et al., 2023, 2024; Zhu et al., 2024) and the continuous monitoring of its effectiveness (Das et al., 2023). Additionally, the activities related to digitalisation, cross-functional collaboration, partnership programmes for accessing innovations, and leveraging digital services to reach market potential (Haryanti et al., 2024). Finally, the continuous changes triggered by C4 require flexibility and the ability to achieve this through strong governing leadership (Das et al., 2022; Tuma Neto et al., 2022). This flexibility includes changes in construction plans, production processes, and supply chain processes (Das et al., 2022).

Process development

Process development is a systematic approach to help an organisation optimise its underlying processes to achieve more efficient results (Harrington H, 1991), which is closely aligned with the principles of lean manufacturing (Mo et al., 2023). Due to the emergence of C4 technologies, organisations require entirely new processes aligned with a long-term strategy (Dolla et al., 2023).

Process improvement involves the introduction of new or improved techniques, equipment and software that necessitate a comprehensive re-evaluation of BPM, including *"the digitisation of enterprise management and project management processes* *which significantly improve the operational efficiency and construction efficiency of enterprises"* (Han et al. 2024, pp. 14). This concept includes identifying the potential process development areas which can support organisations in achieving their strategic goals (Gökalp and Martinez, 2022) and a higher level of maturity (Monshizadeh et al., 2023). Emerging technologies can reshape traditional BPM, transitioning it towards a more exploratory and dynamic framework (Czvetkó et al., 2022). BIM is a key technology that brings challenges and requires continuous process improvement and monitoring for successful implementation (Ferraz et al., 2020). Data analytics and visualisation tools can inform real-time decision-making and streamline operational workflows by utilising advanced technologies, including BIM, GIS, and big data, to develop digital technology platforms for multi-party collaboration in digital design (Han et al., 2024). Innovation, research and development (Das et al., 2023) and quality management (Ávila-Bohórquez and Gil-Herrera, 2022) are key aspects to guide organisations in this new era. The CI can benchmark from I4 and use tools, including key performance indicators, LEAN or calculation methods for innovation ROI to address these aspects. Process development focuses on growth through innovation and the selection of innovations to invest in, with a particular emphasis on return on investment (ROI) (Das et al., 2023). Additionally, implementing KPIs is essential for measuring the success of these improvements (Chen et al., 2023).

Core and Operational processes

Operational and Core processes refer to a set of essential activities that enhance the overall operational efficiency and are crucial for effective construction life-cycle project management to generate financial profit for the organisations and assess how 'building as a product' activities are affected by different technologies.

In the core processes, these activities are design and pre-construction, manufacturing, and assembly and construction (Razkenari and Kibert, 2022). These processes entail comprehensive planning and integrating advanced technologies, including IoT, big data, digital twins, and BIM (Zhu et al., 2024). Additionally, it includes various methodologies such as the application of Integrated Project Delivery (IDP), LEAN construction principles (Wernicke et al., 2023) or the Design for Manufacturing and Assembly (DfMA) approach *"on optimising the design of a product or system to simplify manufacturing and assembly processes"* (Christopher et al. 2023, pp. 9). Effective management of these core processes ensures project success by maintaining quality, schedule, cost, and safety while fostering continuous improvement and strategic competitiveness in a dynamic market environment (Han et al., 2024; Pornthepkasemsant and Charoenpornpattana, 2019; Razkenari and Kibert, 2022; Zhu et al., 2024).

The main activities in the operational processes are internal collaboration, data usage, and knowledge retrieval (Amaral and Peças, 2021). Autonomous processes and IT-enabled planning and steering processes are key to efficient operations (Gökalp and Martinez, 2021a; Wagire et al., 2021).

Supporting processes

Supporting processes encompass essential activities that ensure the smooth operation of core and operational processes in CI.

These processes are the following: human resource (Zhu et al., 2024), IT (Zhu et al., 2024), legal and compliance management (regulatory compliance, contract management, dispute resolution), logistic and supply chain management (material supply planning; inventory planning, transportation planning and equipment planning and management) (Razkenari and Kibert, 2022), marketing and business development, document management (document and version control) (Pornthepkasemsant and Charoenpornpattana, 2019), and financial processes (Han et al., 2024). Support activities encompass security, information management, configuration, documentation, compliance, and incident management (Hortovanyi et al., 2023). Digital technologies also support market data collection, analysis, service improvement, and automation of warehouse operations and transportation planning (Ghobakhloo, 2018; P. Senna et al., 2023). Additionally, these processes encompass the management of laboratory operations, quality measurement, and reporting (Ávila-Bohórquez and Gil-Herrera, 2022; Schumacher and Sihn, 2020).

Technology for Construction 4.0

Technology for Construction 4.0 refers to the usage and maturity of integrated digital tools, systems, and methodologies that drive the transformation of the CI. Numerous studies have attempted to explain new and current C4 technologies, including (Ammar et al., 2022; Ammar and Nassereddine, 2022; El Jazzar et al., 2021; Osunsanmi et al., 2020; Shafei et al., 2022; Souza and Debs, 2023).

Multiple technologies and technology combinations have appeared recently to address productivity challenges. These technology borders are blurred since these technologies are combined for multiple use cases. Our research has shown that companies' technological adaptation cannot be measured simply in terms of technology but rather in the use cases in which the company applies it. These technologies may eventually become the organisation's basic infrastructure. Thus, the technological use case gives a more representative picture of an organisation's technological maturity. C4MM will only examine the different use cases of the core technology groups, namely AI/Machine Learning and Big Data Analytics, IoT and sensors, GIS, Digital Twin, BIM, Construction Robotics and Automation, Extended Reality, and ERP and Project Management Platforms. Based on the latest I4 report for the Building Industry from the leading Australian research centre (Christopher et al., 2023), these categories were chosen to guide and explore use cases in the qualitative research.

Artificial Intelligence *refers to the development of intelligent machines capable of performing tasks that typically require human intelligence. It encompasses techniques such as machine learning, natural language processing, and robotics to enable systems to analyse data, reason, learn, and make decisions."* (Christopher et al. 2023, pp.9). Key applications of AI include automating construction processes, safety, planning, and waste management (Datta et al., 2024).

"***Building Information Modelling*** *is a set of technologies, processes, and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. It allows collaboration, integration, visualisation, and simulation throughout the construction project lifecycl*e." (Christopher et al. 2023, pp. 9). BIM enables design, project management, cost estimation, facility management, and quality control tasks (Bassanino et al., 2014; Whyte, 2019).

Construction Robotics and Automation involves using robots and automated systems to perform construction tasks (Kamath and Sharma, 2019). Robotics enables automated tasks on construction sites and in prefabrication, site monitoring, survey and more sustainable construction (Behzadan et al., 2015; Kamath and Sharma, 2019).

Data analytics involves the process of gaining meaningful information from data (Christopher et al., 2023). Data analytics enables construction companies to forecast financial performance, measure labour efficiency, track asset information, and monitor construction progress and performance indicators (Ahmed et al., 2018).

A **digital twin** is a live digital counterpart of a physical object, process, or system. Unlike static representations found in traditional BIM models, digital twins continuously receive sensor data from real-world assets, allowing for real-time observation, performance analysis, and predictive modelling (Noroozinejad Farsangi et al., 2024). Digital twin enables key activities such as real-time monitoring, predictive maintenance, education, and inspection (Noroozinejad Farsangi et al., 2024).

A Geographic Information System (GIS) allows users to work with data linked to physical locations on Earth. These platforms combine spatial databases with analytical tools to interpret and visualise geographical patterns. These systems integrate location-based data from sources like satellite imaging and mapping, enabling users to store, manipulate, and represent both physical and abstract spatial information (Wang et al., 2019), construction planning, material tracking, facility management, energy optimisation, and environmental monitoring (Yan et al., 2022).

XR technologies create immersive digital environments that interact with the physical world. XR is an umbrella term that includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). While VR is a fully immersive digital environment that simulates physical presence in a virtual world, AR overlays digital information onto the physical world, enhancing real-world environments with virtual elements (Christopher et al., 2023; Ma, 2025).

IoT refers to the network of connected devices embedded with sensors, software, and connections that allow real-time data exchange and communication (Anjum and Ayuns Luz, 2024; Omrany et al., 2024). Furthermore, this category also includes camera technologies that allow users to collect data on a construction site. IoT enables the construction industry to track assets, monitor the environment, and mitigate risks (Anjum and Ayuns Luz, 2024).

Project Management Platforms are cloud-based tools that enable real-time collaboration, communication, and management of construction projects (Rinkesh Gajera, 2019). Key activities with the project management platforms include: progress tracking, collaboration, monitoring, communication and document sharing (Rinkesh Gajera, 2019).

Table 13 Key technologies of the C4MM

Technology	Definition	Key Applications	Reference
AI/ML	systems that are capable of simulating human cognitive abilities	automating construction processes, safety, planning, and waste management	(Datta et al., 2024)
BIM	technologies that enable digital modelling and collaboration	Design, project management, cost estimation, facility management, quality control	(Bassanino et al., 2014; Christopher et al., 2023; Whyte, 2019)
Construction Robotics	Automated task execution	Automated tasks, site monitoring, and sustainability	(Behzadan et al., 2015; Kamath and Sharma, 2019)
Data Analytics	Data mining and insight generation	financial performance forecasting, measuring labour efficiency, asset information tracking, and project monitoring	(Ahmed et al., 2018)
Digital Twin	live digital counterpart of a physical object, process, or system	Real-time monitoring, predictive maintenance, education, and inspection	(Noroozinejad Farsangi et al., 2024)

Technology	Definition	Key Applications	Reference
GIS	Spatial data analysis	construction planning, material tracking, facility management, energy optimisation, environmental monitoring	(Yan et al., 2022)
IoT	a network of connected devices that enables real-time data collection	Asset tracking, environmental monitoring, and risk mitigation	(Anjum and Ayuns Luz, 2024)
XR	immersive digital environments that interact with the physical world	Design review, training, simulation, site safety education, and site inspection	(Bohn and Teizer 2010; García de Soto et al. 2019; Whyte 2019; Ma 2025),
Project Management Platforms	Cloud-based management tools for collaboration and communication	Progress tracking, collaboration, monitoring, communication and document sharing	(Rinkesh Gajera, 2019)

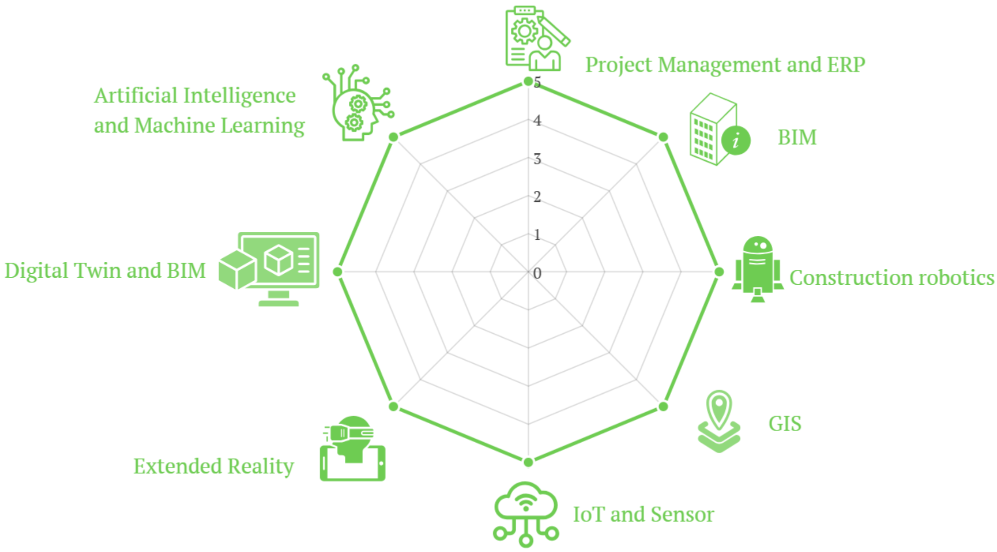


Figure 25 Technology for C4 category

4.4.2. Maturity Level design from the literature review

The following paragraphs summarise the results of the maturity level dimensions from the literature review.

At **Maturity Level 1**, companies lack a digital culture and do not prioritise transformation (Das et al., 2024; Han et al., 2024; Jäkel et al., 2024; Perera et al., 2023), thus neglecting digital skill development (Perera et al., 2023). While some companies implement ERP systems (Razkenari, 2019; Wernicke et al., 2023), these are often used in isolation, lacking integration with other technologies (Razkenari, 2019). Consequently, information exchange remains manual with traditional operation processes (Han et al., 2024; Razkenari, 2019). Furthermore, IT security is not a priority (Han et al., 2024), and management lacks strategic alignment of digital transformation and fails to adopt an organisational structure accordingly (Han et al., 2024). Decision-making is based on personal experience rather than data-driven insights (Razkenari, 2019). The absence of digital tools makes it difficult for companies to assess the return on investment in technology (Han et al., 2024).

The utilisation of essential IT tools, such as email, CAD, websites and spreadsheets, is observed along with the use of local storage (Perera et al., 2023), and standalone tools in individual projects (Han et al., 2024).

At **Maturity Level 2**, companies acknowledge the strategic significance of digital transformation (Han et al., 2024) and seek technologies to address operational challenges (Das et al., 2023). However, traditional processes remain prevalent, and digital adoption is often fragmented and inconsistent (Das et al., 2023, 2024). Efforts to standardise processes emerge through implementing ERP systems and cloud-based services, yet IT deployment lacks integration (Razkenari and Kibert, 2022). Organisations initiate data collection and standardisation efforts but require further development to ensure IT consistency across construction sites and strengthen cybersecurity (Han et al., 2024). Senior management drives strategic planning, aiming to realign organisational structures for digital transformation, though horizontal collaboration remains underdeveloped (Jäkel et al., 2024; Perera et al., 2023). While digital technologies and standardised procurement practices are increasingly adopted, digital implementation remains experimental, primarily within isolated projects (Han et al., 2024; Jäkel et al., 2024). Despite technological roadmaps and process automation progressdigital performance measurement is still lacking (Han et al., 2024).

Emerging adoption of collaboration technologies, IoT, RFID, sensors, BIM, and PMP signals a shift toward integrated digitalisation, though complete ERP and BIM integration remains a challenge (Han et al., 2024; Perera et al., 2023)

At **Maturity Level 3,** construction companies reach a critical transition toward Industry 4.0, shifting from isolated digital adoption to enterprise-wide transformation (Das et al., 2023, 2024). Digital policies emerge, supporting structured training, digital talent development, and governance frameworks for long-term technology adoption (Razkenari 2019; Perera et al. 2023; Han et al. 2024). Companies replace single-use business applications with fully integrated ERP systems, enhancing interoperability and data exchange across projects, departments, and supply chains (Razkenari 2019; Perera et al. 2023; Han et al. 2024). Standardised design protocols, communication frameworks, and managed networks enable secure horizontal and vertical collaboration (Jäkel et al., 2024; Razkenari and Kibert, 2022). Organisations align structures with digital processes, yet fragmentation persists, as digital responsibility remains project- or site-specific rather than enterprise-wide (Han et al., 2024; Wernicke et al., 2023). Performance measurement improves through real-time KPIs, benchmarking, and digital dashboards, while financial support for digital transformation increases, driving greater R&D and ICT investments (Razkenari 2019; Perera et al. 2023; Han et al. 2024).

The adoption of BIM, IoT, big data, and AI advances collaborative project management, alongside emerging experimentation with LiDAR, drones, robotics, and exoskeletons to enhance efficiency and safety (Razkenari 2019; Perera et al. 2023; Han et al. 2024). Despite these advancements, whole Industry 4.0 integration is still in progress, requiring stronger enterprise-wide coordination and strategic commitment (Jäkel et al., 2024; Perera et al., 2023).

At **Maturity Level 4**, construction firms exhibit a fully developed digital culture, where continuous learning, innovation, and digital transformation (DT) are embedded within organisational values and supported by structured internal training initiatives (Han et al., 2024; Perera et al., 2023). Interoperability and standardisation enable cross-company and cross-technology collaboration, ensuring seamless data exchange through interoperable interfaces and policies that align digital investments with measurable KPIs (Han et al., 2024; Jäkel et al., 2024; Razkenari and Kibert, 2022). Digital transformation is a core business strategy, fully integrated into corporate objectives and facilitated by a strong digital vision, which drives further technological and process innovations (Das et al., 2023; Han et al., 2024; Perera et al., 2023). Organisations operate within a fully digitised partner ecosystem, leveraging tailor-made ERP systems with cloud integration, supporting real-time data management and cross-functional interoperability (Perera et al., 2023). Process automation becomes central to long-term portfolio development, with firms successfully applying Construction 4.0 technologies across isolated processes, aiming for continuous efficiency improvements through automation (Jäkel et al., 2024; Wernicke et al., 2023). Investments in R&D and ICT surpass 5% of annual turnover, supporting business model transformation through collaborative R&D initiatives, while real-time performance metrics and well-managed digital investments ensure measurable return on investment (ROI) (Han et al., 2024; Perera et al., 2023; Razkenari and Kibert, 2022).

Advanced digital tools such as digital twins, cyber-physical systems, integrated ERP, BIM platforms, IoT-based decision-making, blockchain for contract security, and robotics for industrialised construction transform operations into highly optimised, data-driven workflows (Han et al., 2024; Perera et al., 2023; Razkenari and Kibert, 2022)

At **Maturity Level 5**, companies achieve full-scale business model innovation (Das et al., 2023, 2024), fostering a culture of continuous transformation and adaptability (Das et al., 2024; Han et al., 2024). Digital technologies are seamlessly integrated across all operations, governed by comprehensive policies and industry standards that ensure efficiency, security, and interoperability (Han et al., 2024). A fully digitised business ecosystem emerges, where all systems operate within an interoperable framework supported by open data exchange formats, enabling seamless horizontal and vertical collaboration across stakeholders (Jäkel et al., 2024). The organisation's advanced IT infrastructure is reinforced by digital business process management systems, optimising workflows and real-time decision-making (Han et al., 2024). At this stage, digital strategy is fully aligned with business objectives, ensuring that technology investments yield high returns on investment (ROI) regarding operational effectiveness and sustainability (Han et al., 2024).

4.4.3. Ontology-Based Validation of the C4MM version 2

Building upon the ontology engineering methodology outlined previously (Section 2.3.5), this section demonstrates how ontology development is a modelling activity and a methodologically rigorous approach to validate the conceptual and structural foundations of the Construction 4.0 Maturity Model version 2. The ontology operationalises the model by formalising C4MM definitions into logical constructs and enables inferential validation of its components.

Ontology key elements and class definitions

Following the clarification of the ontology's scope and in light of the absence of existing domain-specific ontologies, the research progressed to the third step of ontology development: identifying the key elements. These elements were derived from the literature review outcomes, specifically the categories and subcategories of the Construction 4.0 Maturity Model version 2. Accordingly, these model components were formalised as the foundational classes of the ontology, with their definitions serving as the class definitions.

Class hierarchies and structural coherence

Following classifying and defining classes, a hierarchical structure was developed to reflect logical groupings and subclass relations in the Protegé desktop version. For example, “HorizontalCollaboration” was modelled as a subclass of “Collaboration,” reinforcing taxonomic clarity and enabling reasoning engines to infer inherited properties. The structured hierarchy ensured no conceptual overlaps or redundancies remained, thereby validating the model’s internal taxonomic integrity (Figure 26).

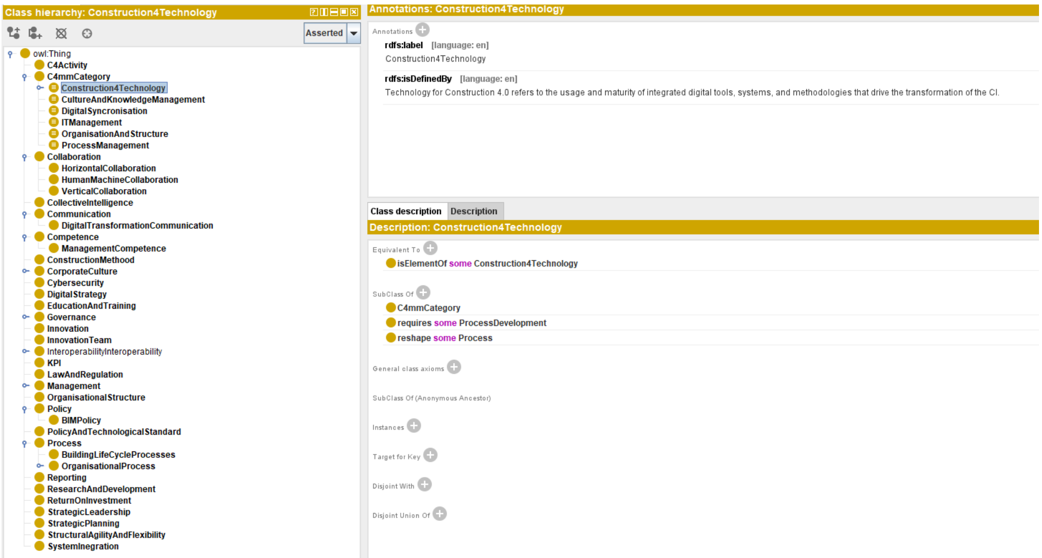


Figure 26 C4MM Class hierarchy

Formalising model constructs into logical triples by defining object properties

The validation process continued with transforming narrative definitions into formal logic-based triples. Each sentence in the category and element definitions of C4MM v2 was deconstructed into subject–predicate–object triples. These triples constitute the core building blocks of the ontology, representing domain-specific relationships in a machine-readable structure. Subjects and objects were defined as classes (e.g. “DataCentricITManagement”) and predicates as object properties (e.g. focusesOn). These logical triples enable semantic precision and eliminate ambiguity in interpreting the model’s relational structure. Classes in RDF language are defined with capital initials without a space between the words, and object properties start with small initials without spaces between the words.

New classes were generated from key terms to enhance semantic granularity and to support interlinkages across the two primary maturity dimensions. For instance, the term “DataProcess” was instantiated under the “Process” class and linked to “DataCentricITManagement” via the “focusesOn” property. Table 14 presents a selection of these triples and their role in formalising the model's logic. Annexe VII demonstrates all triples built from the C4MM version 2.

Table 14 Formulation of classes and relationships from the definition

	Definition	Domain	Object Property	Range
Data-Centric IT management	The objective of Data-Centric IT management is real-time data processing and interoperability to develop and maintain data-driven automatic systems that support daily operations across the organisation with data analytics.	DataCentricITManagement	developsFrameworkFor	TechnologyForC4
	Automatic and real-time data processing requires context-based information and data collection.	DataCentricITManagement	focusesOn	DataProcess
	Data collection includes determining the type and extent of data to be acquired for internal and external data integration.	DataCentricITManagement	determinesRulesFor	SystemIntegration
	Optimal data requires eliminating data duplication.			
	The data collection requires system integration from multiple information systems across the organisation to collect real-time data from cyber-physical systems, digital twins and IoT devices.	DataCentricITManagement	collectsDataFrom	TechnologyForC4
	During data processing, enterprises should safeguard their systems and the data.	Cybersecurity	influences	DataCentricITManagement

Object properties were further specified by defining domain–range constraints and logical characteristics (e.g., transitivity, functionality). These relationships formalise theoretical assumptions embedded within the maturity model and allow the ontology to reflect both vertical and horizontal interdependencies (Figure 27).

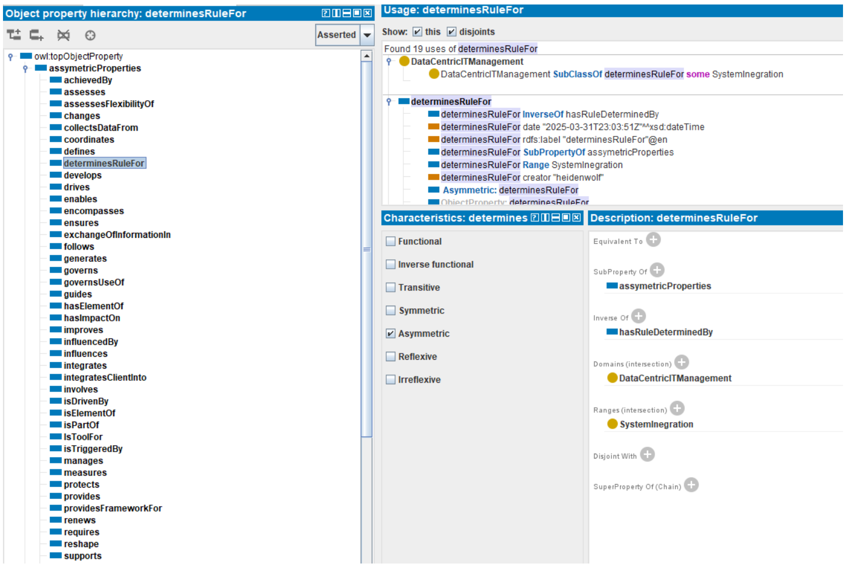


Figure 27 The "determinesRuleFor" object property from Protegé

These object properties were used to connect classes. For instance, "DataCentricITManagement" was connected to the "SystemIntegration" class with the "determinesRuleFor" object property (Figure 28).

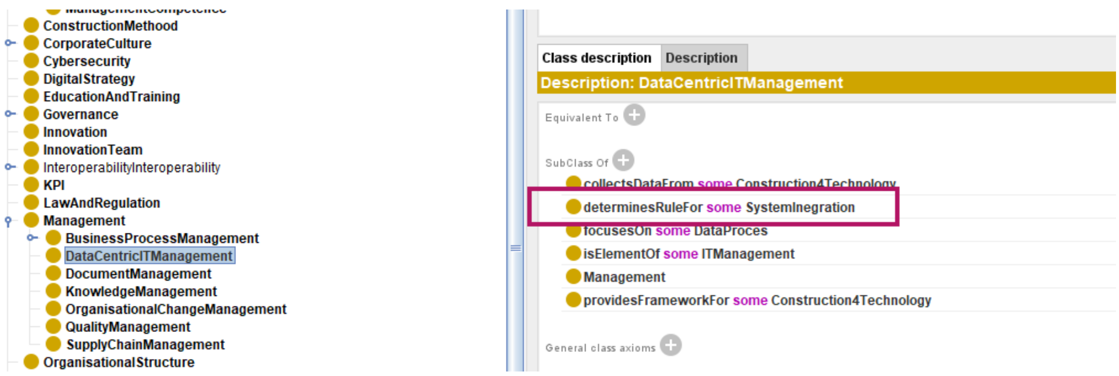


Figure 28 Connect classes with object properties

The ontology was then exported to .rdf format to visualise the ontology with RDFLib, which is an open-source Python library available via GitHub.

Reasoning for Logical Consistency

Reasoners such as Pellet and Hermit were employed iteratively to verify the internal consistency and logical soundness of the ontology. These reasoning tools identify unsatisfiable classes, redundant axioms, and emergent logical contradictions. Through this process, the ontology became free of structural errors and could deduce implicit relationships based on its axioms.

For example, if “DataCentricITManagement” collectsDataFrom “TechnologyForC4”, and “TechnologyForC4” includes “IoT”, then the reasoner can infer that “DataCentricITManagement” is indirectly linked to “IoT”. This conclusion is not explicitly encoded but logically valid within the ontology. Such inferencing validates the model’s structural logic and its semantic richness.

Visualising Ontological Insights

Using RDFLib, the ontology was exported to RDF format for graph-based visualisation. These knowledge graphs revealed three prominent relational clusters within the ontology: Technology, Process Development, and Organisational Change Management. These clusters emerged as relational hubs, with multiple object properties converging around them, indicating their central role in the model.

Figure 29 illustrates the **Construction4Technology** class and its direct connections, represented by blue nodes. Subclass relationships were omitted from the visualisation to focus exclusively on object properties derived from the literature review. The figure highlights **Construction4Technology** as a central integrative hub, linking technological implementation with key organisational and processual elements. It shows that technological adoption *requires* **ProcessDevelopment**, which is *supported by* enabling tools such as **BuildingInformationModelling** and is *influenced by* **OrganisationalChangeManagement**—the latter acting as a triggering factor for successful implementation. Additionally, technologies are shown to *reshape* both **Process** within the organisation and the **BuildingLifeCycleProcess**, reinforcing their broad systemic impact. The model also identifies **DataCentricITManagement** as a mechanism that *collects data from* Construction 4.0 technologies, while **C4Activity** *supports* their implementation. Furthermore, including **LawAndRegulation** as a governing element reflects the importance of compliance and policy frameworks in guiding digital transformation.

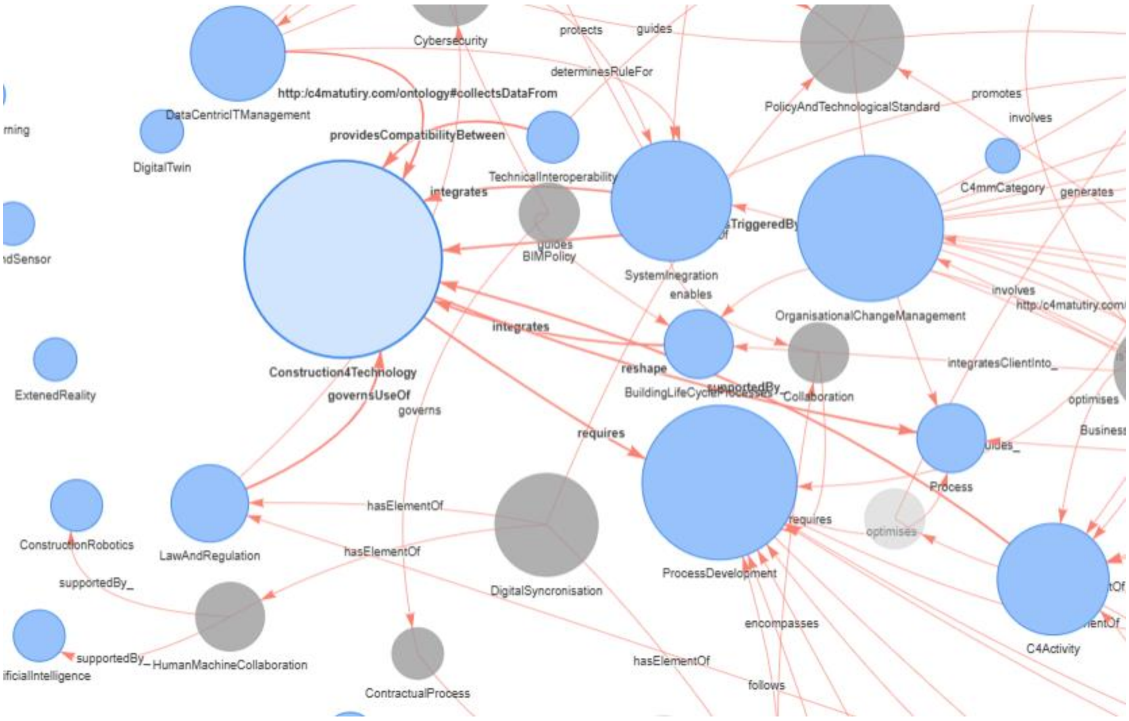


Figure 29 Construction 4.0 Technology view with RDFLib

Figure 30 visualises the **ProcessDevelopment** class and its direct ontological connections, represented by blue nodes. The figure highlights that **ProcessDevelopment** is *required by* **Construction4Technology**, with **BuildingInformationModelling** serving as a key technological enabler (*isToolFor*). The development of processes is *guided by* strategic, quality, and innovation-related dimensions—specifically **StrategicLeadership**, **ResearchAndDevelopment**, **Innovation**, and **QualityManagement**—demonstrating a strong link between high-level organisational strategy and operational evolution. Additionally, **ProcessDevelopment** is *influenced by* **ReturnOnInvestment** and contributes to *enhancing* **KPI**, signalling the mutual reinforcement between process innovation and measurable performance outcomes. The model also shows that these developments *require* **Collaboration**, suggesting that successful digital transformation depends on economic and strategic factors and social-organisational integration.

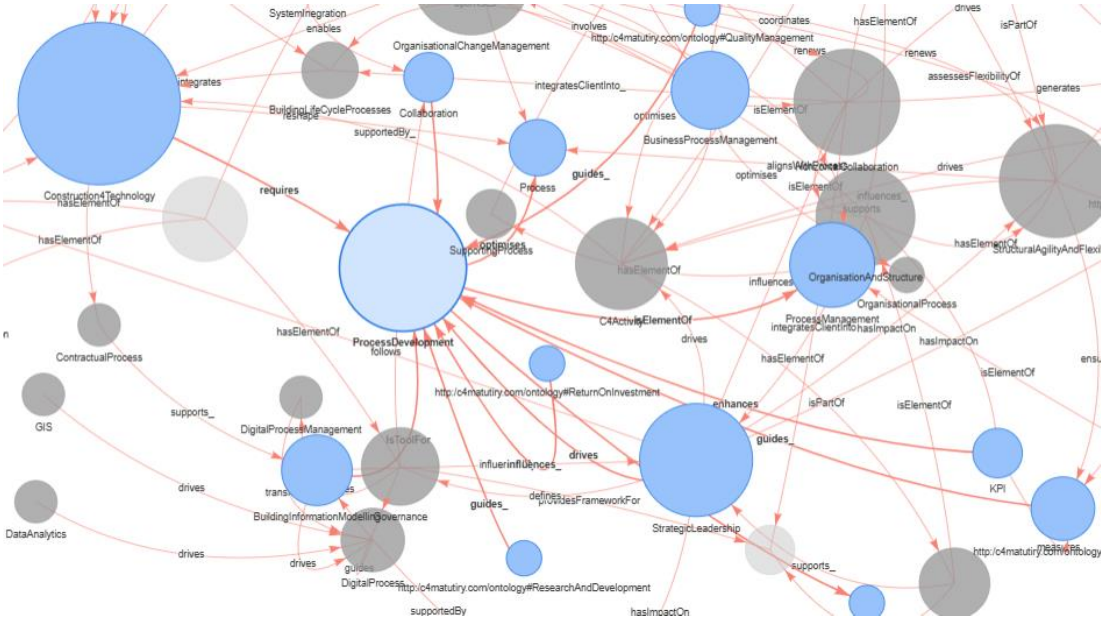


Figure 30 Process Development View with RDFLib

Figure 31 presents the **OrganisationalChangeManagement** *View* of the ontology, visualised using RDFLib. In this figure, the blue nodes represent the classes directly connected to the central concept of **OrganisationalChangeManagement**. This class is conceptualised as a response to and a catalyst for digital transformation. It is *triggered by* **Construction4Technology**, underscoring the role of technological advancements in initiating organisational change. At the same time, it *aligns with* strategic elements such as **DigitalStrategy** and is *supported by* **KPI**, reflecting its embeddedness in strategic planning and performance measurement. **OrganisationalChangeManagement** actively *transforms* critical components of the enterprise, including the **OrganisationalStructure**, the **SupplyChainProcess**, and various forms of collaboration—namely **VerticalCollaboration**, **HorizontalCollaboration**, and **StructuralAgilityAndFlexibility**. Importantly, it also *monitors* **KnowledgeManagement**, suggesting the presence of an evaluative and adaptive feedback loop that ensures responsiveness to change.

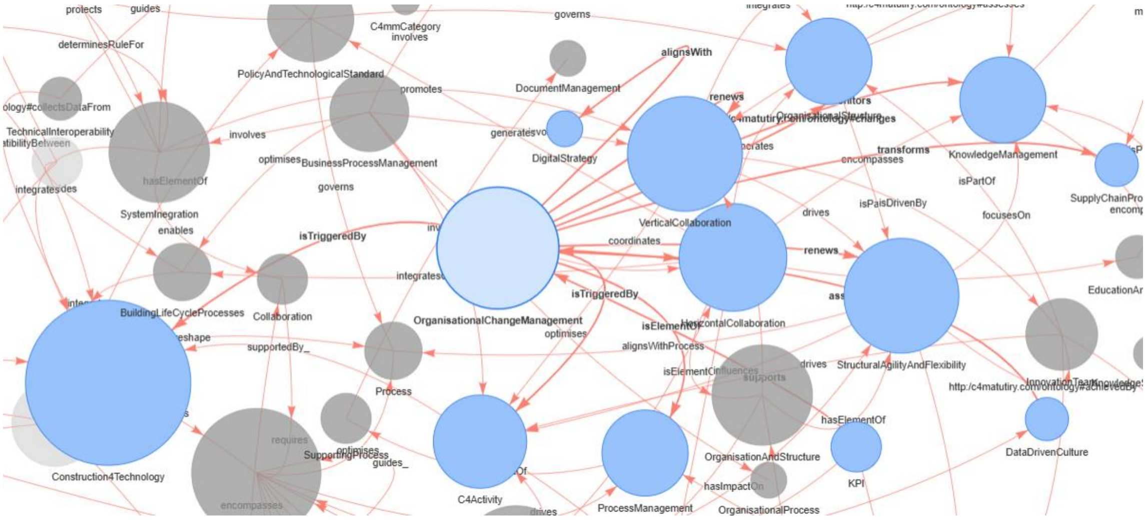


Figure 31 Change Management View with RDFLib

Ontology as a Validation Instrument

The ontology-based approach offered a rigorous validation pathway for the C4MM v2 by enabling formal modelling, semantic consistency checks, and inferential reasoning. Ontology development structured the C4MM into logically coherent components and tested its internal validity through automated logic.

The framework's conceptual integrity and structural robustness were affirmed by aligning classes, relationships, and axioms with theoretical constructs and confirming these through semantic reasoners and visual analytics. Thus, the ontology validated C4MM v2 as a reliable and coherent model for assessing digital transformation maturity within construction organisations.

The developed ontology can serve as a foundation for the future development of a rule-based system for querying the ontology and giving a detailed answer to a specific question.

The full ontology is accessible via GitHub:

https://github.com/nagyorsi21/Construction4MaturityModel

4.4.4. Model development with qualitative research

4.4.4.1. Demographics

During the research, I recruited and conducted thirty-three online interviews with construction experts; of them, only five were female. Most participants were employed by large enterprises with over 500 employees and worked in diverse corporate entities. The majority of the participants had more than 10 years of experience in the construction industry and construction technology. More than half of the participants held an executive role. (Table 15).

Table 15 Participants demographic information

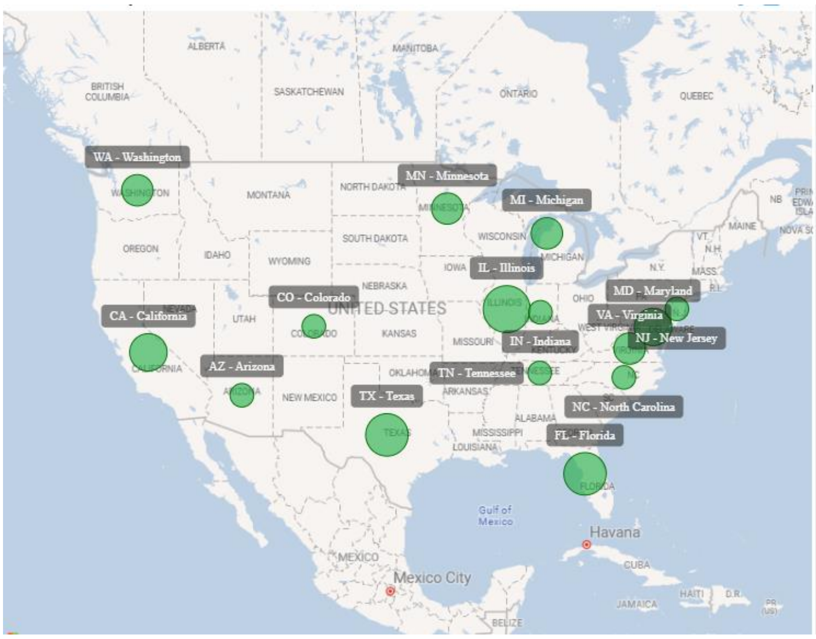
Sample Characteristics	Frequency(n=33)	Per cent (%)
Gender		
Female	5	15%
Male	28	85%
Position		
Executive	19	58%
Manager	14	42%
Experience in Construction		
2-3 years	1	3%
4-5 years	3	9%
5-10 years	3	9%
10-15 years	10	30%
15-20 years	3	9%
20+ years	13	39%
Company Type		
General contractor	9	27%
Technology provider	5	15%
IT consultant firm	1	3%
Construction consultant firm	3	9%
Architect	3	9%
Capital Markets, Real Estate Developer, Architecture, General Contractor, Owner/Operator	1	3%
Construction Technology Consultant	1	3%
Consultant Process Technology & Licensing	1	3%
Civil Engineering Consulting	1	3%
Real Estate Developer/Owner GC	1	3%
Speciality contractor (Trades or Crafts)	1	3%
Construction management firm	2	6%
Manufacturing	1	3%
Engineering Firm	1	3%
Utility	1	3%
Construction Insurance	1	3%
Number of workers		
1-25	7	21%

Sample Characteristics	Frequency(n=33)	Per cent (%)
101-250	5	15%
26-50	1	3%
501+	17	52%

Most of the participants worked for general contractor companies with over 500 employees. In addition to general contractors, the qualitative research incorporated a diverse range of company types. This approach was intended to avoid evaluating firms solely through the lens of general contractors and to capture perspectives they may not fully recognise. However, that other industry actors identify as potential barriers in the digital transformation process. This rationale was also informed by the consideration that less digitally mature general contractors might not yet perceive specific opportunities that other, more advanced stakeholders within the value chain are already leveraging. As such, the research examined, for example, how consultancy firms assess the integration of digital technologies within general contracting firms, and how architectural practices perceive collaborative efficiency when working with general contractors—particularly regarding the technologies that enhance such cooperation. Additionally, the study explored how general contractors influence subcontractors, as these interactions offered valuable insights into cross-organisational digital readiness. This multi-perspective approach thus contributed to the nuanced refinement of a model tailored to the target group.

The sampling process involved selecting participants focusing on construction technology or innovation during their day-to-day job. As a result of this approach, the participants had a wide range of roles, including Project Manager, Consultant, Chief Technology Officer, CEO, Virtual Design Construction Manager, Director of Innovation and Technology, President, Innovation and Technology Manager, Global Digital Lead, Vice President, Director of IT, Process Manager, Senior Manager Data Science, Associate Director, Project Delivery Innovation, Director of Construction Director of VDC, R&D Manager, Construction Manager, Head of Innovation and Sustainability.

The geographical distribution of the participants within the U.S. extended to 15 states. Most participants worked in Illinois, Florida and Texas (Figure 32).



State	Frequency (N=33)	Percent (%)
AZ - Arizona	1	3%
CA - California	3	9%
CO - Colorado	1	3%
FL - Florida	4	12%
IL - Illinois	5	15%
IN - Indiana	1	3%
MD - Maryland	3	9%
MI - Michigan	2	6%
MN - Minnesota	2	6%
NC - North Carolina	1	3%
NJ - New Jersey	1	3%
TN - Tennessee	1	3%
TX - Texas	4	12%
VA - Virginia	2	6%
WA - Washington	2	6%
Total	**33**	**100%**

Figure 32 Geographical distribution of the participants

The interview questions aimed to understand the latest technology integration process and its challenges, identifying which explored maturity model elements were affected by the technology implementation process, thus validating and refining the maturity model. In this process, respondents were asked to identify their most advanced technologies (question 1) and future implementation plans (question 2), with particular attention to the explored technology groups from the C4MM version 2 such as BIM, digital twins, XR, IoT, robotics, AI, machine learning, data analytics, and ERP and Project Management systems (question 3). The interviews also probed the preparatory steps required before implementation (question 3a), the challenges encountered (question 3b)—especially regarding organisational knowledge and skill gaps—and the broader impact on other divisions. Participants were further asked to describe the implementation process both before and after adoption (question 3c), the criteria used to evaluate success (question 4), and whether they utilise platforms that enable system-level collaboration (question 5) (see the interview questions in Annexe VI).

4.4.4.2. Maturity Model Dimensions

The first step in the coding was the creation of a case classification. The case classification includes all demographic data, the leading technology discussed during the interview, and the use case of the technology. The maturity levels were assigned to twenty cases based on the literature review (Figure 33). Maturity levels were not applied to consultant or technology provider companies. This step later supported the creation of a thematic content matrix further to understand the maturity level and the corresponding maturity elements.

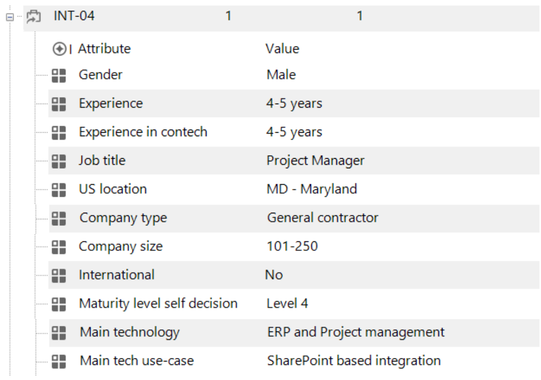


Figure 33 Case classification

Coding will be divided into three phases: initial, focused and theoretical coding (Flick, 2014). Starting coding with a narrow focus or specific definition can make identifying patterns and recognising overarching themes harder(Vaismoradi et al., 2016). Thus, the first step was to develop a coding structure from the C4MM version 2, which determined the main direction of the coding. Conceptual coding was used, which " identifies *key elements, domains and dimensions of the study phenomenon* " (Vaismoradi et al. 2016, pp 103). All transcripts were thematically coded under the relevant maturity model elements (Figure 34 left), and then new codes were created from the themes (right).

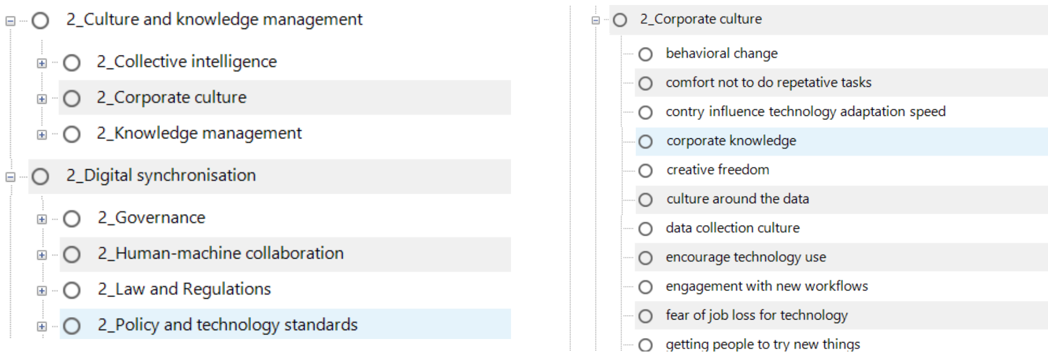


Figure 34 Initial coding structure (left) and the newly created codes (right)

The restructuring of the coding followed this phase. The same concepts were merged, the coding structure was synthesised, and the results were tabulated (Figure 35).

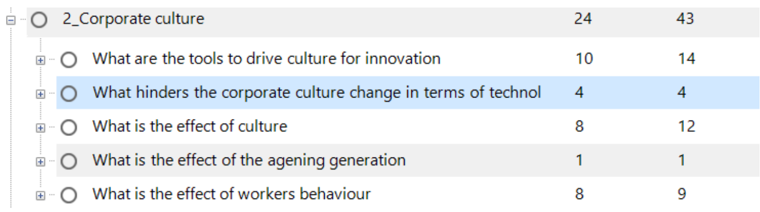


Figure 35 The synthesised coding structure

Two iterative steps were applied during the maturity level development. The first iteration followed the same steps as the maturity dimensions. Each participant was asked to formulate their idea on defining construction digital maturity on a scale of one to five. These paragraphs from the transcripts were coded into maturity levels, and new codes were created from the levels (Figure 37 left) and the mentioned technological use cases (Figure 36 right).

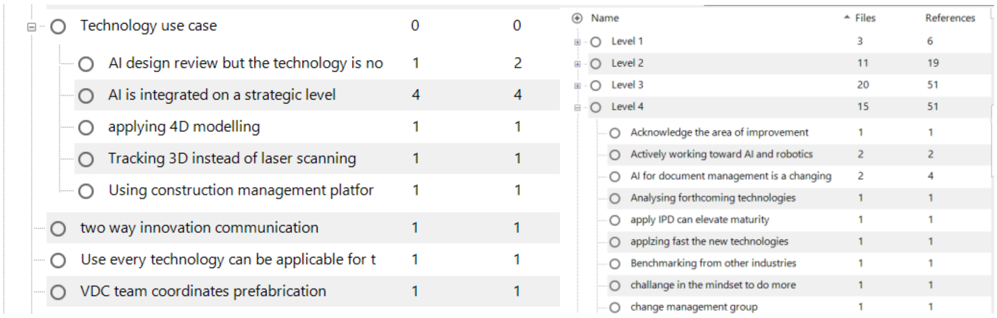


Figure 36 The development of maturity levels

During the second iteration, levels were assigned to the participant companies based on the maturity level definitions developed from literature review results (Section 4.4.7). The level of maturity was not applicable for consultants and technology suppliers; thus, only twenty companies were assigned to different maturity levels. Unfortunately, I could not assign any company to Maturity Level 1; thus, the table shows 0 in this column. Then, a thematic content matrix was created from the qualitative results. The logic behind this table is as follows: Each participant explained a specific technology implementation process and its related processes and challenges. These aspects were used to develop the model elements. After I assigned the maturity level to each company, the thematic content matrix showed the main aspects of each maturity level. These results were used to refine the developed maturity levels from the first iteration and their relation to the model elements (Table 16).

Table 16 Thematic content matrix summary

	Level 1	Level 2	Level 3	Level 4	Level 5
2_Culture and knowledge management	0	12	12	19	33
2_Digital synchronisation	0	4	3	12	6
2_IT management	0	5	7	20	30
2_Organization and structure	0	4	3	20	26
2_Process management	0	9	12	14	27
3_ROI Budget and KPI	0	3	7	9	5

Table 17 introduces the number of themes that evolved during the qualitative data analysis. These themes will be introduced in detail in the following sections. The table shows that Process development was one of the most critical areas of construction organisations' digital transformation journey. This theme was followed by Culture and

Knowledge Management, followed by IT management. The 2 number refers to the C4MM version 2, while 3, such as Risk management and Digital Investment and Performance Metrics, evolved from the qualitative research and were not part of the initial model.

Table 17 Summary of themes evolved from qualitative data analysis

Category	Number of themes	
2_Culture and knowledge management	**99**	
2_Collective intelligence		40
2_Corporate culture		34
2_Knowledge management		25
2_Digital synchronisation	**29**	
2_Governance		3
2_Human-machine collaboration		6
2_Law and Regulations		6
2_Policy and technology standards		14
2_IT management	**79**	
2_Cyber security		18
2_Data-centric IT management		28
2_System integration		33
2_Organization and structure	**66**	
2_Digital transformation communication		9
2_Horizontal collaboration and coordination		15
2_Strategic leadership		17
2_Structural agility and flexibility		20
2_Vertical collaboration and coordination		5
2_Process management	**131**	
2_Core processes		19
2_Organizational change management		31
2_Process development		73
2_Supporting processes		2
3_Risk management		6
3_Digital Investment and Performance Metrics	**28**	

Culture and knowledge management

Collective Intelligence

In the context of construction, **collective intelligence** refers to an organisation's ability to combine human expertise, technological tools, and shared knowledge to adapt to complex digital challenges.

A key finding from the interviews was the growing need for construction companies to shift the skillsets of their current workforce to align with emerging technological demands. In particular, back-office functions increasingly require proficiency in data analytics and a basic understanding of artificial intelligence and its practical capabilities. Long-term goals such as integrating robotics also demand a workforce capable of adapting to new tools, even if full deployment is not yet in place. However, participants noted that delivering practical training remains challenging, especially under complex site conditions with limited time, space, or connectivity.

In addition to individual skills, organisational readiness was seen as a critical enabler of successful technology adoption. Experts emphasised the importance of institutional expertise and the presence of dedicated innovation teams capable of guiding implementation strategies and supporting internal knowledge transfer. These groups act as technology enablers, helping to bridge gaps between operational staff and emerging digital systems. Although certain technologies, such as robotics, may reduce the need for traditional field expertise, their successful integration still relies heavily on internal coordination and a workforce that understands these tools' technical and organisational implications.

The interviews also explored how education and training strategies shape the development of collective intelligence within organisations. Experts stressed that targeted training accelerates the adoption of digital technologies and can generate significant returns on investment. To remain competitive, construction firms must retrain personnel in key areas such as AI functionality, robotics applications, the use of digital twins, and multi-technology systems maintenance. One effective strategy discussed was the designation of technology champions or subject matter experts who can lead by example, support peers, and embed digital competencies across teams. Furthermore, experiential learning was often viewed as more impactful than passive formats such as pre-recorded video modules, especially in complex operational settings. Certification programmes were also highlighted as valuable tools for building individual capability, standardising knowledge across teams, and improving internal processes.

Despite the recognised importance of training, participants also raised concerns about the volume and pace of technological change. The rapid introduction of new software tools across the construction industry has sometimes resulted in information overload, making it difficult for employees to keep pace. Experts noted that an uncoordinated or excessive training approach can overwhelm teams and reduce the effectiveness of learning initiatives. As a result, companies must carefully manage educational demands and prioritise technologies that align with their strategic goals and workforce capacity. Addressing this challenge is particularly important given the industry's varying levels of digital maturity and the steep learning curves associated with many construction technologies.

> "Even just as you use the technology, you're going to get better at it. It's *more like learning as an experience, like experiential learning, because that's how many people learn. The industry, we say in training videos all the time, and nobody watches them anyway."* (Participant 27)

Knowledge Management

One of the main tools identified for strengthening organisational **knowledge management** was the development of internal knowledge bases. Experts suggested that structured platforms could support employees in documenting and sharing insights, particularly through experience-based learning and video content. Building a central repository for lessons learned would allow teams to extract relevant knowledge for future use, enabling a culture of continuous learning and reducing the risk of knowledge loss across projects.

Participants also emphasised that knowledge management systems should directly support training and onboarding processes. Well-prepared training materials not only help existing staff upskill but also play a role in onboarding future employees. Experts noted that training should focus on teaching how to use specific tools, support process adaptation, and foster a mindset open to continuous technological change. Organisations should implement ongoing training programmes that develop technical skills and adaptive thinking to prepare for emerging innovations. One effective strategy mentioned was introducing new training initiatives on smaller projects, which can be scaled up organisation-wide following successful implementation.

Participants identified several challenges despite the recognised value of knowledge management and retention. One concern was the risk of knowledge loss due to an ageing workforce and frequent employee turnover, both limiting the continuity of expertise across projects. Many companies were described as lacking formalised knowledge transfer mechanisms, leading to fragmented information stored in isolated silos. This fragmented structure restricts collaboration and prevents organisations from building on prior experiences.

The limitations of current knowledge management tools and prevailing cultural attitudes were also highlighted as significant barriers. While platforms such as SharePoint are increasingly adopted across the industry, experts argued that these systems often serve as passive storage rather than dynamic knowledge-sharing environments, resulting in knowledge loss. Furthermore, the dominant project-centric mindset in construction hindered the development of centralised, long-term knowledge strategies. Participants also pointed to the difficulty of scheduling corporate training in a fast-moving project environment and the persistence of risk-averse attitudes and naïve forecasting practices. These factors collectively inhibit the proactive planning needed to embed effective knowledge management systems.

> *"People using Notion now for knowledge management is great, but the problem is you can put all this information somewhere. I always used to say that SharePoint was where institutional knowledge goes to die because you put it there and then do all this work to structure it and make sure it's easy to read, and then people don't read it." (Participant 25)*

Corporate culture

The interviews revealed that developing a technology-oriented culture in construction is shaped by a mix of external, organisational, and social factors. External challenges often came from clients who lacked a clear understanding of how digital tools could benefit projects and regional or cultural differences in attitudes toward innovation. One company, for example, shared that its Florida-based teams were generally more receptive to new technologies than other parts of the organisation, pointing to a more innovation-friendly mindset in that region. Language barriers on site—particularly among diverse construction crews—added friction to adoption efforts. Internally, resistance to changing established workflows was common, especially among older employees. Some companies also struggled with decentralised structures, making it harder to consistently roll out new tools across teams. In addition, several participants described low engagement with digital workflows and hesitation to try unfamiliar systems, often rooted in long-standing habits and social dynamics.

Many interviewees shared strategies they had used to shift culture and build comfort with new technologies. Collecting user feedback, showing teams how the tools made their work easier, and automating repetitive tasks were all mentioned as ways to reduce pushback. Several participants stressed the importance of timing—introducing tools too early, or without involving key people, often led to confusion or resistance. One expert said, *"If people don't see the benefit for themselves, they won't use it."* Teams with dedicated innovation groups or clear support from contractors, especially when safety was part of the conversation, were seen as more successful in building long-term buy-in.

While culture influences innovation, participants also reflected on how innovation, in turn, changes culture. In organisations where people were encouraged to share ideas, ask questions, and experiment, new tools were picked up more quickly. A few mentioned that simply giving people space to try something, without fear of failure, helped create momentum. Cultures prioritising information-sharing and open communication also seemed to integrate digital tools more smoothly. Experts warned that adopting too much, too fast—especially without aligning new tools with the company's values or workflows—could backfire.

Finally, individual behaviour came up again and again as a factor that could make or break a digital transformation. Workers used to "the old way" of doing things often needed time and reassurance before they were willing to try something new. In some cases, people worried that AI or automation would eventually take their jobs, which made them hesitant to engage. A few interviewees shared that giving workers some level of control over the tools—whether in how data was used or how automation was applied—helped ease that tension. Still, past experiences and deep-seated mistrust of top-down changes remained real barriers. As several participants noted, it is not just about having the right technology but about whether people are ready and willing to work with it.

> *"We've developed a kind of grassroots effort that is trying to crowdsource excitement around technology. We call them our technology excellence practice, and so it's a kind of volunteer group of excited coworkers that have a Teams channel and regular phone calls that facilitate vendor presentations and a Microsoft Teams environment that is set up with different subject matter experts and has seven different kinds of categories of technology." (Participant 20)*

Digital Synchronisation

Governance

Interviews highlighted that successfully implementing AI required a more holistic approach to data governance and system architecture. Many participants noted that existing data platforms had to be restructured to meet the demands of AI integration. Data analysis had often started in a fragmented and informal way, often driven by grassroots efforts within individual teams. As a result, organisations had to standardise how data was structured, who could access it, and how different systems interacted to enable broader experimentation and collaboration. Key challenges in this transformation included defining clear governance frameworks, unifying data platforms, and building a strong back-end infrastructure to support scalable data pipelines.

> *"Visible to citizen developers and to just more people inside the company to experiment with that kind of led to a holistic view of our data background and data platforms to standardise around, and a new level of governance and a new architecture to enable us for a lot of work." (Participant 8)*

Law and Regulations

The interviews underlined the need for a government-level construction code to solve digitalisation issues. The government should be more receptive to approving AI. State-level and local regulations frequently hinder process development and a centralised organisational system. Privacy regulations also hinder the development of health and safety technologies and their applications. Participants highlighted significant regulatory and legal barriers impacting technology adoption, particularly AI-driven tools for construction monitoring. Privacy concerns governed by state and federal regulations remain contentious, especially regarding video-based monitoring to evaluate worker activities and safety. Although public and private project owners are gradually becoming more open to sharing video data for AI applications, privacy rights pose significant hurdles. Additionally, construction projects face substantial regulatory variability at the local and state levels, making standardised technological implementation challenging. Participants suggested a more unified federal-level construction code could help overcome local regulatory complexities, enabling broader adoption of advanced construction technologies.

> *"If you're using video and AI for, for example, monitoring construction safety and activities, whether people are adequately working or not. Such concerns that relate to privacy are a big issue… But to what extent people's privacy rights allow or not allow the use of such technologies is a big concern within the index." (Participant 14)*

Policy and Technological Standards

Participants emphasised the necessity of practical, interoperable, and implementable standards for information exchange, notably to support digital twin adoption and effective facility management due to frequent building changes. Industry Foundation Class (IFC) file format remained inadequately adopted, creating data silos and hindering integration. Interviewees identified IT policy, contractual language, and data governance as critical to managing data securely and effectively, reflecting an organisation's technological maturity. Furthermore, behavioural shifts toward data capture methods, leveraging AI, robotics, IoT, and drone technologies, were recommended to overcome manual entry challenges and survey fatigue, thus improving data consistency and adoption across the construction industry.

> *"Actual information standards for the building are needed so that information that is new as to new conditions can be injected into the digital twin and updated, and then the old conditions can be archived in the digital twin again. That's why Google Maps is so valuable: it constantly reflects what's currently in the world. " (Participant 4)*

Human-machine collaboration

Effective human-machine collaboration depends on addressing behavioural challenges and clearly defining roles between humans and AI technologies. Employees often resist automation due to fears of job displacement, loss of control, or mistrust toward AI capabilities. Organisations should focus on developing a data-centric environment for workers to trust in the data and AI to use it. Thus, AI should be presented as supportive rather than competitive, emphasising that technology enables employees to focus on higher-value tasks. Interviewees introduced scenarios where human oversight remains essential, such as programming, managing data collected by robots, and ensuring reliability in decision-making processes. Experts recommended that, rather than replacing human roles, AI should enhance human productivity. For example, instead of building simple chatbots, AI can generate steps based on various data and support workers' tasks rather than taking their day-to-day jobs.

> *"When people are given AI tools that help them do their work better versus tools that will automate what they do every day, they get a fear that their services will be less important. It's more of a human fact, a human nature thing." (Participant 1)*

IT Management

Cybersecurity

Cybersecurity is a growing concern within the construction industry, especially as digital tools, IoT devices, and AI-driven systems become more prevalent. Interviewees expressed worries regarding ransomware attacks, unauthorised data access, and vulnerabilities arising from IP-addressable IoT devices. Managing sensitive or proprietary data, particularly classified or controlled information, further amplifies the importance of robust cybersecurity practices. Privacy concerns associated with video monitoring and AI analytics highlighted the balance needed between technology use and individual rights. Interviewees emphasised the necessity of partnering closely with IT and security teams. Practical challenges were mentioned, including fragmented data management and inconsistent security practices. In summary, while there is awareness of cybersecurity risks, implementation often remains challenging due to complexity, varying vendor standards, and organisational resistance.

> *"Can we ensure that if someone chats a question into the generative chatbot, the right data that only they have permission to access comes back out of it?" (Participant 8)*

> *"There were a lot of security concerns around our old system, especially having a network where we could be held ransom, by some Actor who gets access to our network, copies everything, then deletes everything and says pay me this money." (Participant 4)*

> *" We've become much more specific in our requirements, and many vendors now use the trust centre, which is a full roadmap of how their technology is built. All of the intricacies regarding security, cybersecurity, user provisioning, etc. We've had to partner with our IT group and security team to vet various vendors and technology providers, and we come up with different thresholds of how it's used and the duration of use for the level of intensity or scrutiny." (Participant 24)*

Data-Centric IT management

Qualitative research revealed multiple questions in the Construction industry regarding Data-Centric IT management. Firstly, the nature of the data companies collect should be structured information; however, companies still struggle to extract and access that information easily. Secondly, the methodology for data collection should be decided, which can range from manual entry and spreadsheets to automated data capture through robotics, drones, and computer vision. Thirdly, the volume of data that should be collected needs to be decided. The collection of unnecessary data requires extra cloud space, which is becoming more and more expensive. Fourthly, the method for data cleansing often requires behavioural changes, especially if the data is expected to be generated by construction workers. Fifthly, the companies should decide the method for interpreting the collected data. Experts gave detailed examples of defining and structuring core datasets that should be explicitly tailored to organisational needs. Sixthly, the method for sharing and transferring the collected data should be straightforward. Organisations struggled with data silos, fragmented management practices, and duplicated files, which complicated the integration and analysis of collected data. Seventhly, how companies utilise the data interviewees suggested standardised governance, role-based access, clear data relationships, and robust metadata management. Additionally, companies recognised data's financial and operational value; however, practical implementation faced challenges related to data quality, volume management, cybersecurity controls, and vendor integration.

Finally, experts indicated that IT infrastructure should be capable of handling extensive data growth, scalability, and increased computational demands. Their key considerations included adequate hardware (e.g., powerful laptops and servers), effective cloud storage solutions, and seamless data transfer. Significant infrastructure scaling challenges were also mentioned, such as supporting rapid user growth (from a handful to thousands) and securely and handling large-scale data transfers. Developing an IT infrastructure required substantial coordination between operational teams, IT specialists, and technology vendors to address evolving industry requirements.

"Defining a centralised, core data set is very important. When we create this core data structure, we create this data layer first, then it is easy for us to think about other systems that interact with this dataset." (Participant 2)

"If you can have quality data that everyone trusts, that's a big issue and that then can become a document that I can then submit for a permit or submit for payment." (Participant 6)

"We have a couple of Boston and Unitree Go robots. We're partnering with different vendors

in the industry, both ground and aerial robotics, just for the data image capture to generate that structured data out of it." (Participant 8)

"Formatting the data is probably the most important thing for a smooth implementation. So that goes down to how that Excel document is formatted? Revit has a very defined structure, so if you understand how Revit data is being formatted and people use it correctly, you can get that pretty reliably." (Participant 13)

"For a company to implement robotics, there are many more considerations. What do you do with the data? How much data are you collecting? What's the quality of the data? Right for a point cloud? But is it? Is it tight like a terrestrial scan or fuzzy like a mobile scan? And then how do you like that with coordinate systems and all this stuff in that space?"(Participant 27)

System Integration

Interviews revealed syntactic, semantic, technical and organisational interoperability regarding system integration.

In terms of syntactic interoperability (the basic ability of different systems to exchange data), interviewees highlighted challenges stemming from diverse software platforms used across different client projects. For instance, participants emphasised reliance on open-source tools or generalised software (e.g., Autodesk suite, Procore) to bridge different file formats. However, proprietary software solutions remain widespread, causing compatibility issues as vendors prefer closed ecosystems, making seamless integration complex and time-consuming (e.g., Autodesk vs. Trimble vs. Procore).

In terms of semantic interoperability (automation of meaningful information and data exchange between software), the research revealed a gap in achieving a consistent understanding of data across platforms. Experts mentioned how different tools (Autodesk, Trimble, Procore) often use their own file format, complicating integration even when APIs exist. Thus, semantic interoperability remains difficult without standardised terminologies and industry-wide data dictionaries. BIM Collaboration Format (BCF) is mentioned as an example of overcoming these challenges.

Regarding technical interoperability, Virtual Design Construction (VDC) and innovation management were frequently mentioned as positions that required in-house expertise capable of operating complex BIM systems. Furthermore, some participants mentioned the challenges relevant to cybersecurity in integrating innovative solutions within the organisation.

Experts frequently mentioned the requirement for technological standards in terms of legal interoperability. However, only two participants confirmed they possessed this standard within the organisation.

Organisational interoperability, organisational fragmentation, and legacy systems were recurring challenges. Participants highlighted that building owners often have older, isolated platforms (e.g., CMMS, PMIS, Archibus) scattered across organisational silos. Integrating these systems into a digital twin is difficult and costly, limiting the industry's ability to achieve holistic digital solutions and full interoperability, especially when organisations resist changing workflows or lack sufficient data governance. Regarding human factors within the organisation, interviewees highlighted that scattered data management practices, lack of training, and limited organisational awareness are significant barriers.

Participants highlighted both current best practices and limitations in their integration approaches. Platforms like Autodesk Build and Procore serve as hubs to integrate multiple data formats (e.g., 3D photos, BIM). However, interviewees also indicated that these integrations often rely heavily on manual processes, or "bridge" tools like Speckle, due to the lack of native, out-of-the-box integration capabilities.

"We're not going to see those large-scale products anymore; they're actually going out of business. We will see these wonderful gems of applications that do a very specific and discreet function. Which means it's great at doing things like RFIs, change orders or any sort of function like that. This means that the data becomes more important because as it flows into that work." (Participant 6)

"There is an approach, and that's what I found to be the most important, is that someone or a

team has sat down and thought about their approach of how they would go about systematically implementing." (Participant 8)

"You want a tool to integrate to be able to do photo taking for you, and that's something that you should test early on and make sure that the data is flowing where you need it to go. And then sometimes things just don't integrate. So you just end up with a ton of apps, but this is where what I was saying earlier, like teams that have data analysts on board, can help figure out how to bridge that information or how to do reporting. So it makes sense to know where the data is going. And there is a lot of information in construction. So every piece of data that's important should have an established. Again, going back to the standard operating procedure, a place where it's being reported and then synthesised into something that can be meaningfully drawn into a report." (Participant 9)

Organisation and Structure

Digital transformation communication

Effective communication requires clear and continuous information flow across organisational teams. Interviewees emphasised the importance of educating employees about new technologies and explaining their reliability, benefits, and limitations. Challenges often arose from resistance due to insufficient early involvement or a lack of understanding of the technology's real value, leading to reluctance or mistrust among end-users. A combined approach of top-down leadership communication and bottom-up feedback was mentioned as an example, supported by clearly documented and regularly updated standard operating procedures. Additionally, interviewees mentioned positioning new technologies, especially AI, as supportive tools rather than competitive threats, helping employees build trust through continuous monitoring, testing, and visible benefits in their daily work.

"A lot of our challenges are both on education and communication to the broader company on what it is, what AI is reliable for, what AI is not reliable for, where it can be used, where it can't be used, where it shouldn't be used" (Participant 8)

"Some team members, especially if they didn't get buy-in early on the selection and roll-out, they're basically going to say Well, why do I have to use? I don't necessarily want to use it. I like my old way of doing things" (Participant 9)

Horizontal Collaboration and Coordination

Interviews emphasised that horizontal collaboration can drive digital transformation through design-associated relationships, process education, and digital partnerships with research institutions or technology vendors.

First, early-phase project partnerships, such as IPD, can enhance design-associated relationships (customer-centric mindset) by developing tools that make processes more cost-effective. For example, BI dashboards can help clients understand the current status of the design and provide detailed information about the project easily and understandably.

Second, companies should align their work process with technologies through training to effectively utilise both parties' technology. Consultant companies should also develop their technological skills to support these processes. A contract can drive these processes by including the applied technology usage in the subcontractors' contract. Technologies should be explained by contractors so that clients can understand the benefits of these technologies, especially regarding cybersecurity concerns for private investments.

Third, digital partnerships appeared in different aspects. Partnering with research institutions can support testing and developing digital technologies that benefit both parties. Collaboration with Technology Vendors can help with system integration problems and build better business relationships. Partnering in supply chain collaboration can enhance digital technology usage. For example, a company mentioned partnering with a subcontractor that owned cranes, and they were responsible for renting and paying for an IoT tool that helped to collect data from the crane's hook to work faster on the project.

"We worked closely with the software vendor to customise integrations and ensure seamless operations" (Participant 8)

"We tried to incorporate this into our contract documents, saying that we use this platform, and we asked them to enrol." (Participant 15)

Vertical collaboration and coordination

Participants mentioned that legacy systems create organisational silos, preventing higher-level technology integration and effective vertical collaboration. Additionally, a shift from the utilisation of files, documents and technology silos to a focus on data flow was revealed as a driving force in this collaborative environment. Cross-functional teams can drive these new processes and the understanding of technology system benefits within the organisation. For example, integrating shared drives and cloud storage has been identified as a significant enabler of collaboration. Project management platforms, particularly their capacity for version management of the documents, have emerged as a pivotal catalyst. One interesting aspect revealed how in-house AI training is related to vertical collaboration. One expert mentioned that the training of AI should include a common understanding of multiple communication styles to give similar answers to users, develop a common understanding from the AI responses, and foster collaboration.

"They don't necessarily talk using the same language. An asset to a portfolio manager is the whole building, an asset to a facility manager is a pump and an asset to a design and construction person. They don't even really think that way. They're thinking about how to look at the building in terms of master format. In all of the divisions of the disciplines of the Building, there's not even really a common language across these legacy silos, so that's the single biggest challenge." (Participant 5)

"Training the AI to understand each salesperson's communication style was crucial." (Participant 18)

Strategic Leadership

Expert opinions revealed multiple factors as strategic leadership challenges in digital transformation. Experts mentioned that companies lack a digital transformation strategy. Technology implementation depends on top management, who should be interested in technology to invest, support and understand the necessary changes that technology requires. Discouraging technology hinders data standards; thus, the evolution of maturity is hindered. Furthermore, interviews revealed a vast knowledge and mindset gap between innovative people and executive leadership. Thus, leaders should understand how to manage people through technology. They need education and knowledge, especially in the field of BIM. By understanding BI-based decision-making and what AI can do, they can see the benefits of technology and further drive digital transformation through digital strategy and strategic decisions on technology rollout. Furthermore, they should also be key technology team or innovation group stakeholders to elevate this strategy.

"It's regrettable that our leadership discourages us from trying to push one software down to all of our projects. Like we can't just go and say, Alright, we're all going to use Procore or we're all going to use Autodesk Construction Cloud tomorrow. That would make things very easy for us from a data perspective and from a standards and consistency perspective. " (Participant 20)

"...first to give them knowledge of what AI or such technologies would do for the company, so they have to be on board" (Participant 14)

Structural agility and flexibility

Experts emphasised the need for new roles, agile teams and strong collaboration between these new roles and the existing ones, especially with the IT department. The lack of an in-house development team hinders digital growth. Thus, organisations should create new positions, teams and departments that align with their C4 strategic goals. Participants mentioned multiple new positions and groups that foster innovation goals, including VDC manager, innovation manager, and data analyst expert. Furthermore, they emphasised the need for new teams and departments, including the VDC team, the data analyst, AI or GIS teams, and the research and development or innovation team that focuses on educating, searching, testing and piloting innovations. These new roles and teams should foster strong collaboration with the IT department, continuously support knowledge creation, and transfer to project managers and construction workers to enhance more efficient core processes. Furthermore, the study revealed that organisational matrix structure can drive DT; however, there is still a knowledge gap between different organisational levels in these organisations.

"Right now, there's a transformation process in process being driven by outside technology innovations." (Participant 6)

"We have developed a kind of grassroots effort that is trying to crowdsource excitement around technology. We call them our technology excellence practice. It's a volunteer group of excited coworkers with a Teams channel and regular phone calls that facilitate vendor presentations. It also has a whole Microsoft Teams environment that is set up with different subject matter experts and has six different categories of technology. Fields like lean construction, like our VDC efforts, and then even within that organisation, there are different products or different user groups that kind of create this community that is searchable and discoverable within our Microsoft environment. So that you know that we can learn from each other." (Participant 20)

Process Management

Organisational Change Management

The research identified mindset shifts and behavioural change as obstacles to effective change management. A common perception among participants, particularly those from older generations and senior management, was that engaging with new technologies wastes time. One participant reported that the initial implementation of AI-based tools generated employee resistance. Additionally, risk aversion in adopting new technologies was frequently linked to budgetary constraints, influencing construction project managers' decisions to integrate innovative solutions. A key finding was the importance of understanding and updating standard operating procedures as a necessary part of the change management process. Organisations adopted bottom-up and top-down approaches to address these challenges, with mixed pilot groups playing a supportive role. IT or VDC managers often led change initiatives and provided technological guidance and project coordination. Furthermore, one giant organisation mentioned that its change management department drives significant organisational changes. Finally, targeted training programs that highlight the benefits and ease of use for teams strengthened the outcome of the process.

"We also, even from a divergent standpoint, have someone who handles change management as well, and he looks for different solutions for our company…There is a group when it comes to that type of global change within our organisation. (Participant 31)

"The problem lies in terms of change management. But you can't have change management without a standard process in which to investigate technology or investigate problems to understand how you might solve them, and how you might automate. The problem is we're not teaching these. We're forcing them to learn how to do an RFI, or run a CPM schedule" (Participant 11)

Process development [15]

The research revealed that the technology implementation is closely related to process development. Thus, a Construction 4.0 technology implementation process was developed based on expert interviews on construction technology implementation strategy. This model follows the main steps of process development, including process discovery, process design and development, process implementation, and process monitoring and improvement. These phases were refined based on the construction technology implementation process, and the following steps were developed: technology identification, evaluation (process discovery), business case development (process design and development), and implementation (process implementation) with change management (process monitoring and improvement). (Fig. 45)

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[15] This paragraph was published in Emerging Construction Technologies Implementation Challenges and Processes in the US

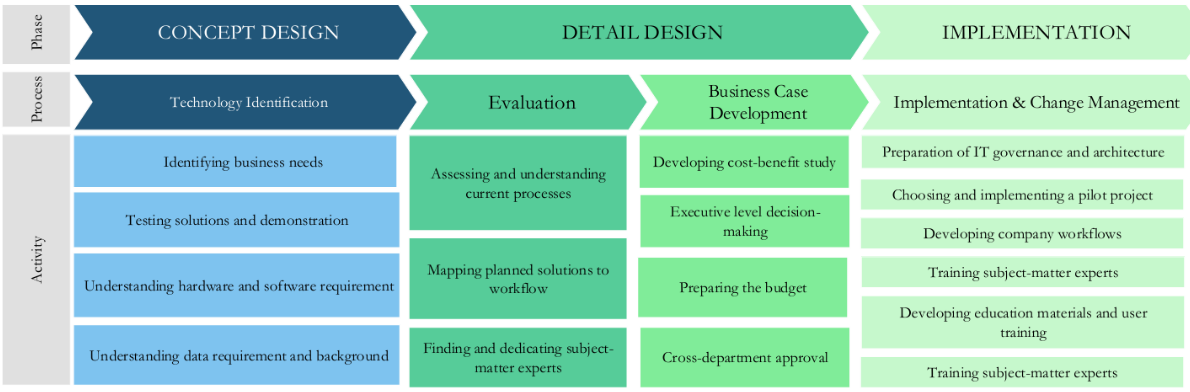

Figure 37 Construction 4.0 technology implementation process based on the Holistic technology implementation model (Schnell et al., 2022) **and the Cambridge Business Model Innovation Process** (Geissdoerfer et al., 2017)

Companies identified their business needs, operational issues, and the scale of the problem during the technology identification process. Engaged innovation teams explored solutions, directing the company to the required technological use case. Various technologies require different IT infrastructures to align with the planned solution. The interviews demonstrated that involving construction project managers accelerated decision-making and increased mid-manager innovation engagement during this process. The selection of a construction project management platform is determined by the possible software integrations, for instance, including open-source solutions, the type of 360-degree camera, and the cost associated with the data collection platform. Participants indicated that understanding their existing data structure and the required one was a significant issue. Additionally, they noted the need for a mechanism that enables software applications of different data types to interoperate.

"And what we could do to solve it is to ideate all that good stuff and then, you know, my team would basically define a business case, cost all that good stuff." (Participant 11)

"We usually ask for a demo and then that demo. There are a lot of people from my team, and after the demo, they all gave me their opinions, If the opinion is a plus one and we see a benefit, then we will implement it. If the overall opinion is that it's not as good or we don't need it, then we won't use it." (Participant 23)

The first step of the evaluation process was knowing actual workflows and examining how the suggested change might affect them. *This allowed businesses to emphasise places where the technology* might boost efficiency and grasp the effects across several divisions. *Although some technologies require process development, maintaining minimum changes* minimises organisational shock, leading to a smoother transition. Engaging technology champions and developing training materials on the newly developed processes paves the way for organisational acceptance. One participant mentioned that implementing GIS-based dashboards for project management required a complete transformation of the business model. To minimise organisational disruption, they established a new data analytics department, conducted preliminary training of subject matter experts, and developed training materials on the newly established processes.

"Any company or business in the construction industry that does not do business process mapping, just mapping, understanding how work gets done, will fail." (Participant 6)

"I'm assuming that there's an evaluation and testing phase done, and like people know about it already, but there are quite a few moving parts. So, one is just kind of mapping out where this new solution impacts current processes." (Participant 9)

The cost-benefit study includes the expected value of the innovation, calculating the time saving of the technology, and analysing the impact of the subscription model on the company's business model. Approval from executive leadership gives a green light for budgeting the proposed technology. It paves the way for cross-department collaboration, including IT, finance, and HR, supporting vertical integration, minimising resistance to change and fostering a culture of collaboration and adaptability. Participants focused on measuring time savings through technology when they prepared a cost-benefit study. Additionally, companies applied diverse decision-making approaches. Some experts noted that executive approval means fully implementing the technology across the organisation. Alternatively, other organisations added the technology to their portfolio as an optional component that allows them to select the technology for specific projects and propose it to clients during the tender phase.

"The organisation's top management has to be fully on board with such changes. In some cases, they may or may not be. That's the first to give them knowledge of what AI or such technologies would do for the company, so they have to be on board." (Participant 14)

Implementing change management processes includes preparing the IT infrastructure and architecture to accommodate the new technology and refining the IT governance framework. Thus, the technological deployment aligns with existing systems and processes. Identify key IT stakeholders leading the solution's deployment, managing single sign-on capabilities, and directing team members to support the necessary resources. A pilot project enables the company to refine its workflows, resulting in close cooperation between the implementation and IT departments. Which allows teams to identify potential issues in a controlled environment. Technological training of champions on the selected solution helps to establish clear leadership responsibility and supports integration with other users.

Additionally, companies can capture knowledge within the organisation by developing online education materials and comprehensive training for all users. Experts noted that AI-driven data management integration requires IT governance and architecture refinement. They also noted that preparing online education materials by screen recording enables them to refine their workflows. Finally, the implemented technologies can help to measure KPI and maintain the change. One expert mentioned an example of using generative AI to analyse survey feedback.

"They need to consider which projects will use the solution, the potential for a piloting phase, and the implications for financial reporting. Identifying a main IT person for the solution, managing single sign-on, and directing team members to support resources. SMEs should be involved in the decision-making process." (Participant 9)

"One of the big things we do is try to solicit feedback through surveys. It is from our different project teams. I'm working on one right now for a multibillion-dollar project where we sent a survey out to 1000 people, and we may only get a 10% response rate, but that's still 100 open-ended feedback responses that typically would have taken me half a day. To kind of organise

the thoughts and kind of develop some themes around them that we could then take and actually act upon, I can do all of that in a matter of 30 minutes and using, you know, ChatGPT." (Participant 20)

Core and Operational processes

Experts provided several examples of how digital technologies are reshaping core processes in the construction industry, including trade coordination, reporting, contractual frameworks, and supply chain management. A key theme was the need for companies to revise their standard operating procedures. Such revisions enable the application of data-driven approaches. Furthermore, they emphasised the benefits of modular construction and Integrated Project Delivery (IPD). Supply chain management and contractual processes were core rather than supporting processes compared to the literature findings.

Contractual language was also described as an indicator of a company's technological maturity. Experts noted the importance of having a clearly defined digital execution plan that outlines how project deliverables will be managed and communicated in a wholly digital environment. Regarding trade coordination, one expert identified 3D coordination as the most transformative development, significantly improving clash detection and potentially tripling productivity. To support this, participants emphasised the importance of continuously updating the BIM model throughout construction to ensure data remains up-to-date.

Integrated Project Delivery (IPD) was highlighted as a method to build trust among stakeholders and overcome resistance rooted in traditional delivery models. Similarly, modular construction requires a straightforward planning process that changes the site inspection process while reducing overall project time. Experts also underscored the importance of understanding local supply chain dynamics and subcontractor work habits to ensure operational efficiency.

"Everybody's talking about data and AI, and the big challenge in the industry is that people don't have their processes standardised, and they can't even incrementally improve on them, and they jump to technology and then say, I want data, and I want AI so we have a very

challenging problem in the industry right now." (Participant 9)

"The most advanced companies I see when I'm working with them in that space are if the project is not in BIM, then it's an upcharge, then it costs more. Because they understand that the risks are higher with the 2D process than with the 3D process. So, looking at contractual language is a great way to understand maturity, and technology maturity because how they handle the management of Revit data, and all the data that's generated by a project and how that's handled contractually between the two parties is very telling of where they are, which on maturity level" (Participant 25)

Supporting processes

Technologies are transforming how construction companies manage and support processes. Experts highlighted the role of financial processes during the decision-making process on the technology, how the companies are considering innovation in their project budget and how they save money by applying these new tools. Furthermore, continuous maintenance should also be considered regarding data management and machines, especially in construction robotics. Human Resources should also change its standard procedure and focus on supporting knowledge management in this evolving technological environment.

Risk management

The qualitative research revealed risk management as a new maturity element, where two themes evolved: how to mitigate risk with technologies and choose technology to meet the companies' risk tolerances. Technologies can support proactive approaches, especially in high-risk environments, such as offshore operations, where safety depends heavily on early risk detection. IoT devices and robotics were typically mentioned in these environments. Respondents also highlighted the value of technological tools in addressing client-side skill shortages, helping ensure project deliverables remain understandable and accessible without advanced technical expertise. Insurance providers and financial institutions were reported to increasingly promote digital solutions—particularly AI-based tools for Projection—for identifying risk. A ranking innovation by risk was described as an effective strategy for technology adoption to meet the required risk tolerance. Finally, participants emphasised the importance of moving beyond past experiences and applying tailored, project-specific risk assessments to meet the demands of evolving challenges.

"We can reduce a lot of safety incidents, and people don't get injured or even die in some cases, where if you have a fire on a platform, no way people can just escape from it. So that way we are reducing the safety, as well as for the people who are working offshore." (Participant 9)

"There's the fear or the risk associated with the skill set not being available on the client side or the owner side does not arise because of the deliverable itself." (Participant 22)

Digital Investment and Performance Metrics

Qualitative analysis revealed that digital investment and performance metrics are a new category of the C4MM. Construction organisations increasingly recognise the need for a multidimensional evaluation framework that extends beyond short-term return on investment (ROI) to fully capture the interplay between initial digital expenditures, long-term adaptability, and ongoing operational efficiency.

Interview data revealed a range of financial strategies used to manage innovation and technology adoption. Companies with more mature digital portfolios often allocate a dedicated innovation budget to project teams, giving them the autonomy to select appropriate technologies. However, these organisations also acknowledged the inherent difficulty in calculating ROI for tools not yet tested in practice. To address this, one expert recommended evaluating performance metrics across extended timeframes and multiple dimensions to gain a more technological value. In other cases, firms assign innovation budgets to the individual level, providing more targeted investment control.

One participant illustrated the importance of strategic foresight in digital asset acquisition, noting that certain initial investments—though lacking immediate application—can accrue significant long-term benefits as organisational needs evolve. In contrast, another participant described an outsourcing strategy, where tasks such as drone photography were delegated to external providers to maximise operational efficiency and reduce internal costs. Several experts highlighted measurable outcomes such as reduced labour hours, which directly enhanced competitiveness in bidding and improved profitability. However, not all technology investments produced net savings. One participant noted that while 3D coordination can generate substantial cost reductions, the expense of hiring highly skilled experts and the need for continuous training often absorb these savings, presenting a significant challenge to maintaining cost-effectiveness.

> *"I have a drone, but it makes sense for me to pay somebody 300 bucks to come out to fly his own drone, get site photos, and meet the specs. But it makes sense for me to pay him because he's got his insurance. He's got his stuff... Those photos are worth that money to me. And so, I don't fly the drone. He flies it. So that I'm doing something else." (Participant 4)*

> *"One of the things for robotics, specifically what we did, is we calculated out by an acreage… So, if a person mows a square acre, how much gas, how much maintenance, and how many labour hours are we using that one square of acreage? And then now, how could a robot do it better? And that's how we kind of track it. So, you kind of look at the whole picture as if you could break every piece of detail. Down to shop maintenance, blade oil, gas, labour hours, drive time… I think it was $45.00 a square acre for a human to do it versus a robot to do it, and it ended up being like $20.00 an acre."(Participant 18)*

> *"For example, how many hours did we think it was in the bid? How many weeks did we think it would take in the bid, How many PM hours did we think it would take? How many production hours and how many cubic yards of concrete? Then, these jobs pull out of our Vista accounting system, which is dollars and hours. And we also pull the actual quantities that were installed, cubic yards of concrete, you know, big, and the things that we track. And so, it's real-time pulling real accounting data out when the projects are finished." (Participant 19)*

Technology for Construction 4.0

Qualitative research underlined the preliminary assumptions that the application of combined technologies, with only minor elements, could be measured by technology elements. Thus, this category will be measured as use cases in the maturity level and introduced in the next section.

4.4.4.3. Maturity Levels

Development of the Technological aspects

The interviews focused on technology implementation processes and their related challenges. The following technologies were discussed during the interviews: AI, Automation and Robotics, BIM, Data analytics, Digital Twin, ERP and Construction Project Management platform (ERP/PMP), IoT and GIS, and Extended Reality (Table 18). The interviews covered multiple use cases of these technologies, such as 3D AI progress tracking or construction site printing. The technological borders between the technologies mentioned are blurred; thus, multiple technology combinations related to the focus technology were mentioned. These technologies can be seen in columns four to eight.

Table 18 Summary of the discussed technologies, their use-cases and the maturity dimensions

ID	Interview focus technology	Use-case	ERP/PMP	AI	BIM	IoT	Robotic:
P-08	AI	Integrated AI with generative chatbot	no	yes	no	no	no
P-14	AI	AI video analytics to extract data	no	yes	no	yes	no
P-17	AI	AI-based workflow generation from emails	yes	yes	no	no	no
P-20	AI	Integrated AI with generative chatbot	no	yes	no	no	no
P-32	AI	AI properatoriy platform for inspection	no	yes	no	no	no
P-07	Automation and Robotics	Modular construction	no	no	no	no	no
P-11	Automation and Robotics	Robotics with AI for build solar farms	no	no	no	no	yes
P-18	Automation and Robotics	Autonomous Mowers and AI Adoption	no	no	no	no	yes
P-27	Automation and Robotics	Robotic total station for automatic layout	no	no	no	yes	yes
P-29	Automation and Robotics	Construction site print	no	no	no	no	yes
P-06	BIM	Design automation	no	yes	yes	no	no
P-13	BIM	BIM based BI dashboards	no	yes	yes	no	no
P-16	BIM	AI-based design tools	yes	yes	yes	no	no
P-19	Data analytics	Data analytics for bid management	no	yes	no	no	no
P-05	Digital Twin	Digital Twin for facility maintenance	no	no	yes	no	no
P-10	Digital Twin	Offsite project maintenance	no	no	yes	yes	no
P-25	Digital Twin	Sensor based humidity data construction digital twin	no	no	yes	no	no
P-04	ERP/PMP	SharePoint based integration	yes	no	no	no	no
P-09	ERP/PMP	Construction Project Management system	yes	no	no	no	no
P-15	ERP/PMP	Construction Project Management system	yes	no	no	no	no
P-01	ERP/PMP	360 camera and BIM for project tracking	no	no	yes	no	no
P-23	ERP/PMP	Construction Project Management system	yes	no	yes	no	no
P-21	ERP/PMP	3D AI progress tracking	no	yes	no	no	no
P-31	ERP/PMP	3D AI progress tracking	yes	yes	yes	no	yes
P-24	GIS	GIS system implementation to monitor site condition	no	no	yes	no	no
P-30	GIS	GIS system implementation to monitor site condition	no	no	yes	no	no
P-12	IoT	Construction safety	no	no	no	yes	no
P-26	IoT	Crane camera inspection	no	no	no	yes	no
P-03	Maturity assesment	System integration	yes	no	no	no	no
P-33	Maturity assesment	Readiness assesment	no	no	no	no	no
P-02	Maturity assesment	System integration	no	yes	no	no	no
P-22	XR	virtual prototyping with VR	no	no	no	no	no
P-28	XR	VR-AI-BIM to pre-train workers and detect issues	yes	yes	yes	no	no

Interestingly, this data shows that the following technology combinations are emerging. AI was mentioned with ERP, especially in enterprise-level AI integration. Another combination with AI is PMP, as these platforms started to apply AI for image processing and IoT to collect data. Robotics combined with IoT devices indicate the need for autonomous data collection solutions. The combination of BIM and AI indicates the future trend in design automation. At the same time, the application of BIM with IoT refers to a higher level of BIM maturity inside the company, as they are already developing in the direction of being capable of applying Digital Twin. XR, in combination with BIM, AI, PMP, and Automation and Robotics, refer to technological capability. For instance, this combination was mentioned in a high-safety environment where the company developed an image-processing AI that detects issues on site. VR was used to simulate and discuss the daily tasks with construction workers before they started the job.

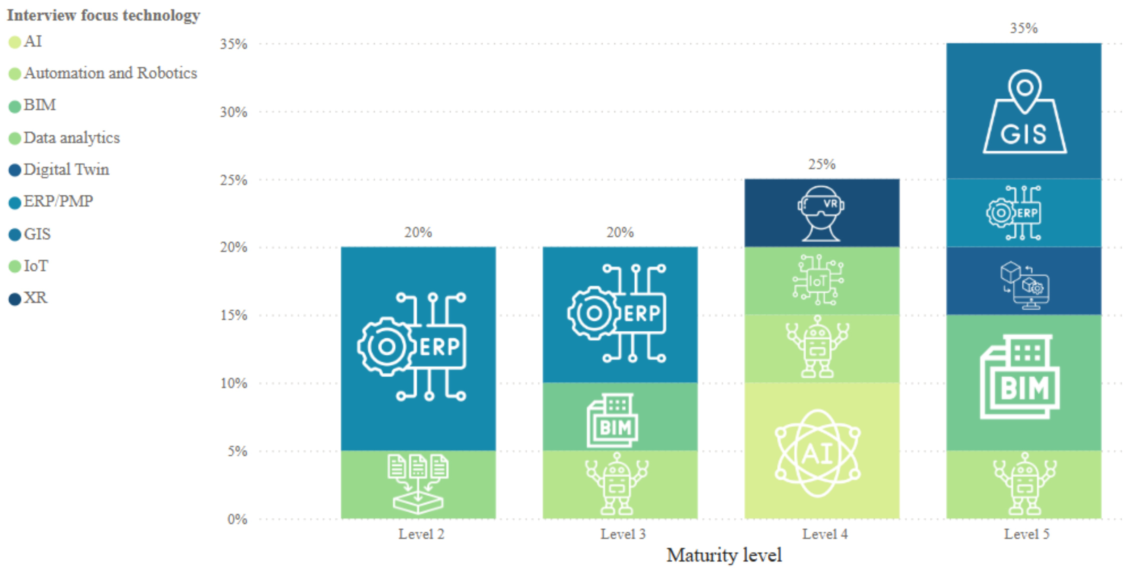

Figure 38 Technology implementation on different maturity levels

Each company was categorised into a maturity level based on the maturity levels developed in the literature review (Section 4.4.2) to reveal further maturity aspects. Results showed that companies with maturity Level 2 have not yet started to focus on AI and BIM. At Level 3, companies started to use Automation and Robotics, BIM and PMP. The majority of companies at Level 4 extensively focused on implementing AI in multiple use cases and on an enterprise level. Companies at Level 5 implemented technologies in ERP/PMP, BIM, Digital Twin and GIS (Geographic Information System) with continuous data analytics to support construction managers (Figure 38).

What is interesting about this data is that most of the participants focused on the construction project management platform, automation and robotics, and BIM during their latest technology implementation project, indicating that those technologies have a high efficiency impact on construction companies (Figure 39).

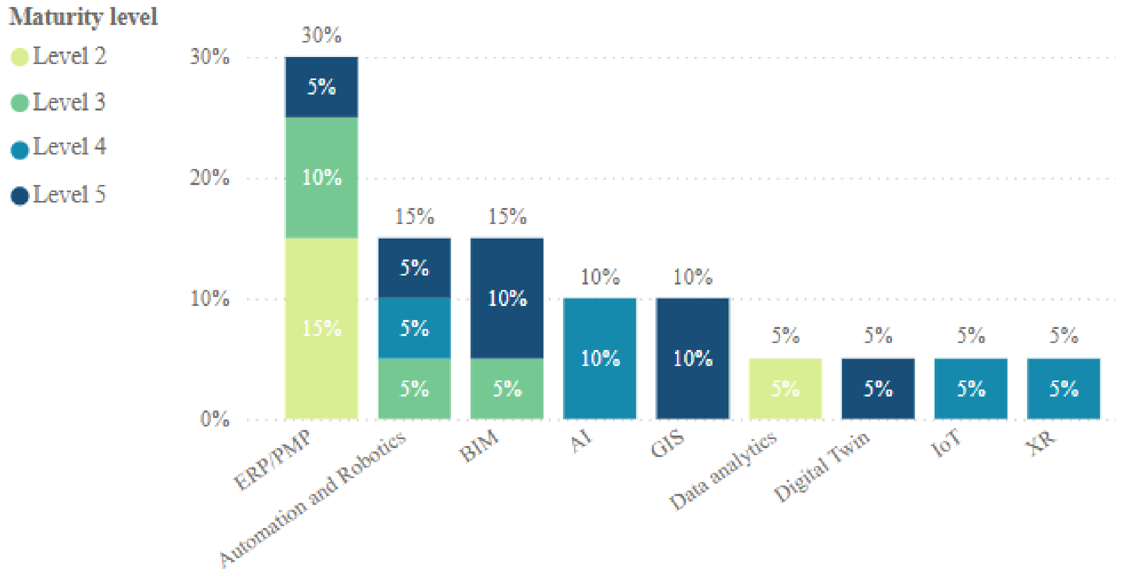

Figure 39 Discussed technologies and maturity levels

Various digital technologies were discussed during the interviews based on specific use cases and their corresponding maturity levels (Table 19).

- Level 2 represents emerging technologies with limited adoption, such as data analytics for bid management and early-stage implementation of ERP/PMP systems, like project tracking with 360 cameras. Companies mentioned examples of these technologies, such as in-house data analytics system development, OpenSpance and Procore.
- Level 3 shows a shift toward automation in design and project monitoring. Use cases included the application of modular construction, AI-based design tools or 3D AI progress tracking with Blueprint, Schema, or Track3D AI.
- Level 4 indicates a greater integration of AI and automation with AI-powered generative chatbots, autonomous construction robotics, and combined technologies with AI-VR-BIM for training and issue detection. These use cases mentioned the following platforms: Chat GPT, Microsoft Copilot, Versatile AI, and in-house AI development trained by photos for tracking issues and training workers.
- Level 5 refers to full technological maturity, with use cases such as design

automation, construction digital twin, 3D AI progress tracking, autonomous robots on site, the combination of BIM and BI, and GIS with advanced data analytics. The following software combinations are mentioned for these use cases: Track3D AI, HP Site print combined with robotics total station, Speckle combined with Revit and Power BI, and ESRI combined with Power BI.

Table 19 Technology use-cases by maturity levels

Interview focus technology	Use-case	Maturity level	Occurance
Data analytics	Data analytics for bid management	Level 2	1
ERP/PMP	360 camera and BIM for project tracking	Level 2	1
ERP/PMP	Construction Project Management system	Level 2	2
Automation and Robotics	Modular construction	Level 3	1
BIM	AI-based design tools	Level 3	1
ERP/PMP	3D AI progress tracking	Level 3	1
ERP/PMP	SharePoint based integration	Level 3	1
AI	Integrated AI with generative chatbot	Level 4	2
Automation and Robotics	Autonomous Mowers and AI Adoption	Level 4	1
IoT	Crane camera inspection	Level 4	1
XR	VR-AI-BIM to pre-train workers and detect issues	Level 4	1
Automation and Robotics	Robotic total station for automatic layout	Level 5	1
BIM	BIM based BI dashboards	Level 5	1
BIM	Design automation	Level 5	1
Digital Twin	Sensor based humidity data construction digital twin	Level 5	1
ERP/PMP	3D AI progress tracking	Level 5	1
GIS	GIS system implementation to monitor site condition	Level 5	2
Total			**20**

These developed levels were used to define the final maturity levels. I will introduce these levels in the next section.

The Developed Maturity Levels

The maturity level development followed a three-step iterative process. In the first step, maturity levels were developed from a literature review. In the second step, the maturity levels were assigned to twenty cases developed from the literature review. Maturity levels were not applied to consultant or technology provider companies. Finally, in the third step, I coded each interview participant's answers for the question of how they would define Construction 4.0 maturity level on a scale of one to five. This process later supported the creation of a thematic content matrix to further understand the maturity level and the corresponding maturity classes (Table 201). The following paragraphs summarise the results (Section 4.4). In this table, number two (2) refers to the model element developed from the literature review (Section 4.4.1), and number three (3) refers to a new model element revealed from the interviews.

Table 20 Maturity Model Elements and their relevance at different levels

	Level 1	Level 2	Level 3	Level 4	Level 5
2_Culture and knowledge management	0	12	12	19	33
2_Collective intelligence	0	4	7	9	14
2_Corporate culture	0	5	4	6	15
2_Knowledge management	0	3	1	7	5
2_Digital synchronisation	0	4	3	12	6
2_Governance	0	0	0	3	0
2_Human-machine collaboration	0	0	1	2	1
2_Law and Regulations	0	4	0	0	0
2_Policy and technology standards	0	0	1	7	4
2_IT management	0	5	7	20	30
2_Cyber security	0	0	1	5	6
2_Data-centric IT management	0	1	0	11	15
2_System integration	0	4	6	5	11
2_Organization and structure	0	4	3	20	26
2_Digital transformation communication	0	0	0	5	2
2_Horizontal collaboration and coord.	0	1	0	2	10
2_Strategic leadership	0	0	1	5	4
2_Structural agility and flexibility	0	2	2	8	9
2_Vertical collaboration and coordination	0	1	0	1	4
2_Process management	0	9	12	14	27
2_Core processes	0	0	1	2	11
2_Organizational change management	0	2	9	6	4
2_Process development	0	7	3	7	11
2_Supporting processes	0	0	0	0	0
3_Risk management	0	0	0	0	1
3_Digital Investment and Performance Metrics	0	3	7	9	5

Organisations at **Maturity Level 1** show a profound resistance to digital transformation. The absence of technological training reinforces dependence on paper-based methodologies. Data is either siloed or not collected at all. Moreover, leadership remains disengaged from digital transformation, causing operational misalignment. The organisation demonstrates an aversion to technological investments. Finally, implementing emerging technologies—such as AI, BIM, IoT, Automation, robotics, and XR—is either absent or applied inconsistently. Rather than leveraging BIM for model-based decision-making, the organisation limits its use to 2D drafting.

"But we see that in certain processes, your ERP is so dated that you are using an on-premises ERP or something like a non-cloud version, not a connected version kind of thing. We feel that within your ERP or your penance and like invoicing and all, you're still at maturity level 1." (Participant 2)

Organisations at **Maturity Level 2** lack culture around the data; thus, corporate culture remains resistant to technological change. Low digital knowledge and limited training opportunities are available only for office and site personnel during technology implementation. However, organisations recognise the need for skilled personnel, and a growing awareness of creating a knowledge base exists. There is no established process for aligning digital strategies across teams, limiting the potential for seamless collaboration and automation. Significant changes are necessary in standard operation processes to implement technology. The organisation struggles to understand ROI for digital transformation, leading to hesitancy in investing in technology. The absence of performance-tracking mechanisms and structured KPIs makes it challenging to assess the financial impact of digital initiatives. PMP might be applied (e.g. Procore), but AI, machine learning and big data analytics are underutilised, with the company relying primarily on Google Sheets.

"One to two, they probably aren't super ready to have the conversation, or they don't believe that they need technology. " (Participant 9)

"For level 2, I put that as simple. Procore use. They may be utilising Teams, holding meetings and sharing data semi-efficiently. They are still running on data silos, and they are probably running into a lot of back and forth and not having the full picture of how their company is being operated, how efficiently it is running and most of their people in the field and the office are not properly trained on the technology they have at their hands." (Participant 32)

Maturity **Level 3** is a turning point for organisations. The company at this level realised the need for change. It has made notable progress in training back-office personnel, and site personnel are also receiving training. Furthermore, the company acknowledges the need for external expertise to strategise technology implementation. Additionally, it is starting to develop business standards for various technologies and recognises the opportunity to benchmark with other industries. Contracts are digitally stored; however, they remain customised for each project. Human-machine collaboration remains a challenge as workers' AI competency and trust remain at a low level. File interoperability is a rising challenge to bridge multiple software without a development team. Efforts to mitigate data silos have begun, and shared folders are now utilised. The company is now starting to focus on the development of the BIM or VDC team. Coordination has been initiated but remains partially implemented, with manual reporting still dominant. Innovation is not yet deeply embedded in the organisation’s processes. However, process development is beginning to receive attention. The company is starting to test technologies and recognising the need for workflow changes. However, the lack of advanced financial tracking methods and performance evaluation tools limits the ability to assess the ROI of these technologies. Drones are being introduced for site surveys. 3D laser scanning for BIM and reality capture is now in use. PMP has been adopted, and all employees are trained in it. BIM / VDC coordination is at an early stage. However, the organisation continues to rely on Google Sheets and Excel-based spreadsheets for reporting, data tracking and analytics, with no significant adoption of AI-driven processes.

“They have adopted some software, and a lot of them now have Procore, which is obviously a big project management tool for construction. They've adopted the fact that they started doing training on it. Some of their teams are using it, but they're definitely not experts in Procore. “ (Participant 17)

“Three is a lot of technology, technology is isolated to a pocket of the business, right? There's a level of inconsistency or non-acknowledgement of what's going on.” (Participant 24)

“There are quite a few fewer that are going to be probably in the one to three range, where either they're not implementing, or they don't have it at all in terms of digital workflows,

digitisation, VDC coordination." (Participant 29)

At **Level 4 maturity**, the organisation is fostering a culture of knowledge sharing and evolving its corporate culture to promote employee motivation, creative freedom, and innovation. A new level of governance has been achieved by redesigning the IT architecture to align with seamless data flow. High-level IT policies have been established, including data capture, cybersecurity, and AI policies. The company maintains a growing technology portfolio for projects with calculated ROI and is developing business standards for various technologies. The project-centric mindset is shifting toward a process-centric approach, with active efforts to advance human-machine collaboration. A systematic implementation plan has been developed to support system integration. While data interoperability continues to influence technology selection, data integration has been effectively implemented across actively used platforms. Cybersecurity remains a key focus throughout the integration process. The organisation operates within a matrix structure and consistently communicates the benefits of digital innovation. Strategic leadership, guided by a formal digital strategy, drives the transformation. As a result, dedicated in-house departments for AI, data, and innovation are in place, with personnel actively testing technologies and identifying pilot projects to support ongoing innovation.

"Four means we have reviewed every technology available on the market and made a decision not to use some of them because the juice just isn't worth the squeeze" (Participant 4)

"If you're starting to do analysis on your models and starting to implement simulations and stuff, I think you get to level 4 " (Participant 13)

"AI for managing their document would be a good use of AI for them and would then increase or help them implement AI in other aspects of their work, like field work. Because if they see success in document management of their standard specifications and pulling out even to manage contracts and to create draft contracts based on data from old, similar contracts are becoming very prevalent"(Participant 14)

At **Level 5 maturity**, the organisation has fully trained its staff in technology, with ongoing investment in upskilling to ensure digital fluency across all levels. Training increasingly focuses on robotics to reduce on-site labour, supported by active knowledge sharing and a culture of continuous learning. Digital transformation is communicated through open, two-way dialogue, with partners and stakeholders encouraged to advance their digital maturity. The organisation has digitised its policy and contract management systems, developed business standards for adopted technologies, and benchmarked practices against other industries. Complete system integration has eliminated data silos, enabling seamless access through a centralised data warehouse, while AI tools support automated analytics and decision-making. High-level cybersecurity is in place. A top-down approach to innovation is driven by C-suite leadership, supported by dedicated teams for data, innovation, product development, and an incubator programme. A life-cycle mindset and innovation budget reinforce sustained transformation. The company has implemented Integrated Project Delivery (IPD) and fully embraced Virtual Design and Construction (VDC), with strong change management and high-level supply chain collaboration. Processes are advanced and aligned with data workflows, and technologies such as IoT, GIS-integrated BIM, robotics, drones, and 3D tracking are actively used. 3D model-based estimation, 4D simulation, VDC-enabled prefabrication and the application of Construction Digital Twin further enhance project predictability and efficiency.

"A level five would be organizationally and technologically; a company is fully optimised for delivering projects as quickly and efficiently as possible, but they're also thinking about the building's life cycle, not just this one project. And so they're concerned with making sure that the building owner has a good set of data that they turn over after Construction because they know at some point they're going to have to come in and do a major renovation to the same building." (Participant 5)

"A level five has an established innovation team. They have a budget set aside for innovation. They have a data team. There's someone specifically in the C-Suite who is driving data and innovation. For the company, there are, I guess, end users or peer groups or community groups within the company that are helping to socialise innovation and create that culture. And that it's a two-way communication. Team members are communicating up like, hey, here,

here's this innovative tool or thing that I want to try and also leadership saying, hey, we actually are rolling out this innovative tool, who wants to go ahead and kind of be our SME. A five is where there are maybe incubator programs within the company, and also some construction companies as well have their investment arm….” (Participant 9)

4.5.Demonstration of the Artefact

The demonstration involves using the developed artefact in a real-life or illustrative case to prove its feasibility and show that it can solve an instance of the problem (Johannesson and Perjons, 2014).

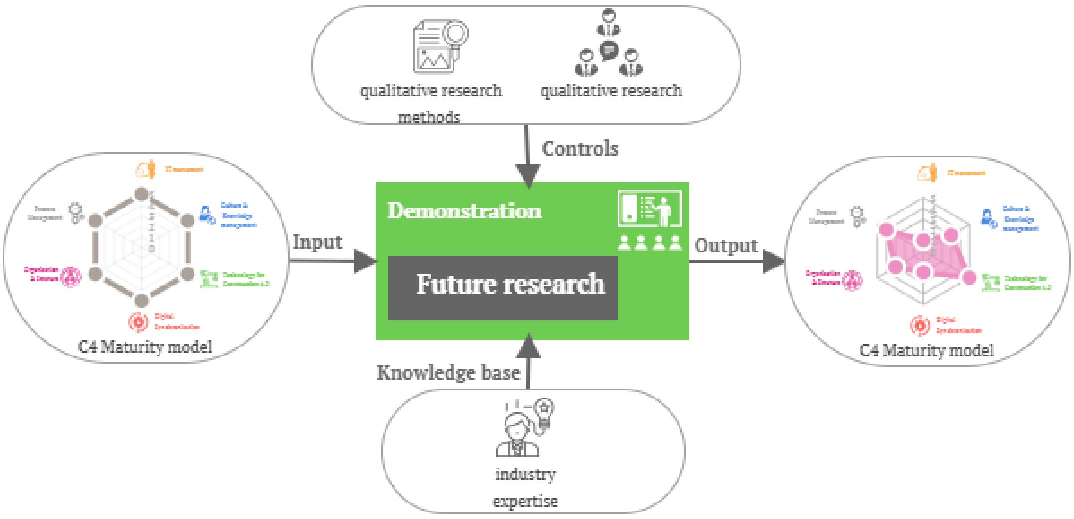

Figure 40 The Artefact Demonstration

The developed artefact, C4MM, serves as the input for demonstrating and testing the newly developed model. Industry expertise is a knowledge base for interviews to develop the C4MM measurement criteria. The output of this step will be a tested model that can measure construction companies' maturity. This step will be part of the future research after the dissertation.

4.6.Evaluation of the Artefact

The evaluation assesses how effectively the artefact meets the requirements and addresses the practical problem that motivated the research (Johannesson and Perjons, 2014). In the evaluation phase of the research, the metrics of the developed model will be validated through a survey. Then, the final model will be tested on the market. Finally, the results obtained will be evaluated and compared with the developed model. This step is also part of the future research after the dissertation.

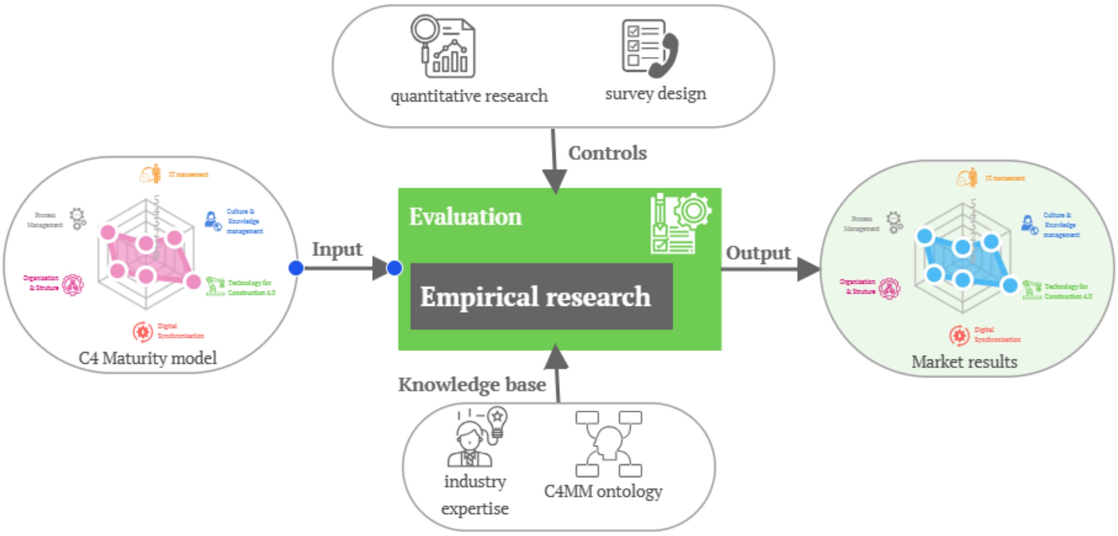

Figure 41 Evaluation of the Artefact

5. DISCUSSION

5.1. Summary of Key Findings

The primary objective of this research was to explore and characterise the factors that influence the digital maturity of construction organisations within the framework of C4, resulting in the C4MM version 2. The model offers a multidimensional, empirically grounded approach to understanding how DT unfolds across the CI's organisational, technological, and cultural domains.

The finalised C4MM comprises seven interrelated categories: Culture and Knowledge Management, IT Management, Digital Synchronisation, Organisation and Structure, Process Management, Digital Investment and Performance Metrics, and Technology for Construction 4.0. These categories emerged from a rigorous synthesis of existing literature. They were then refined and validated through ontology modelling and developed further with 33 construction industry professionals, the majority of whom held senior roles in large firms operating across the U.S. Each of these six dimensions encapsulates critical levers for achieving digital maturity. *Culture and Knowledge Management* encompasses collective intelligence, knowledge management, and fostering innovation-friendly corporate cultures. *IT Management* includes cybersecurity, data-centric IT management, and system integration. *Digital Synchronisation* captures governance, internal and external regulations, corporate standards and human-machine collaboration. *Organisation and Structure* focuses on strategic leadership, structural agility and flexibility, and internal-external collaboration and coordination. *Process Management,* mentioned the most frequently in qualitative interviews, includes change management, process development, and operational efficiency in terms of core and operational processes. *Digital Investment and Performance Metrics* evolved as a new category of the model from qualitative findings. This category refers to the volume of investment in digital innovation and how they measure its success and their daily performance with digital tools. Finally, *Technology for C4* delineates key technologies such as BIM, digital twins, IoT, AI, XR, GIS, Project Management platforms and construction robotics as maturity indicators.

The model proposes five maturity levels: from ad hoc, siloed efforts (Level 1) to fully integrated, ROI-optimised ecosystems (Level 5). Each level is defined by technological adoption and the degree of integration, standardisation, strategic alignment, and cultural readiness. For instance, a firm operating at Level 3 may use advanced digital tools, yet still struggle with fragmented knowledge systems or underdeveloped metrics.

Empirical data from semi-structured interviews confirmed that digital maturity is not a linear investment or tool acquisition outcome. Somewhat, maturity is shaped by the interaction between technological capabilities and organisational readiness. Process development and digital knowledge transfer were consistently identified as catalysts for sustained transformation. Meanwhile, organisational culture—particularly attitudes toward risk, automation, and learning—was seen to either enable or inhibit technology adoption.

Additionally, the model was validated through ontology engineering, ensuring formal consistency and semantic coherence. Interestingly, return on investment also appeared during the ontology engineering as a critical factor of the model. The logical structuring of C4MM into RDF classes and relationships enabled the model to be tested using reasoning tools and visualised through RDF graphs. This affirms the model's conceptual integrity and positions it as a scalable, machine-readable framework for future decision-support applications.

5.2. Integration with Existing Literature

The Construction 4.0 Maturity Model developed in this study affirms and extends the current literature on digital transformation. The research offers a comprehensive framework that addresses both technical and organisational maturity dimensions by triangulating insights from a systematic literature review, qualitative interviews, and ontology-based modelling. This section positions the empirical findings within the broader scholarly discourse, highlighting areas of alignment, divergence, and innovation.

Culture and Knowledge Management

This study confirms the literature that continuous training and reskilling are critical to enhance professional capabilities in the C4-driven transformation (Chen et al., 2024, Das et al., 2022, 2023). However, it extends the literature by identifying the rising need for upskilling in AI, data analytics, and robotics—areas not yet fully integrated in standard training frameworks. This research stresses the role of internal innovation teams and technology champions as practical enablers. A notable divergence from the literature is the observed workforce fatigue due to the speed of technological change, highlighting the need for culturally adaptive transformation strategies. Furthermore, the interviews revealed that developing a technology-oriented culture in construction is shaped by a mix of external, organisational, and social factors. The findings also extended the literature by highlighting that external challenges often came from clients who lacked a clear understanding of how digital tools could benefit projects and regional or cultural differences in attitudes toward innovation. Participants also observed that while innovation depends on company culture, it simultaneously reshapes it, particularly in how organisations communicate and collaborate. However, rapid technological change without cultural alignment was viewed as potentially disruptive, as well as worker behaviour in technology adoption. These findings indicate that construction companies should consider process transformation in their digital transformation journey.

Digital Synchronisation

Interviewees highlighted the need for a holistic approach to data governance and IT architecture, reinforcing (Gökalp et al., 2022) the argument that governance provides critical frameworks for decision-making. The qualitative results and literature emphasised the importance of standardising data platforms and ensuring data integrity, usability, and security, as Tuma Neto and Araujo de Souza Junior (2022) indicated. Nevertheless, the interviews reveal a more fragmented reality: regulatory inconsistencies and a lack of interoperability (especially around digital twins and BIM standards) hinder progress. Meanwhile, literature tends to focus more on structured frameworks and clearly defined standards (Chen et al., 2024). The interviewees provided real-world implementation hurdles such as organisational autonomy and behavioural challenges, emphasising that standardisation efforts must be complemented by behavioural and practical considerations to bridge theory with practice effectively. These practical challenges contrast with the literature's often prescriptive tone, bringing attention to behavioural inertia and decentralised IT governance as significant barriers. Moreover, this perspective aligns with (Maurtua et al., 2017), who advocate human-machine collaboration to enhance productivity, efficiency, and safety by combining human cognitive skills and robotic capabilities.

IT management

Interviewees emphasise the critical need for robust cybersecurity and offer concrete illustrations of how vulnerabilities—such as ransomware, IoT security breaches, or AI privacy breaches—impact digital uptake. These findings are consistent with those of Das et al. (2022), which focus on secure data storage and integrity protocols. The literature widely discusses interoperability(Shehzad et al., 2021; Turk, 2020). Nevertheless, the empirical data expose the limited penetration of standardised frameworks. However, clear process definitions appeared only at a higher maturity level, where BCF was also mentioned as an example of overcoming these challenges. The findings reinforce that interoperability is not only a technical issue but one of leadership, training, and contractual clarity—factors frequently overlooked in existing maturity models.

Organisation and structure

The research revealed a sobering picture of the leadership compared to the literature findings. Despite the literature mentioning that strong vision and roadmap drive organisations toward advanced technology application (Haryanti et al., 2023; Schumacher et al., 2019), only the most advanced companies were focused on a digital transformation strategy. One interesting finding extended the literature knowledge on digital transformation communication by communicating AI as a supportive tool rather than a competitive threat, helping employees build trust through continuous monitoring, testing, and visible benefits in their daily work. The research expanded existing knowledge by showing that collaboration tools like cloud storage facilitate vertical integration. At the same time, matrix structures and innovation roles improve structural agility, subtleties often generalised or underemphasized in the literature. Additionally, the study revealed that contractors are key in driving digital transformation by explaining technology benefits and cybersecurity challenges to their clients during the project life cycle. VDC managers drove these negotiations. One interesting finding also revealed from the study is that AI training should focus on a common understanding of multiple communication styles to give similar answers for users, making collaboration more effective.

Process Management

The findings align with existing literature that emphasises the importance of structured training, cross-functional collaboration, and strong leadership in driving digital transformation change management (Das et al., 2023; Haryanti et al., 2023, 2024; Tuma Neto et al., 2022; Zhu et al., 2024). While the literature highlights digital competencies and partnership programmes as strategic tools, the results revealed that practical implementation relies heavily on outdated processes, adapting standard procedures, and involving both top-down and bottom-up approaches. Supporting Das et al. (2023) and Gökalp and Martinez (2022), the findings affirm that process development requires strategic alignment and technological integration. However, this research challenges the overemphasis on BIM by highlighting a broader, multi-technology process ecosystem. It also introduces the idea that digital transformation shifts contractual and support processes (e.g., HR, budgeting, marketing) from peripheral to strategic, reflecting an evolution not yet widely acknowledged in existing studies.

Digital Investment and Performance Metrics

The Digital Investment and Performance Metrics category evolved from qualitative findings. The findings expand existing literature by illustrating how construction organisations approach innovation investment with a long-term, multidimensional perspective. While (Das et al., 2023) emphasise the importance of selecting innovations based on return on investment (ROI), participant examples suggest that ROI must be understood in immediate financial terms and through operational efficiency, productivity gains, and strategic flexibility over time. This reinforces the argument by Chen et al. (2023). Implementing key performance indicators is essential in capturing the success of innovation efforts, particularly when extended to include both tangible and intangible metrics.

Maturity Level 1 – Organisational resistance

At Maturity Level 1, there is resistance toward digital transformation. These findings, in alignment with empirical results, highlight a lack of digital culture, strategic alignment, and leadership commitment (Han et al., 2024; Perera et al., 2023). Findings revealed that technological training is absent, reinforcing dependence on manual, paper-based methods (Jäkel et al., 2024; Razkenari and Kibert, 2022). The results of the study underlined that data silos, minimal IT security, and isolated tool usage (e.g., CAD, email, spreadsheets) obstruct systemic adoption of digital workflows (Han et al., 2024), resulting in experience-based decision-making rather than data-driven insights (Razkenari, 2019). At the same time, the literature acknowledges the use of ERP systems (Razkenari and Kibert, 2022; Wernicke et al., 2023). Findings revealed that such systems, if present, are likely to be non-cloud-based and poorly integrated. The qualitative research revealed that at this level, BIM is appearing; however, it is a symbolic rather than a strategic use.

Maturity Level 2 – Strategic Misalignment

The findings at Maturity Level 2 reveal a misalignment between the strategic recognition of digital transformation and its practical execution. Areas where significant differences have been found include performance tracking, process standardisation and the application of technologies. While the literature identifies a general lack of digital performance measurement frameworks (Han et al., 2024), the empirical data further illustrate how the absence of structured KPIs and ROI assessments results in organisational hesitancy in investing in digital technologies. The study revealed significant changes in standard operation processes to implement technology are necessary. In contrast to the study results, the literature highlights that companies have formulated technology roadmaps (Jäkel et al., 2024) and initiated process automation efforts (Perera et al., 2023) at this level. Literature mentions technologies including IoT utilised (Perera et al. 2023), while BIM and PMP are in their early implementation phase (Han et al. 2024), in contrast to the study findings, where emerging technologies have not been applied yet; PMP is in an early implementation phase.

Maturity Level 3 - Digital Awareness

At Maturity Level 3, there is an apparent change toward digital transformation. The findings indicate progress in training both back-office and site personnel, aligning with literature highlighting the emergence of structured training and talent development at this stage (Han et al., 2024; Perera et al., 2023). The literature presents a more advanced picture, describing fully integrated ERP systems and secure data exchange across departments (Han et al., 2024), while the qualitative findings revealed that companies using shared folders are still struggling with interoperability challenges and isolated technologies. Areas where significant differences have been found include the performance metrics and the level of technological maturity. In contrast to literature findings, no evidence of performance measurement, benchmarking, and digital dashboards supporting data-driven decision-making (Han et al., 2024; Perera et al., 2023; Razkenari and Kibert, 2022) was detected. Results show a lack of advanced financial tracking methods and performance evaluation tools at this level. Literature highlights that at this level, Construction 4.0 technologies, such as BIM, IoT, and AI, are combined to drive process automation (Perera et al. 2023; Han et al. 2024). differ from qualitative findings, whereas organisation has begun applying robotics, drones, and VDC coordination is at an early stage, with learning processes, but automation is still lagging. Additionally, the organisation continues to rely on Google Sheets and Excel-based spreadsheets for reporting, data tracking and analytics, with no significant adoption of AI-driven processes.

Maturity Level 4 – Strategic Integration and Innovation

At Maturity Level 4, there is a shift toward strategic integration and innovation. I revealed several parallel concepts between literature and empirical findings. Both sources identify a well-established digital culture, supported by structured governance frameworks and training initiatives (Perera et al., 2023; Razkenari and Kibert, 2022).

Strategic leadership guided by a formal digital strategy is central in both cases. This includes structured governance through IT architecture and policy frameworks (Razkenari and Kibert, 2022). While both findings recognise innovation as a central part of the maturity level, the empirical findings revealed in detail this concept, the establishment of in-house departments for AI, data analytics, and innovation teams. A company with a growing technology portfolio and a focus on return on innovation supporting the strategy, similar to the literature's emphasis on measurable KPI-driven investment (Razkenari and Kibert, 2022). A shift from project-centric to process-centric operations is evident in the study and the literature, emphasising system integration (Han et al., 2024) and long-term transformation (Das et al., 2023), where cybersecurity is a key priority. Areas where significant differences have been found include the applied Construction 4.0 technologies. The literature portrays organisations already deploying advanced tools like digital twins, cyber-physical systems, and blockchain at scale (Han et al., 2024; Razkenari, 2019), whereas qualitative research results show that organisations are still in the phase of testing these advanced tools.

Maturity Level 5 – Full Integration and Strategic Innovation

Maturity Level 5 is the complete integration and strategic innovation. Executive leadership, dedicated innovation teams, and structured innovation programmes echo the literature's emphasis on a culture of continuous transformation and adaptability. Additionally, the organisation's digital strategy is aligned with business goals (Han et al., 2024). Literature highlighted that the organisation applies workforce-wide human capital development (Das et al., 2023; Wernicke et al., 2023), where the study revealed this training includes robotics for upskilling current workers. Both study findings and the literature describe complete digital integration across operations, supporting a digitally mature, data-driven ecosystem (Han et al., 2024). The organisation has established robust governance (digitised policy, contract management, cybersecurity), aligning with literature on comprehensive policies and industry standards. Seamless access through a centralised data warehouse underlines literature findings of interoperable frameworks and open data exchange, enabling collaboration.

5.3. The role of ontology

Using ontology-based modelling constitutes a methodological contribution to the maturity model literature. This study operationalised the C4MM using an RDF-based semantic model, translating conceptual categories into logical triples and validating them through reasoning engines. This approach moves beyond heuristic classification toward a formal, machine-readable structure, enabling both theoretical diagnosis and computational reasoning. It also supports integration into digital tools such as dashboards, automated assessments, and AI-driven decision support systems.

The developed ontology provides a foundation for future model enhancement, allowing company maturity assessments to consider not only individual dimensions—such as rating digital transformation communication on a scale from 1 to 5—but also interdependencies between various organisational and technological aspects. Conditional logic (if-then-else) can be embedded within the system to evaluate readiness. For example, previous research indicates that digital capabilities critically influence technology implementation. Based on this insight, one could define a rule whereby effective GIS adoption requires a company to reach level 4 in knowledge management and at least level 3 in system integration.

Beyond this example, the dissertation findings underscore the complex interdependencies inherent in construction sector digital transformation, affecting multiple organisational areas simultaneously. The ontology enables the representation of these relationships and supports a rule-based evaluation system. The system can identify maturity levels and generate tailored recommendations for further development based on questionnaire responses. In this way, the ontology forms the basis for an expert system—the envisioned goal of future research. As Morris (2006) defines*, "an expert system is an artificial intelligence application that performs symbolic reasoning over a knowledge domain."* By formalising human reasoning through rules, such systems can reveal hidden patterns beyond the explicit structure of the maturity model.

Therefore, The research results establish the foundation for future software development. Grounded in artificial intelligence and supported by the developed ontology, this software could analyse interrelationships between organisational development and technology adoption to identify improvement areas to accommodate innovation. As a decision-support system, it could guide managers by evaluating current states and recommending necessary transformations across processes, technologies, and human resources. Ultimately, it would support construction companies in addressing Construction 4.0 challenges and advancing toward a more digitally mature and sustainable operation.

Compared to existing models, the C4MM stands out for its integrated scope and dynamic structure. Whereas other models tend to focus narrowly on technical readiness or BIM capability, the C4MM interweaves technological, organisational, cultural, and regulatory factors. Its layered ontology also allows for extensibility—new technologies, subcategories, or contexts can be incorporated without compromising conceptual coherence. Furthermore, the C4MM addresses a key critique in the literature: that many maturity models lack empirical grounding and formal validation. By combining expert interviews with ontological rigour, this study answers the call for evidence-based, verifiable frameworks that are both theoretically robust and operationally useful.

The developed ontology thus lays the groundwork for an AI-driven expert system capable of diagnosing organisational maturity, identifying key development areas, and offering targeted recommendations. This tool could significantly assist construction companies in overcoming C4-related challenges and pursuing more sustainable, innovation-ready operations.

5.4. Unexpected Results and Their Interpretations

While developing and validating the C4MM, several findings emerged that either diverged from existing assumptions in the literature or revealed new nuances not previously addressed in digital transformation frameworks.

Perhaps the most notable empirical gap was the role of virtual design and construction managers. Companies that have seriously committed to digital transformation and have already started to hire VDC managers are already at Level 3 maturity. Perhaps these roles can speed up the whole organisation's digital transformation journey, not only from technological but also from cultural and strategic alignment in digital transformation.

Another unexpected finding was the complete absence of companies classified at Maturity Level 1—the stage defined by fragmented digital use, lack of strategic alignment, and minimal digital culture. Despite initial expectations that some participants would exhibit low maturity, all twenty companies assessed fell into Levels 2 through 5. Several interpretations may explain this. The study design may have sampling bias, as participants were primarily drawn from large organisations and many held executive or innovation roles. These actors are more likely to be engaged in, or at least aware of, digital initiatives.

Another significant but underexplored dimension revealed in the interviews was the emotional and cultural *resistance to automation and artificial intelligence*. While the literature often frames human-machine collaboration as a technical integration challenge, this study finds that *perceptions of job security, control, and identity* play a central role in mediating acceptance. Thus, successful human-machine integration requires technical compatibility, narrative framing, participatory change design, and psychological safety.

In response, future models and tools may need to incorporate modular or distributed maturity diagnostics, enabling firms to identify their overall maturity level and the differential states of their subunits or processes.

5.5. Limitations and Methodological Constraints

While this study offers a comprehensive and empirically grounded maturity model for guiding digital transformation in the construction industry, several limitations must be acknowledged regarding sampling, applied methodology, and ontology usability.

The participant sample was composed primarily of senior executives, innovation leaders, and digital specialists from medium to large construction firms, with a concentration in the United States. While this focus was intentional, reflecting a goal to examine organisations actively engaged in Construction 4.0 initiatives, it inevitably introduces selection bias. Smaller firms, subcontractors, and organisations with lower technological adoption were underrepresented, as were perspectives from emerging markets or non-Western contexts. This limits the generalisability of the C4MM, particularly with respect to SMEs or firms operating under different regulatory, economic, or infrastructural conditions. Furthermore, the absence of Level 1 maturity cases may indicate a gap in the model's applicability to firms at the beginning of their digital journey.

The study employed a cross-sectional qualitative design, capturing a snapshot of digital maturity and transformation experiences simultaneously. While this method yielded rich insights into organisational perceptions and strategies, it does not account for how maturity evolves longitudinally through project cycles, leadership changes, or economic fluctuations. This is particularly salient in construction, where project-based operations and rapid shifts in market conditions can dramatically influence digital uptake. The primary data collection method, semi-structured interviews, relies on self-reported information, which carries inherent limitations. Participants may have selectively emphasised successes, downplayed challenges, or responded in ways that reflect social desirability bias. Moreover, the qualitative nature of the data makes it difficult to independently verify claims or compare responses across a uniform set of metrics. Although content analysis was applied, and responses were triangulated with literature and model design, the findings remain interpretive rather than statistically generalisable.

While the ontology-based validation added structural and logical rigour to the model, it is important to note that this process tested internal consistency, not practical usability. The OWL ontology confirms that the relationships between model components are semantically coherent and computationally valid. However, it does not assess how end users interact with the model in real-world contexts. Nor does it evaluate the completeness of the categories from an industry-wide perspective. There remains a risk that certain emerging technologies, regulatory changes, or context-specific challenges were not fully captured within the seven dimensions of the model. These constraints suggest a need for future field testing and participatory validation, particularly with user groups beyond the research sample.

5.6. Practical Implications

The model offers industry practitioners a structured yet flexible diagnostic and planning tool. It enables organisations to assess their current state, identify capability gaps, and prioritise areas for investment or organisational change. Its modular design allows it to be applied at multiple organisational levels, making it adaptable to diverse contexts and firm sizes. The findings also underscore that digital maturity is not just a technological goal but an organisational capability. Effective digital transformation requires leadership commitment, cultural readiness, and process integration. As such, firms must go beyond digital procurement and address governance, training design, stakeholder engagement, and internal knowledge management questions.

At a *policy level*, the C4MM provides a valuable framework for public procurement, regulation, and capacity-building initiatives. Governments and industry bodies can use the model to set digital capability benchmarks, structure innovation funding, and guide the digital upskilling of the workforce.

For *higher education and professional development*, the C4MM highlights the need for interdisciplinary curricula that blend construction engineering, information systems, and organisational psychology. Preparing future leaders for Construction 4.0 requires more than technical proficiency; it requires systems thinking, change management skills, and a deep understanding of digital ethics and governance.

6. CONCLUSION AND FUTURE WORK

This dissertation presented the design, development, and validation of the Construction 4.0 Maturity Model, a novel framework for assessing and advancing digital maturity in construction firms. Grounded in the Design Science Research methodology, the research addressed critical gaps in the conceptualisation and operationalisation of Construction 4.0, synthesising literature, qualitative insights, and ontological formalisation into an empirically grounded and scalable maturity model.

This inefficiency in the construction industry resulted from outdated technologies and processes. The implementation of technology has the potential to significantly improve the efficiency and drive the sector towards a more efficient and sustainable vision (Schönbeck et al. 2020). Despite advancements in C4, most construction firms face significant challenges in integrating these tools and technologies effectively (Oesterreich & Teuteberg, 2016). However, the lack of a comprehensive and systematic approach to assessing digital maturity hinders strategic alignment and continuous improvement (Chen et al. 2023). Several digital maturity and readiness models have been developed to assess how companies have embraced digitalisation and facilitated their seamless adoption of C4 technologies.

Thus, the overarching aim of this study was to understand how digital maturity in the construction industry can be systematically characterised and formalised, and to design a diagnostic tool that supports strategic digital transformation. The core objective was to develop a robust, ontologically validated model—the C4MM—that guides construction companies in assessing and enhancing their digital capabilities across technological, organisational, and human dimensions.

6.1. Summary of the C4MM Development Process

This dissertation introduced the development of the C4MM based on DSR (Figure 42). The blue rectangles show the steps introduced in detail during the model development (Section 4). The green rectangle represents the future research that will continue after this dissertation. As a result of this research, a C4MM was developed with three iterations that can be further refined and used to assess construction companies' digital maturity.

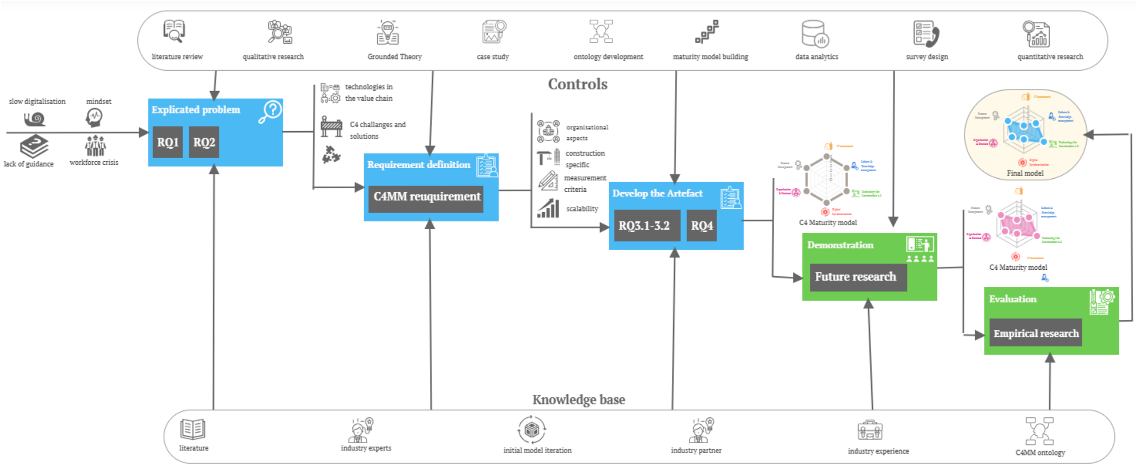

Figure 42 Artefact Design and Development Steps Summary

Each of the six research questions was addressed through the phases of model development and validation:

RQ1: What is C4, and what are its challenges and solutions?

Following the DSR steps, the explicated problem revealed from qualitative research that the C4 paradigm represents a novel construction ecosystem (Section 4.1) encompassing three fundamental pillars: (1) integrated technologies and cyber-electronic systems, (2) methods and processes, and (3) human resource competencies. These three pillars are supported by automation and data analytics. In this ecosystem, sustainability represents a significant goal which industry players can achieve by enhancing the efficiency and productivity of construction processes (Heidenwolf and Szabó 2024).

Grounded Theory revealed (Section 4.1.1) that although technology offers a variety of promising solutions at various stages of the construction value chain, the emergence of C4 has already resulted in the emergence of complex challenges for companies. The current workforce crisis in the construction workforce is not the sole human resources challenge; the adaptation to new technologies also necessitates social and attitudinal changes on a management level. There is a clear need for comprehensive training and education to prepare the workforce for innovations such as human-robot collaboration.

The DT process has several obstacles, including outdated workflows and a dearth of innovative culture. Effective data management and pursuing strategic thinking are paramount for successfully transforming organisational structures. (Nagy et al., 2021).

RQ2: What solutions do innovations bring through the CI value chain?

C4 impacts every stage of the CI, from the initial planning and design stages to the demolition and integration of completed projects into the broader infrastructure of smart cities. Innovations can bring multiple solutions to the CI value chain (Section 4.1.2). Technologies such as BIM and 3D libraries facilitate enhanced design efficiency, cost estimation and collaboration. During the construction, innovations such as mobile applications and robotics facilitate enhanced project management and safety. In the operation phase, real-time monitoring enables optimised maintenance, while demolition benefits from 3D modelling for sustainable practices. Integration into smart cities leverages real-time data and human-centred infrastructure, necessitating public education and addressing legal and ethical concerns (Nagy and Szabó Zs. 2021).

The explicated problem was followed by the requirement definition (Section 4.2). This step guided the main aspects of the C4MM and served as input data for the development phase.

RQ3: What factors influence the C4MM in the CI? How to characterise and formalise construction companies' technology adaptation readiness? – Phase I

The artefact development answered the question of what factors influence the C4MM in the CI and how to characterise and formalise construction companies' technology adaptation readiness (RQ3). This process introduced multiple iterative phases.

The preliminary C4MM version 0 was developed from the initial literature review in the first phase. This version further guided the development of C4MM version 1 (Section 4.3) and finally the development and refinement of the second model version (Section 4.4).

RQ3.2: How can the C4MM be validated by a case study?

This early version of the model was applied to a single case study, highlighting its diagnostic potential and informing refinements in structure and content (Section 4.3.2). The verification of the C4MM version 1 was strongly influenced by subjectivism, as the validation of the model relied solely on a simple case study, which can strongly influence the research outcome (Peshkin, 1988). Thus, a second development phase was necessary.

RQ3: What factors influence the C4MM in the CI? How to characterise and formalise construction companies' technology adaptation readiness? – Phase II (see in Section 4.4.1-4.4.2)

As an output of the first development phase, the C4MM version 1 was used as a guide – the coding structure of the literature review - to redesign the artefact and formulate precise definitions for each model element (Section 4.4.1) for C4MM version 2. This model has the following six categories: Culture and Knowledge Management, Digital Synchronisation, IT Management, Organisation and Structure, Process Management, and Technology for Construction 4.0 and the five maturity levels of the model: Initial, Managed, Defined, Optimised and Transformative (Section 4.4.2).

RQ3.1: How can the C4MM be validated by ontology?

After multiple iterations, this model provided a solid base to refine the developed model by ontology (Section 4.4.3). Ontology engineering was employed to ensure this model's logical consistency, semantic clarity, and extensibility. The formal OWL structure and RDF graphs confirmed the centrality of core concepts and enabled reasoning capabilities for future digital applications.

RQ4: What correlations and characterisation of the C4MM can be explored based on input from industrial experts?

Multiple correlations and characterisation of the C4MM were explored from qualitative research with 33 industrial experts (Section 4.4.4), resulting in C4MM version 3. The final model has seven categories: Culture and Knowledge Management, Digital Synchronisation, IT Management, Organisation and Structure, Process Management, Digital Investment and Performance Metrics and Technology for Construction 4.0 and the five maturity levels. The qualitative research revealed the addition of the "Digital Investment and Performance Metrics" category and further enhanced the model's empirical grounding.

The evolution of the Construction 4.0 Maturity Model

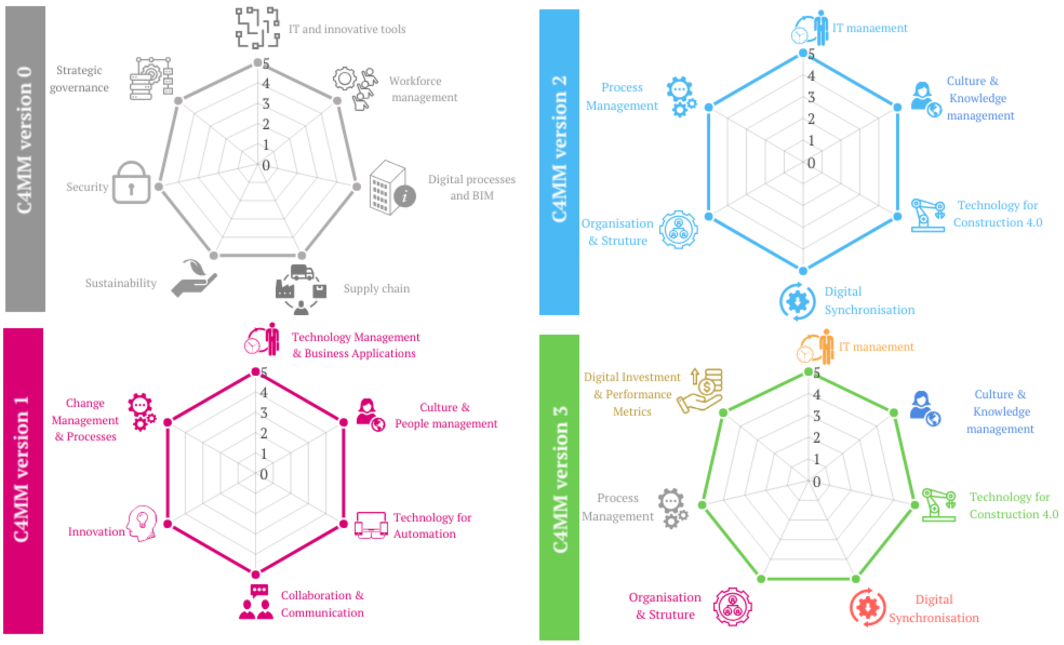

Figure 43 The evolution of the C4MM

The model was developed through three major iterations using the Design Science Research approach. C4MM v0: A conceptual structure was developed from the definition of C4 and the most cited I4 maturity models. This model guided the development of C4MM v1. The model was refined and tested through a single case study, but was limited by subjectivist interpretation. Thus, C4MM v2 was developed. This model was strengthened by formal definitions developed from a systematic literature review and validated through ontology modelling. Finally, this model evolved to C4MM v3 based on qualitative research findings. This final version integrated expert insights from 33 industry professionals, expanding the model to seven categories and enhancing practical relevance. As a result, the C4MM comprises seven categories—Culture and Knowledge Management, Digital Synchronisation, IT Management, Organisation and Structure, Process Management, Digital Investment and Performance Metrics, and Technology for

Construction 4.0—mapped across five maturity levels: Initial, Managed, Defined, Optimised, and Transformative.

6.2. Summary of Limitations

Limitations include a geographically and organisationally narrow sample (mostly large, U.S.-based firms), the absence of longitudinal tracking, and the lack of practical ontology testing in operational environments.

6.3. Directions for Future Work

The development and validation of the Construction 4.0 Maturity Model opens up multiple pathways for scholarly and practical exploration. While the current study offers a robust conceptual and empirical foundation, the rapid evolution of digital tools, shifting regulatory environments, and diversity of organisational contexts underscore the need for ongoing research. Thus, this research will continue after this dissertation to develop a rule-based AI system in the evaluation phase. The following areas are proposed as priorities for future investigation (Figure 44).

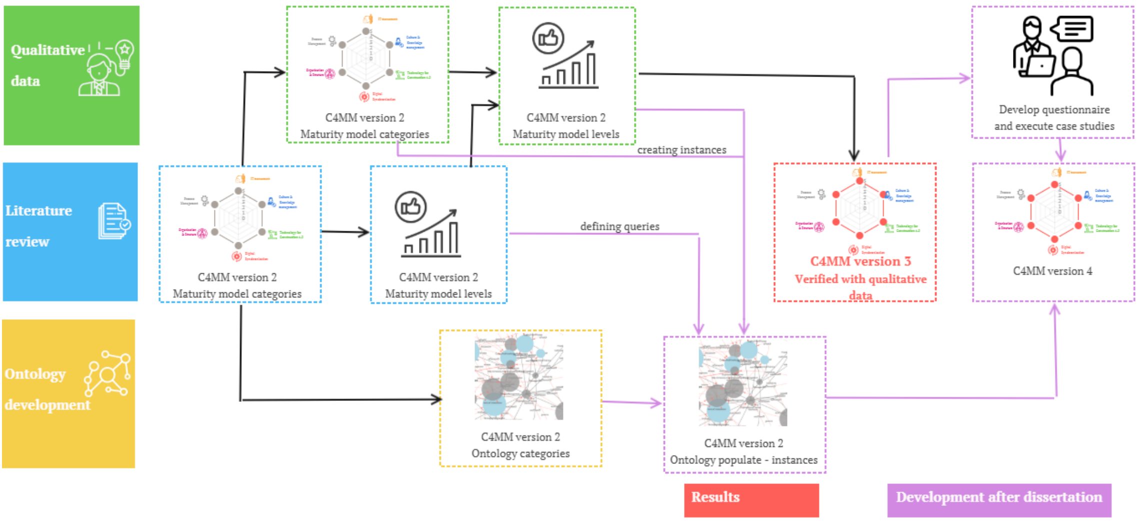

Figure 44 The iteration process during the model development

Future research will complement the qualitative findings with quantitative validation, using the collected quantitative data to validate relationships between maturity factors and organisational performance. After quantitative data analysis, we plan to conduct a second round of qualitative data collection to validate the model further. Such research could culminate in a performance-indexed version of the C4MM, linking maturity levels to tangible business outcomes.

The formal ontology developed in this study offers a strong foundation for digital tools and intelligent systems. Thus, the future work will include populating the ontology with instances resulting from the qualitative research. The developed maturity model levels will support the creation of queries, which will be the input questions of the model. As a result, an interactive C4MM diagnostic platform for self-assessment, AI-based recommender systems for tailored technology adoption or the integration of the C4MM ontology into existing construction management software can be developed.

The developed ontology can also serve as a base for a Retrieval Augmented Graph that supports knowledge extraction from multiple documents with AI. For example, the Retrieval Augmented Graph can extract information based on the developed ontology from a construction company's strategy document, and by combining it with AI, the system can answer the company's current level in digital maturity without needing an extra questionnaire.

Given that the sample in this study focused primarily on large, U.S.-based firms, future research could also seek to test the *C4MM in small and medium-sized enterprises*, particularly in developing countries. SMEs often face unique challenges requiring tailored models or simplified diagnostic tools. Comparative studies across regions could also illuminate how cultural, infrastructural, and policy differences influence digital maturity trajectories. Such research would enhance the global applicability of the C4MM and potentially surface new maturity dimensions not captured in the current model.

6.4. Concluding Remarks

In summary, this dissertation offers both a robust theoretical model and a practical roadmap for the digital transformation of the construction sector. As the construction industry becomes increasingly shaped by digital technologies, sustainability imperatives, and global uncertainties, models like the Construction 4.0 Maturity Model will be essential for navigating this complex terrain. This research contributes to measuring progress and a language for strategic reflection, encouraging organisations to ask not just "*What technologies do we use?*" but "*How do we evolve as a digitally mature organisation?*"

Ultimately, this study affirms that digital transformation in construction is a continuous journey that requires vision, adaptability, and an integrated understanding of the technological and human systems at its core.

I believe the result of my dissertation can equip construction companies with the tools needed to guide them to successful Construction 4.0 digital transformation.

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ANNEXES

Annexe I. Details of companies involved in interviews

Table 21 Details of companies involved in interviews

ID	Dominant Industry	Stakeholder in Construction	Country	Organisation Type	Position	*
1	Construction	Consulting/Technology Investor/Association	United Kingdom	MNE/SME/NGO	Manager/ CEO/Founder	5+
2	Construction	Technology provider	USA	DLC	Director	10
3	Real estate	Consulting/Technology investor/Investor	USA	DLC	CEO	25
4	Construction	Technology investor and provider	Germany	DLC	CEO	15
5	Construction	Technology investor	Israel	DLC	CEO	25
6	Construction	Research and development	Portugal	EDU	Employee	5+
7	Real estate	Research and development	Finland and India	EDU	Associate Professor	15
8	Government	Authority	Poland	GOV	Employee	5+
9	Government	Authority	Estonia	GOV	Director	5+
10	Electronic automotive	Investor	United Kingdom	MNE	Manager	15
11	Construction	Designer	Finland	MNE	Director	15
12	Construction	Consulting	United Kingdom	MNE	Employee	5+
13	IT	Investor/Technology provider	USA	MNE	Director	15
14	Construction	Consulting	Nigeria	NGO	Employee	5+
15	Construction	Research and development	United Kingdom	NGO	Manager	5+
16	Construction	Consulting	Finland	SME	CEO	35
17	Construction	Consulting	United Kingdom	SME	CEO	10
18	Construction	Technology provider	USA	SME	Manager	5+
19	Construction	Technology provider	USA	SME	Manager	5+
20	Construction	Consulting	USA	SME	CEO	20
21	Construction	Consulting	USA	SME	CEO	25
22	Construction	Consulting	United Kingdom	SME	Manager	20
23	Manufacturing	Technology provider	United Kingdom	SME	Manager	5+
24	Construction	Consulting	Netherland	SME	CEO	15
25	Construction	Consulting	United Kingdom	SME	CEO	20
26	Construction	Consulting	United Kingdom	SME	Director	15
27	Construction	General contractor and education	India	SME/EDU	Manager/lecturer	5+

28	Construction	Consulting	Latvia	SME/EDU	CEO	10
29	Construction	Consulting	Hungary	SME/EDU	CEO/researcher	5+

Notes: EDU = education, GOV = government, MNE = multinational enterprise, DLC = domestic large company, SME = small and medium enterprise. * = business experience

Source: (Nagy et al. 2021)

Annexe II. C4MM – Case study verification results

Level	Type	Description	Workflow elements	Verification	DT phase	Score
L0	Category	**Technology for Automation**				4.6
L1	Subcategory	Automated/robotic devices (3D printing, drones, robotics)				5
L2	element	Robotics strategy	Develop a robotic environment	Verified with changes	Phase IV	5
L2	element	Robotics-focused process development		Verified with changes		5
L2	element	Robotics usage		Verified with changes		5
L2	element	ESG - Robotics		Recommended	NA	5
L1	Subcategory	Information modelling techniques (BIM / Digital Twin)				4.4
L2	element	BIM-focused Leadership	Develop a BIM environment	Verified with changes	Phase III	5
L2	element	Regulatory policy		Verified with changes		3
L2	element	Contractual policy		Disproven		2
L2	element	Workflow	Plan cloud-based workflows	Verified	Phase II	4
L2	element	Products & Services related process	Develop a BIM environment	Verified with changes	Phase III	5
L2	element	Preparatory process		Verified with changes		5
L2	element	Resource process		Verified with changes		5
L2	element	Software for information modelling		Verified with changes		5
L2	element	Hardware for information modelling		Verified with changes		5
L2	element	Network for information modelling		Verified with changes		5
L1	Subcategory	Internet of Things (IoT) and Sensing Systems				5
L2	element	IoT Strategy	Integrate IoT and Sensing systems	Verified with changes	Phase III	5
L2	element	Asset management		Verified with changes		5
L2	element	Application management		Verified with changes		5
L2	element	IoT and sensing system usage		Verified with changes		5
L1	Subcategory	Data-driven technologies	Predictive data-driven decision			3.8

Level	Type	Description	Workflow elements	Verification	DT phase	Score
L2	element	Data structure and management	Business Intelligence system	Verified	Phase IV	5
L3	element	Data life-cycle management	Integration into project-specific processes	Verified	Phase III	5
L2	element	AI-ready employees	Internal education	Verified with changes	Phase III	5
L2	element	AI Strategy	Not part of the workflow diagram	Disproven	NA	0
L1	Subcategory	Wearable devices and Human-machine interfaces (mobile phone, AR, VR, wearables)				5
L2	element	WD and Human-machine interface focus on strategy	Not part of the workflow diagram	Disproven	NA	5
L2	element	WD and HM interface education	Internal education	Verified with changes	Phase III	5
L2	element	WD and HM interface usage	Monitor Human-machine interface usage		Phase IV	5

Annexe III. Artefact Design and Development Steps Summay

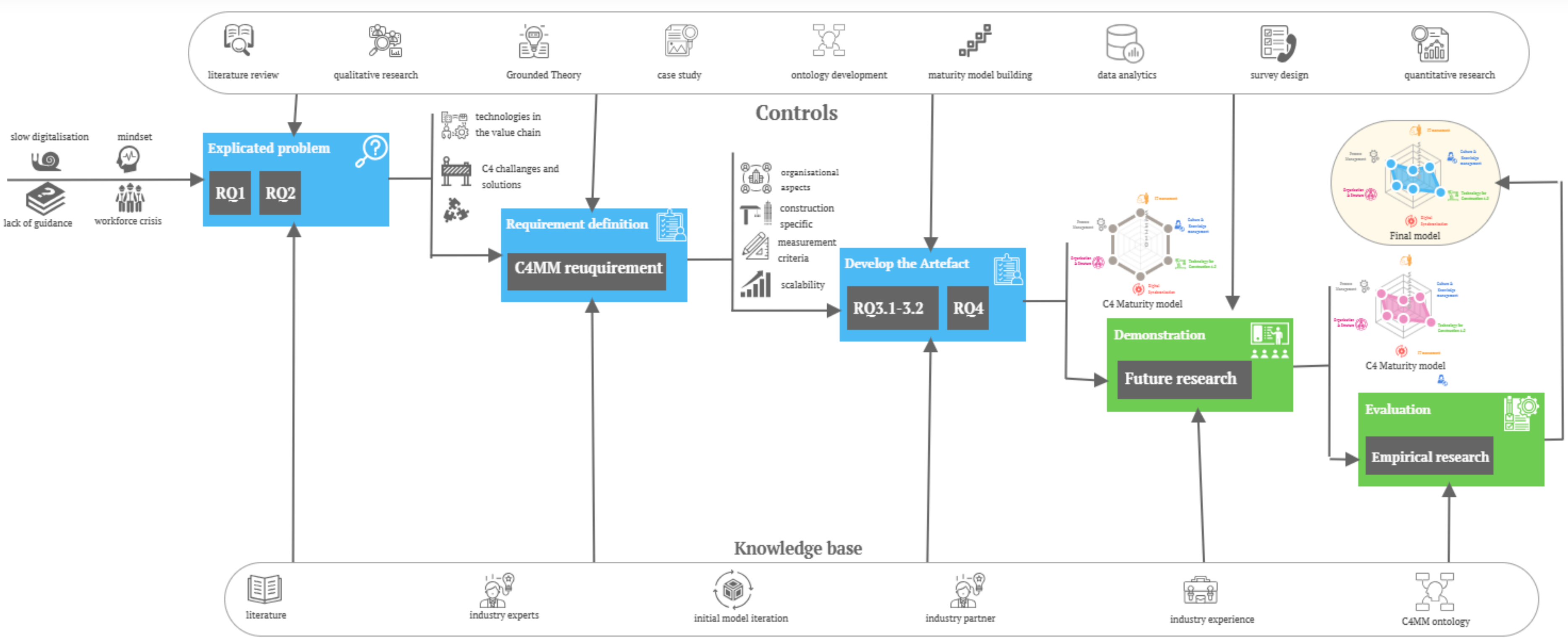

Figure 45 Artefact Design and Development Steps Summary

Annexe IV. Consent form

VIRGINIA TECH.

Information Sheet for Participation in a Research Study

Principal Investigator: Kereshmeh Afsari
IRB 24-948
Title of Study: Construction 4.0 Maturity Assessment research
Sponsor: NKFI K-146826 sourced from the Hungarian National Research, Development, and Innovation (NRDI) Fund

You are invited to participate in a research study. This form includes information about the study and contact information if you have any questions.

➢ WHAT SHOULD I KNOW?

If you decide to participate in this study, you will complete an interview, then we will ask you to complete a follow-up survey. As part of the study, we will start the meeting with a 30-minute online Zoom interview, during which we will discuss a few research questions. The questions are related to the latest technology implemented by your company (e.g. BIM, IoT, ERP, AI, construction robotic), the procedure used to implement it, and the metrics used to assess the success of the procedure. The Zoom meeting will be recorded for transcription later. Once the interview is complete, you will be sent a link to complete a 15-minute follow-up survey about the technology discussed.

The study should take approximately 30-45 minutes of your time.

We do not anticipate any risks from completing this study.

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

➢ CONFIDENTIALITY

Virginia Tech Information Sheet version 1.0.1

We will do our best to protect the confidentiality of the information we gather from you, but we cannot guarantee 100% confidentiality.

Any data collected during this research study will be kept confidential by the researchers. Your interview will be audio-recorded using a digital recorder and then transcribed. The researchers will code the transcripts using a pseudonym (false name). The recordings will be uploaded to a secure password-protected computer in the researcher's office. The researchers will maintain a list that includes a key to the code. The master key and the recordings will be stored for 5 years after the study has been completed and then destroyed.

We will only keep identifiable data in a key file that will include the participant's name. e-mail address, and its unique ID. All other collected data will be de-identified and only its unique ID will be used. The de-identified data can be only identifiable by the key file which will be stored in a separate Excel file.

If identifiers are removed from your private information or samples that are collected during this research, that information or those samples could be used for future research studies or distributed to another investigator for future research studies without your additional informed consent.

- **WHO CAN I TALK TO?**

If you have any questions or concerns about the research, please feel free to contact Orsolya Heidenwolf at orsolyah@vt.edu . You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research participant, contact the Virginia Tech HRPP Office at 540-231-3732 (irb@vt.edu).

Please print out a copy of this information sheet for your records.

Annexe V. Demographic survey

Demographic information

This includes **name**, **gender** (female, male, non-binary, other (please explain)), **years of experience in the construction industry** (no experience, less than one year, 1-2 years, 2-3 years, 3-4 years, 4-5 years, 5-10 years, 10-15 years, 15-20 years, 20+ years), **years of experience using construction technology** (no experience, less than one year, 1-2 years, 2-3 years, 3-4 years, 4-5 years, 5-10 years, 10-15 years, 15-20 years, 20+ years), **current job title** [CEO/CFO, CTO, President, Director (IT/R&D/Innovation/HR/Technology), Business Manager (IT/ R&D / Innovation /HR / Process /Technology), Project Manager, Consultant], **current working location state within the U.S.**, **type of company** (architect, designer, general contractor, specialty contractor (Trades or Crafts), construction management firm, technology provider, construction consultant firm, IT consultant firm), **company size** (1-25, 26-50, 51-100, 101-250, 251-500, 501+), **company global presence**

Annexe VI. Interview Questions

Study Title: Construction 4.0 Maturity Assessment IRB# 24-948
Principal Investigator: Kereshmeh Afsari
Researcher: Orsolya Heidenwolf

Interview Questions

Demographic information

https://forms.office.com/r/VewX4sKxJi

https://forms.office.com/r/Bz1ACA3aS4

Technical interview questions:

1- What are the most advanced technologies and use-cases your company uses?
2- What is the upcoming technology that your company will start to implement in the future?

3- What was the **latest technology** your company implemented/started to use and why did you started to use it? (examples BIM or digital twin, XR, IoT, Robotics, AI, machine learning, data analytics, ERP)
   a. What **other technical steps** did you have to take **before implementing** this technology?
   b. What **challenges** have you faced **during** the implementation process? How did you address those challenges? Did those challenges impact other divisions? If yes, how?
      i. Did you face **any challenges that were related to the knowledge**, skills, and abilities regarding this technology?
   c. Could you please explain what the **overall process was before and after** implementing this technology/solution?

4- What measurement criteria does your company use to measure a successful technology implementation?
5- How would you **define Construction 4.0 digital maturity levels** on a scale of one to five?
6- Do you have any platform where you are able to collaborate with other systems?

End of the interview

Would like to add anything else? Is there anything in this meeting that we discussed, and you don't want us to use in our research?

Would you please also fill out a follow-up survey about this topic?

Was there a question you expected me to ask because it was important, but I didn't ask it?

Was there anything that came to mind in the process, but you didn't tell me for some reason and you thought it was important to tell me in the context of the topic

Could you recommend another person who could participate in the research?

What old technology would work better than a new one for your company?

Annexe VII. Follow-Up Questions

Construction 4.0 Digital Maturity Assessment - Follow up survey

IRB# 24-948

* Required

General information

1. What is your name? *

2. What category would you put the **technology** that we just discussed? *

Please select one category that best describes the technology / solution

- ☐ **Building Information Modelling and Digital Twin** (A digital representation of physical and functional characteristics of a facility)
- ☐ **AI / Machine Learning or Big Data Analytics** (Techniques for extracting insights from vast datasets).
- ☐ **Robotics and Automation** (A bridge for digital systems to interface with the physical world).
- ☐ **Extended Reality** (VR, MR, AR The visual communication of digital information).
- ☐ **IoT and Sensors** (A connection linking digital systems to the physical world).
- ☐ **Project Management Platform and ERP** systems (The integration of tools and processes to plan, track, and optimize resources, schedules, and financials across an organization).
- ☐ Other

Culture and Knowledge Management

*Please consider all your answers regarding the **[technology]** we discussed, and you choosed during the second question.*

3. C.1 How did the company have to **organize collective intelligence** for implementing this [technology]? *

Please select based on your experience with the technology mentioned

- ◯ The company had no structured approach to pooling skills and knowledge
- ◯ The company had to occasionally collaborate, but efforts are informal and not consistent across teams.
- ◯ The company established collaboration processes supported by this [technology], and competency-building is formalized.
- ◯ The company consistently uses this [technology] for collaboration across the organization, with a strong focus on competency mapping and employee autonomy.
- ◯ The company fully leverage this [technology] with other digital tools for real-time collaboration, with dynamic competency development and high employee autonomy to drive innovation
- ◯ Other

4. C.2 Did the company implement specific **internal** initiatives (e.g., internal training sessions, workshops, or knowledge-sharing platforms) to build knowledge about this [technology]? *

- ◯ Yes, before we started the implementation
- ◯ Yes, after we implemented the technology.
- ◯ No

5. C.2 Did the company undertake any **external** knowledge acquisition efforts (e.g., consulting with experts, attending external training, or partnering with other companies or academic institutions) to implement this [technology]? *

- ◯ Yes
- ◯ No

6. C.2 This [technology] helped us *

Select all that apply

- ☐ to **generate** corporate knowledge **inside** the company
- ☐ to **store** corporate knowledge **in digital systems**
- ☐ to **share** corporate knowledge via **digital systems**
- ☐ to **transfer** corporate knowledge in **organized circumstance**s (e.g, workshops, trainings, mentor programs, etc.)
- ☐ to **monitor** these activities
- ☐ none of them above

7. C.3 Which of the following is required to successfully and effectively use this [technology]? *
Select all that apply

- [ ] long-term **continuous education** (e.g., ongoing training, certification programs, peer-to-peer education)
- [ ] **management level education** (e.g., leadership development for digital skills)
- [ ] **employee mentoring** (e.g., one-on-one mentoring, department-led guidance programs)
- [ ] none of them above

Digital Synchronization

8. D.1 How do you agree with the following statement? *

Please, rate all statements from 1-5 (1 - Strongly disagree, 5 - Strongly agree).

	1-Strongly disagree	2-Disagree	3-Neither agree nor disagree	4-Agree	5-Strongly agree	Don't know
The [technology] helps the company **align its digital strategy** effectively.	◯	◯	◯	◯	◯	◯
The [technology] enables the company to **digitally manage finances** more efficiently.	◯	◯	◯	◯	◯	◯
The [technology] supports **digital management** of the company's **human resources**.	◯	◯	◯	◯	◯	◯
The [technology] **improves collaboration across teams** and **departments**.	◯	◯	◯	◯	◯	◯

9. How do you agree with the following statement? *

Please rate all statements from 1-5. (1 - Strongly disagree, 5 - Strongly agree)

	1-Strongly disagree	2-Disagree	3-Neither agree nor disagree	4-Agree	5-Strongly agree	Don't know
D.2 The **regulatory environment was complex** and hard to understand in terms of implementation of this [technology]	○	○	○	○	○	○
D.3 The company has supported the implementation of this [technology] through its **corporate policies and technology standards.**	○	○	○	○	○	○
D.4 The use of this [technology] **improves collaboration between human workers and machines.**	○	○	○	○	○	○

IT Management

10. I3. Did the company possess the basic IT infrastructure required by implementing this [technology]? *

◯ Yes

◯ No

11. I.1 How do you agree with the following statement? *

Please rate the statement from 1-5. (1 - Strongly disagree, 5 - Strongly agree)

	1-Strongly disagree	2-Disagree	3-Neither agree nor disagree	4-Agree	5-Strongly agree	Don't know
I.1 The company had to **prioritize cyber security to safeguard both data and systems** during the implementation of this [technology]	◯	◯	◯	◯	◯	◯

12. I.2 This [technology] enables the company *

Select all that apply

☐ to **generate data** in source (transactional) systems

☐ to **collect data from** source systems (transactional, IoT devices, etc.) and process and transform the data for analytical purposes

☐ to **execute data analytics** (analyzing reports, charts, building ML models)

☐ to **enhance the activities real-time**

☐ None of them

13. I2. Do you agree with the following statement? The continuous application of this [technology] requires data governance (including guidelines and policies) *

◯ Yes, I do agree

◯ No, I don't agree

14. I.3 What solution do you use to integrate this technology to other systems? *

Select all that apply

- [ ] No integration
- [ ] Inhouse development
- [ ] Peer-to-peer connection
- [ ] Using a common platform (service-oriented IT architecture)

Organization and Structure

15. O1.1 The company communicated clearly the implementation of this [technology] by setting clear objectives. *

Select all that apply

- [ ] at employee level
- [ ] at management level
- [ ] at C-level
- [ ] at none of them

16. O.1.2 Please rate these activates in terms of importance to implement this [technology]. The activities refer to the **horizontal** collaboration between the **company and its partners.** *

Please rate all activities from 1-5 (1 - Not at all important, 5 - Very important).

	1-Not at all important	2-Slightly Important	3-Important	4-Fairly important	5-Very important	Don't know
change the company **processes** to **collaborate** with its **partners** at **operational level**	○	○	○	○	○	○
use digital platforms/system integration to **enhance collaboration** at operational level	○	○	○	○	○	○
change the company's **processes** to collaborate with its partners at decision making level	○	○	○	○	○	○
use digital platforms/system integration to **enhance collaboration** at **decision making level**	○	○	○	○	○	○
change the company's **processes** to **collaborate** with its **partners** at **strategic planning**	○	○	○	○	○	○
use digital platforms/system integration to **enhance collaboration** at **strategic planning**	○	○	○	○	○	○

17. O.1.3 Please rate these activates in terms of importance to implement this [technology]. The activities refer to the **vertical** collaboration **inside the company** *

Please rate all activities from 1-5 (1 - Not at all important, 5 - Very important).

	1-Not at all important	2-Slightly Important	3-Important	4-Fairly important	5-Very important	Don't know
change the company's **processes to enhance collaboration between employees** at operational level	○	○	○	○	○	○
use digital platforms/system integration to enhance collaboration between employees at **operational level**	○	○	○	○	○	○
change the company's processes to **enhance collaboration between employees** at **decision making level**	○	○	○	○	○	○
use digital platforms/system integration to enhance collaboration between employees at decision making level	○	○	○	○	○	○

18. How do you agree with the following statement? *

Please rate all statements from 1-5 (1 - Strongly disagree, 5 - Strongly agree).

	1-Strongly diagree	2-Disagree	3-Neither agree nor disagree	4-Agree	5-Strongly agree	Don't know
O.2 The company had a **strong vision** for this [technology] implementation	○	○	○	○	○	○
O.2 The company shifted from a project-centric view to a **process-centric view** as a result of implementing this technology.	○	○	○	○	○	○
O.3 The company have developed and implemented a **continuous education** for this [technology] **inside the organization.**	○	○	○	○	○	○
O.3 The company could **utilize** the **employee's expertise to implement** this [technology]	○	○	○	○	○	○
O.3 The company's **organizational structure enabled it to rapidly implement** this [technology]	○	○	○	○	○	○

19. O.3 Did the company have to hire new employees to acquire new skills or knowledge to implement this [technology]. *

- ○ Yes
- ○ No

20. How do you agree with the following statement? *

Please rate all statements from 1-5 (1 - Strongly disagree, 5 - Strongly agree).

	1-Strongly disagree	2-Disagree	3-Neither agree nor disagree	4-Agree	5-Strongly agree	Don't know
P.1 The company's **organizational structure had to align to the digitalization strategy** for facilitating [technology] implementation	○	○	○	○	○	○
P.1 The **continuous change** is achieved through **strong governing leadership.**	○	○	○	○	○	○
P.2 Implementing this [technology] has **improved** the company's ability to **make decisions in real time and collaborate effectively on projects.**	○	○	○	○	○	○
P.2 The integration of this [technology] enables the company to **apply key performance indicators (KPIs)** to measure the its effectiveness.	○	○	○	○	○	○
P.3 The [technology] **generates financial profit** after implementation.	○	○	○	○	○	○
P.3 This [technology] enables the company to work more effectively based on **LEAN construction principles**	○	○	○	○	○	○
P.3 This [technology] enables the company to work more effectively based on **Integrated Project Delivery principles**	○	○	○	○	○	○

21. P.3 How do you agree with the following statement? The company's core processes are more effective by using this [technology] in terms of... *

Please rate all construction phases from 1-5 (1 - Strongly disagree, 5 - Strongly agree).

	1- Strongly disagree	2 - Disagree	3 - Neither agree nor disagree	4 - Agree	5 - Strongly agree	Not relevant
Planning and Design	◯	◯	◯	◯	◯	◯
Construction	◯	◯	◯	◯	◯	◯
Manufacturing	◯	◯	◯	◯	◯	◯
Facility Maintenance	◯	◯	◯	◯	◯	◯

22. P.4 How do you agree with the following statement?

The company's supporting processes are more effective by using this [technology] in terms of... *

Please rate all fields from 1-5 (1 - Strongly disagree, 5 - Strongly agree).

	1-Strongly disagree	2-Disagree	3-Neither agree nor disagree	4-Agree	5-Strongly agree	Don't know
Human Resource	◯	◯	◯	◯	◯	◯
Marketing	◯	◯	◯	◯	◯	◯
Financial processes	◯	◯	◯	◯	◯	◯
Document management	◯	◯	◯	◯	◯	◯
Reporting	◯	◯	◯	◯	◯	◯
Quality Management	◯	◯	◯	◯	◯	◯

Annexe VIII. The formulated triples from the C4MM definitions

Element	Definition	Domain	Property	Range
Collective intelligence	Collective intelligence incorporates the pooling of skills, knowledge, creativity, thinking, and problem-solving abilities.			
	The synergic combination of these terms is facilitated by a collaborative culture and supported by digital tools.	CollectiveIntelligence	isFacilitatedBy	CorporateCulture
	Key components include competencies, skill acquisition and employee autonomy, competency mapping, competency building, and personnel training to enhance professional abilities and expertise in the C4 era.			
	Health, safety and environmental protection are key elements of CI corporate intelligence knowldege			
Knowledge management	Knowledge management includes " capturing, organizing, filtering, sharing, and retaining keyenhances corporate knowledge as an assetcollective intelligence. ".	KnowledgeManagement	manages	CollectiveIntelligence
	Knowledge management encompasses the creation of knowledge, the development of digital systems for its storage, and the implementation of knowledge-sharing processes, including continuous training.	KnowledgeManagement	encompasses	KnowledgeSharingProcess
	The transformative CI requires continuously maintaining the expertise and education of emerging technologies and identifying employees with advanced technological competencies to support effective knowledge transfer with critical thinking.	EducationAndTraining	isPartOf	KnowledgeManagement
Organisational Culture	Corporate culture assesses the organisation's flexibility for change through employees' mindset for innovations and collaboration which is supported by continuous professional development including management-level education, and mentoring	CorporateCulture	assesses	VerticalCollaboration
		CorporateCulture		
		DataDrivenCulture	assessesFlexibilityOf	ChangeManagement

Element	**Definition**	**Domain**	**Property**	**Range**
	An organizational culture that values digital technology innovation and employees' mindset toward adopting those technologies is crucial for DT.			
	The capacity for digital innovation is indicative of the organisation's influenced by research and development competence and thus influences transformation and overall efficiency.	-	-	-
	Adapting organizational structures, work processes , and employee skills while promoting a digital culture is vital.	CollectiveIntelligence	promotes	CorporateCulture
		DigitalOrganisationalCulture	facilitates	BusinessDigitalisationProcess
		OrganisationalStructure	promotes	CorporateCulture
Digital Synchronisation	Digital synchronisation refers to aligning and integrating various digital elements within an organisation to achieve seamless operation and transformation.			
	This involves establishing robust governance, adhering to legal and regulatory frameworks, and implementing comprehensive standards to guide digital activities and initiatives.	Governance	guides	DigitalWorkProcess
	Human-machine collaboration is another element of digital synchronisation that supports automated systems and humans seamlessly working together.			
Governance	Governance encompasses the strategic oversight and management of digital resources and processes.	Governance	encompasses	DigitalProcessManagement
	It provides a framework for decision-making processes and accountability, facilitating the alignment of digital initiatives with organisational goals.	Governance	providesFrameworkFor	DecisionMakingProcess
	It encompasses utilising management platforms for collaboration to integrate and enhance the intelligence of financial management, and human resource management.	Governance	encompasses	Collaboration
	This includes data governance, which guides the availability, usability, integrity, and security of data used within an organization.	DataGovernance		

Element	**Definition**	**Domain**	**Property**	**Range**
	Furthermore, it incorporates waste management, ethics, and human rights			
Law and Regulations	Law and Regulations refer to the regulatory environment and policies influencing a company's DT.			
	The economic and regulatory environment plays a significant role in shaping DT, especially in the regulations that govern the use of ~~new digital technologies~~Construction 4.0 technologies.	LawAndRegulation	governsUseOf	TechnologyForC4
	The law and Regulations category includes regulations related to technology such as BIM and IoT, finance and taxation, labour rights, legal protection to safeguard intellectual property and data security	LawAndRegulation	guides	Cybesecurity
	~~The government has a key role in establishing open digital industry platforms or databases to provide technical support and data resources to promote digital technology integration.~~			
Policy and Technological standards	Policy and Technological Standards are a comprehensive framework of principles and guidelines that govern organisational activities.	PolicyAndTechnologicalStandards	governs	Process
	This framework encompasses documentation and modelling standards, procedures, and guidelines for strategic planning.	PolicyAndTechnologicalStandards	supports	StrategicPlanning
	It includes policies and standards related to BIM, IoT, technology research and development, and digital talent training.	PolicyAndTechnologicalStandards	isPartOf	Policy
		-	-	-
	Additionally, it defines the division of responsibilities and rights among participants, such as data ownership and access rights.	StructuralAgilityAndFlexibility	improves	OrganisationalStructure
		PolicyAndTechnologicalStandards	governs	OrganisationalStructure
	BIM policy plays crucial preparatory, regulatory, and contractual roles in the design, construction, and operation processes	BIMPolicy	governs	ContractualProcess
		BIMPolicy	guides	BuildingLifeCycleProcess

Element	**Definition**	**Domain**	**Property**	**Range**
Human Machine collaboration	This concept aims to describe a collaborative working environment between human cognitive skills to support real-time decision-making and robotic capabilities to perform complex or repetitive tasks in dynamic environments or site conditions to enhance productivity, efficiency, and safety.	HumanMachineCollaboration	supportedBy	ConstructionRobotics
		HumanMachineCollaboration	supportedBy	ArtificialIntelligence
Cybersecurity	The emergence of internet-based technologies demands robust cybersecurity measures to protect systems from cyberattacks.			
	Cybersecurity's focus is to prevent cyber-attacks and unauthorised access to the systems by preserving the confidentiality, integrity and connectivity of computer systems, which should be a priority for enterprises to safeguard data and systems.	Cybersecurity	protects	SystemIntegration
	It involves data security and integrity, ensuring secure data storage, adhering to data security standards, and maintaining robust data security protocols. Furthermore, it includes continuous security maintenance to protect data sources and compliance with legal requirements	PolicyAndTechnologicalStandards	guides	Cybesecurity
Data-Centric IT management	The objective of Data-Centric IT management is real-time data processing and interoperability to develop and maintain data-driven automatic systems that support daily operations across the organisation with data analytics.	DataCentricITManagement	developsFrameworkFor	TechnologyForC4
	Automatic and real-time data processing requires context-based information and data collection.	DataCentricITManagement	focusesOn	DataProcess
	Data collection includes determining the type and extent of data to be acquired for internal and external data integration.	DataCentricITManagement	determinesRulesFor	SystemIntegration
	Optimal data requires eliminating data duplication.			

Element	**Definition**	**Domain**	**Property**	**Range**
	The data collection requires system integration from multiple information systems across the organisation to collect real-time data from cyber-physical systems, digital twins and IoT devices.	DataCentricITManagement	collectsDataFrom	TechnologyForC4
	During data processing, enterprises should safeguard their systems and data.	Cybersecurity	influences	DataCentricITManagement
System integration	System integration involves creating and managing multiple connected software and systems, providing a core ecosystem of DT for the organisation.			
	This ecosystem unifies construction 4.0 technologies, providing a single operating interface and a data interaction platform.	SystemIntegration	integrates	TechnologyForC4
	This process can help companies share seamless information and enable collaborative work to enhance efficiency, preventing the need for data	SystemIntegration	enables	Collaboration
Digital transformation communication	Digital Transformation Communication refers to systematically disseminating the vision, strategies, and processes essential to DT to enhance interactions and networks and support decision-makers.	DigitalTransformationCommunication	supports	DecisionMakingProcess
		DigitalTransformationCommunication	supports	StrategicLeadership
	Effective communication ensures systematic information integration to support decision-makers.			
	This approach facilitates C4 activities by setting clear employee objectives and involving all organisational levels to increase employee engagement and commitment to DT.	DigitalTransformationCommunication	supports	C4Activity
Horizontal Collaboration and	Horizontal Collaboration and Coordination examining customer integration into design, production and construction processes, enhancing value propositions, and increasing customer engagement and trust through tools and transparent information exchange.	HorizontalCollaboration	integratesClientInto	BuildingLifeCycleProcess

Element	**Definition**	**Domain**	**Property**	**Range**
	The digital platform integration facilitates the seamless and transparent data and information exchange among teams and partners, providing transparent communication channels which promote a more profound connection towards common goals.			
	This integration permits customers to participate in the decision-making process, thereby enhancing the overall value proposition which increases customer engagement, and trust.	HorizontalCollaboration	integratesClientInto	DecisionMakingProcess
	Horizontal integration requires consolidated data usage by removing old processes and developing entirely new processes.	HorizontalCollaboration	requires	ProcessDevelopment
	These generate new organisational policies, positions, and standards that require talent training to elevate DT inside the organisation.	HorizontalCollaboration	generates	OrganisationalStructure
		HorizontalCollaboration	generates	EducationAndTraining
		HorizontalCollaboration	generates	PoliciesAndTechnologicalStandard
	Additionally, this collaboration encompasses digital technology-related knowledge and information sharing across organisations	HorizontalCollaboration	encompasses	KnowledgeManagement
Vertical collaboration and coordination	Vertical collaboration and coordination refer to the systematic integration and alignment of various organisational levels and functions to achieve effective DT and operational efficiency	VerticalCollaboration	integrates	OrganisationalStructure
	This involves cooperation and collaboration between functional organisational units, cooperation with networks and the centralised coordination of C4 activities across the organisation which is supported by IT-enabled resources to facilitate comprehensive digital integration across all functional areas.	VerticalCollaboration	coordinates	C4Activity
		C4Activity	supportedBy	TechnologyForC4
		VerticalCollaboration	supportedBy	SystemIntegration

Element	**Definition**	**Domain**	**Property**	**Range**
	In this environment, established dedicated teams can drive digitalisation efforts, ensuring continuous progress and adaptation to new technologies.	VerticalCollaboration	isDrivenBy	InnovationTeam
		InnovationTeam	isPartOf	OrganisationalStructure
		InnovationTeam	drives	C4Activity
		InnovationTeam	drives	BusinessDigitalisationProcess
	Effective vertical collaboration also encompasses the organisation's capacity to coordinate digital initiatives and operations across different levels, promoting seamless integration and efficiency.	SystemIntegration	promotes	VerticalCollaboration
		VerticalCollaboration	drives	StructuralAgilityAndFelxibility
Strategic Leadership	The Strategic Leadership category investigates the degree of alignment between the management mindset and the strategy with C4 objectives.		-	-
		ManagementCompetence		
	This involves the creation and execution of strategies including governance, strategic planning, and resource allocation to embrace C4 and balance long-term and short-term goals	StrategicLeadership	defines	Governance
		StrategicLeadership	hasImpactOn	StructuralAgilityAndFelxibility
	A strong vision and roadmap inspire the organisation and leverage technology for the future with shared value. Top management commitment has a **significant impact** on driving C4 maturity, fostering a data-driven culture and prioritising data-driven decision-making, goal-setting and continuous improvement.	StrategicLeadership	hasImpactOn	DataDrivenCulture
		StrategicLeadership	hasImpactOn	DataDrivenDecisionMakingProcess
		StrategicLeadership	drives	ProcessDevelopment

Element	**Definition**	**Domain**	**Property**	**Range**
	Nevertheless, it is of the utmost importance that the CI undergoes a fundamental shift in its managerial approach, moving away from a project-centric mindset towards a process-oriented one			
	Applying agile management, leaders can focus on forming flexible communities, promote digital leaders to drive transformation, and foster dynamic and digital partnerships.	StrategicLeadership	influences	HorizontalCollaboration
		StrategicLeadership	drives	C4Activity
	Furthermore, they should also follow the continuously changing digital environment, which brings legal, financial and regulatory developments, and emphasise the importance of health, safety and environmental (HSE) management	StrategicLeadership	follows	LawAndRegulation
Structural agility and flexibility	Structural agility and flexibility refer to the capacity of an organizational framework to adapt swiftly to market shifts by utilizing comprehensive human resource planning, and management systems, and aligning organisational processes with C4 goals to ensure continuous adaptation and innovation.	StructuralAgilityAndFlexibility	alignsWith	Process
		StructuralAgilityAndFlexibility	ensures	Innovation
	Structural agility and flexibility refer to the capacity of an organizational framework to adapt swiftly to market shifts by utilizing comprehensive human resource planning, and management systems, and aligning organisational processes with C4 goals to ensure continuous adaptation and innovation.	StructuralAgilityAndFlexibility	influences	C4Activity
	This can be done by eliminating rigid hierarchical structures significantly impacting the development and execution of the enterprise processes . Human resources should also focus on increasing and maintaining workers' continuous engagement through frequent knowledge and skill development .	StructuralAgilityAndFlexibility	focusesOn	KnowledgeManagement
	This can be achieved by empowering employees based on their expertise and dedication of subject matter or digital experts who can speed up the DT process inside the organisation .	StructuralAgilityAndFlexibility	achievedBy	InnovationTeam

Element	**Definition**	**Domain**	**Property**	**Range**
Process Management	The digitalization of business processes and management is a core part of the digital transformation of construction companies.			
	The Process Management category is defined as follows: Processes can be defined as a set of interrelated or interacting activities that transform inputs into outputs for the purpose of enabling the digital transformation of the organization.	ProcessManagement		
	While the maturity model's key element is the processes category that drives DT it facilitates the organisation's value proposition by transforming workflows to digital work processes to increase organisational work efficiency and by creating new processes to collect and share data.	DigitalProcessManagement	transforms	DigitalWorkProces
	BPMN can significantly accelerate the DT in CI, which is defined as the following: Business process management (BPM) is a discipline involving any combination of modelling, automation, execution, control, measurement, and optimization of business activity flows in applicable combination to support enterprise goals, spanning organizational and system boundaries, and involving employees, customers, and partners within and beyond the enterprise boundaries.	BusinessProcess Management	optimise	OrganisationalProces
		BusinessProcess Management	involves	HorizontalCollaboration
		BusinessProcess Management	involves	VerticalCollaboration
		BusinessProcess Management	involves	StrategicPlanning
		BusinessProcess Management	optimise	BuildingLifeCycleProcess
		BusinessProcess Management	involves	SystemIntegration
		BusinessProcess Management	optimise	C4Activity
Organisational Change Management	Organisational Change Management is a process that drives the transition from the current state of an organisation to a desired future state.			
	This approach emphasises renewing the organisation's direction, structure, and capabilities to meet evolving internal and external requirements through innovations.	OrganisationalChangeManagement	renews	StructuralAgilityAndFelxibility

Element	**Definition**	**Domain**	**Property**	**Range**
		OrganisationalChangeManagement	renews	HorizontalCollaboration
		OrganisationalChangeManagement	renews	VerticalCollaboration
	Multiple business fields are connected through Organisational Change Management. Firstly, the strategies to manage individuals ensure alignment with the organisation's digital strategy, structure, and key performance indicators.	OrganisationalChangeManagement	alignsWith	DigitalStrategy
		KPI	supports	OrganisationalChangeManagement
		OrganisationalChangeManagement	changes	OrganisationalStructure
	Secondly, the development of digital competencies through the implementation of structured training programs and integrated digital skills within the organizational culture and the continuous monitoring of its effectiveness	-	-	-
		OrganisationalChangeManagement	monitors	KnowledgeManagement
	Additionally, the activities related to digitalisation, cross-functional collaboration, partnership programmes for accessing innovations, and leveraging digital services to reach market potential			
	Finally, the continuous changes triggered by C4 require flexibility and the ability to achieve this through strong governing leadership.	OrganisationalChangeManagement	isTriggeredBy	TechnologyForC4
		OrganisationalChangeManagement	isTriggeredBy	C4Activity
	This flexibility includes changes in construction plans, production processes, and supply chain processes	OrganisationalChangeManagement	transforms	SupplyChainProcess
Process development	Process development is a systematic approach to help an organisation optimise its underlying processes to achieve more efficient results, which is closely aligned with the principles of lean manufacturing.			
	Due to the emergence of C4 technologies, organisations require entirely new processes aligned with a long-term strategy.	TechnologyForC4	requires	ProcessDevelopment

Element	**Definition**	**Domain**	**Property**	**Range**
	Process improvement involves the introduction of new or improved techniques, equipment and software that necessitate a comprehensive re-evaluation of BPM, including *the digitisation of enterprise management and project management processes which significantly improve the operational efficiency and construction efficiency of enterprises*.	ProcessDevelopment	develops	ProjectManagementProcess
		ProcessDevelopment	optimise	Process
	This concept includes identifying the potential process development areas which can support organisations in achieving their strategic goals and a higher level of maturity .			
	Emerging technologies can reshape traditional BPM, transitioning it towards a more exploratory and dynamic framework.	TechnologyForC4	reshape	Process
	BIM is a key technology that brings challenges and requires continuous process improvement and monitoring for successful implementation.	BusinessProcess Management	subclassOf	ProcessDevelopment
		BIM	isToolFor	ProcessDevelopment
	Data analytics and visualisation tools can inform real-time decision-making and streamline operational workflows by utilising advanced technologies, including BIM, GIS, and big data, to develop digital technology platforms for multi-party collaboration in digital design.	DataDriven DecisionMakingProcess	supportedBy	BIM
				GIS
				BigDataAnalytics
				DataAnalytics
		BIM	drives	DigitalProcess
		GIS	drives	DigitalProcess
		DataAnalytics	drives	DigitalProcess
	Innovation, research and development and quality management are key aspects to guide organisations in this new era.	Innovation	guides	ProcessDevelopment
		ResearchAndDevelopment	guides	ProcessDevelopment
		QualityManagement	guides	ProcessDevelopment

Element	**Definition**	**Domain**	**Property**	**Range**
	The CI can benchmark from I4 and use tools including key performance indicators, LEAN or calculation methods for innovation ROI to address these aspects.	ReturnOnInvestment	influences	ProcessDevelopment
		KPI	enhances	ProcessDevelopment
	Process development focuses on growth through innovation and the selection of innovations to invest in, with a particular emphasis on return on investment (ROI) .	ProcessDevelopment	focusesOn	Innovation
	Additionally, implementing KPIs is essential for measuring the success of these improvements.	KPI	measures (the succsess of)	Innovation
Core and Operational processes	Operational and Core processes refer to a set of essential activities that enhance the overall operational efficiency and are crucial for effective construction life-cycle project management to generate financial profit for the organisations and assess how 'building as product' activities are affected by different technologies.	CoreAndOperationalProces	manages	BuildingLifeCycleProcess
	In the core processes, these activities are design and pre-construction, manufacturing, and assembly and construction.			
	These processes entail comprehensive planning and integration of advanced technologies, including IoT, big data, digital twins, and BIM.	BuildingLifeCycleProceses	integrates	TechnologyForC4
	Additionally, it includes various methodologies such as the application of Integrated Project Delivery (IDP), LEAN construction principles or the Design for Manufacturing and Assembly (DfMA) approach *"on optimising the design of a product or system to simplify manufacturing and assembly processes"*.			

Element	**Definition**	**Domain**	**Property**	**Range**
	Effective management of these core processes ensures project success by maintaining quality, schedule, cost, and safety while fostering continuous improvement and strategic competitiveness in a dynamic market environment.			StrategicCompetitiveness
	The main activities in the operational processes are internal collaboration, data usage, and knowledge retrieval.	-	-	-
	Autonomous processes and IT-enabled planning and steering processes are key to efficient operations.			
Supporting Processes	Supporting processes encompass essential activities that ensure the smooth operation of core and operational processes in CI.	-	-	-
	These processes are the following: human resource, IT , legal and compliance management (regulatory compliance, contract management, dispute resolution), logistic and supply chain management (material supply planning; inventory planning, transportation planning and equipment planning and management, marketing and business development, document management (document and version control), and financial processes.	SupportingProcess	involves	DocumentManagement
		SupportingProcess	subclass	ContractProces
	Support activities encompass security, information management, configuration, documentation, compliance, and incident management.	-	-	-
	~~Digital technologies also support market data collection, analysis, service improvement, and automation of warehouse operations and transportation planning.~~	-	-	-
	Additionally, these processes encompass the management of laboratory operations, quality measurement, and reporting.	-	-	-
System integration definíció bővítése	In the CI system integration key obstacle is interoperability. Interoperability issues generate increased costs for organisations and all stakeholders in the building life-cycle.	SystemIntegration	provides	Interoperability
	Thus, BIM interoperability – as the core technology of CI digital transformation – influences organisations digital maturity. It is shaped by multiple interrelated factors, including “legal, organisational, technical, and semantic interoperability”	Interoperability	isChallengeForIntegration	BIM

Element	**Definition**	**Domain**	**Property**	**Range**
	On the legal interoperability level, organisational policy and applied technological standards, and contractual structures can either support or limit BIM implementation.	LegalInteroperability	isSubclassOf	Interoperability
		LegalInteroperability	builtOn	PolicyAndTechnologicalStandard
		LegalInteroperability	builtOn	ContractualProcess
		BIMPolicy	influence	Interoperability
		BimContractualProcess	supportImplementationOf	BIM
	Internally, an organisation's capacity to adopt BIM depends on its digital maturity and strategic leadership support.	OrganisationalInteroperability	isSubclassOf	Interoperability
		OrganisationalInteroperability	builtOn	StrategicLeadership
		BIM	influencedBy	StrategicLeadership
	Additionally, integrating BIM with XR demands not only technical compatibility but also a shift toward collaboration among internal and external stakeholders.	BIM	usageInfluencedBy	HorizontalCollaboration
		XR	usageInfluencedBy	HorizontalCollaboration
	Technical aspects involve the ability to manage diverse data formats, exchange information effectively especially with IFC, and maintain in-house expertise capable of operating complex BIM systems.	TechnicalInteroperability	isSubclassOf	Interoperability
	Additionally, the used platforms should meet cybersecurity requirements especially access rights. The applied technologies should be compatible with each other to support continuous data flow.	Cybersecurity	safeguards	TechnicalInteroperability
		TechnicalInteroperability	providesCompatibilityBetween	TechnologyForC4

Element	**Definition**	**Domain**	**Property**	**Range**
		TechnicalInteroperability	supports	DataProcess
	Semantic interoperability refers to the seamless exchange of information between different software tools, which requires consistent application of data standards and clear process definitions to enable meaningful system-to-system communication.	SemanticInteroperability	isSubclassOf	Interoperability
		SemanticInteroperability	exchangeOfInformationIn	DataProcess
	This layer also includes syntactic interoperability which refers for the basic ability of different systems to exchange information.	SyntacticInteroperability	isSubclassOf	Interoperability

8. LIST OF PUBLICATIONS

Journal paper

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[16] This paper was published with my previous name, Orsolya Nagy
[17] This paper was published with my previous name, Orsolya Nagy

Book chapter paper

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