Justification of Construction 4.0 maturity model with a case study of a data-driven façade company

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Abstract

The European Parliament released the 2030 Digital Compass, identifying the construction sector as one of the five key ecosystems in the digital transformation process. A Construction 4.0 maturity model (C4M) was created to lead companies through their digital transformation journey. This research aimed to justify the model categories of the developed C4M using a qualitative case study methodology. The case study highlighted the practical relevance of the model by identifying three areas within the C4M that were the main drivers of digital transformation: cloud-based systems, knowledge management and system integration to drive digitalisation further. It was revealed that the digital processes in the design, production, and construction phases are connected to each other through system integration.

Keywords –

construction 4.0, maturity model, digital transformation, data-driven organisation, AI

1 Introduction

In recent years, an emerging number of studies have been published on Construction 4.0 (C4) phenomena. In this paper C4 is defined as a new construction ecosystem that incorporates (1) integrated technologies and cyber-physical systems [1,2], (2) methods and processes [3,4], and (3) human resource competencies [3]. These three pillars are supported by automation and data analytics. In this ecosystem achieving sustainability is a crucial objective for industry players which can be attained by improving the efficiency and productivity of construction processes. However, only a few research efforts have addressed the systematic integration of C4 into the construction organisations' life-cycle and the tools that can support companies in this endeavour [5].

The European Parliament has released the 2030 Digital Compass, which identifies the construction sector as one of the five key ecosystems in the digital transformation process. The report emphasises that the Construction industry has had the lowest productivity of all major sectors in the last 20 years. Executives believe that new production technologies and digitalisation can be the drivers of change [6].

The strategic implementation of C4 requires a shift in management mindset towards digitalisation [10] and to effectively use a toolset that supports digital transformation. One such tool is a maturity model, which helps assess a company's evolution stage-by-stage in a specific area [7]. Building Information Modelling (BIM) can also contribute to digitalization endeavours but researchers studied BIM Maturity Matrix from the perspective of designers rather than general contractors or subcontractors [8,9]. However, these matrixes often lack of 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. Therefore, our research focuses on them.

This paper presents our Construction 4.0 Maturity Model (C4M) and how the qualitative case study of a Hungarian façade contractor revealed the relevance of each category element, and the connections between them. The selected company places significant emphasis on digitalisation, in particular, data-driven artificial intelligence (AI) solutions and its development. This case study helped us to justify the C4M developed from the literature review with a real-world example.

2 Research Methodology

The research applied Design Science (DS) framework to prepare the C4M. DS methodology provides steps to design artifacts such as algorithms, applications, information systems and so on. In DS research the design *"focuses on the use of scientific principles, technical information and imagination in the definition of a structure"*[10]. It illustrates the relevance underpinned by the business need arising from the environment and the rigour in the form of applicable and new knowledge.

In our research, problem space defines the environment which encompasses the construction firm's existing and planned technological infrastructure that enhances its productivity. Businesses are inclined to lead this transformation process seamlessly. This induces the need for developing a C4M and justifying it. The knowledge base foundation includes the steps for developing the model (scope-design-populate-test-deploy-maintain) [11]. The DS process steps are introduced in the following paragraphs.

2.1 Problem identification

C4 presents numerous challenges at the organizational level [12]. The maturity model can be a useful tool in addressing these challenges and facilitating companies' digital transformation. A solution is required that considers companies' technological perspectives rather than solely focusing on the digital maturity of a construction project.

2.2 Objective and Solutions

The objective of the C4M is to conceptualise and quantify C4 in construction business activities and make them measurable over time. Our long-term purpose is to develop a rules-based information system. It will measure how ready a company is to adopt a particular technology. This C4M model serves as its basis, extended with a fuzzy inference engine built on an ontology[13]. DS recommends developing an artifact iteratively using a lot of feedback. This paper presents only one iteration. The case study will determine if the model accurately represents the company's digital maturity aspects and if it is practical to use from a market professional's perspective.

2.3 Development

During the model development phase, we aimed to identify distinct categories (level 1) underlying families (level 2), and elements (level 3). The developed model is based on the BIM Maturity matrix [9], which plays a central role in the digitalisation of the construction industry. In the second phase of model development, the main elements of the BIM Maturity Matrix model have been examined and expanded to include areas that can be important for the digitalisation of an organisation using Industry 4.0 and other construction-specific maturity models.

A literature review was conducted 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 business model. The literature review identified 22 relevant articles in the field of Industry 4.0 and only 3 in the construction industry. A matrix was created during the review to establish the main pillars of the C4M. These pillars supported the next phase of development where further literature was identified using the following keywords: pillar name + maturity model/readiness model, pillar name + construction + maturity model/readiness model. The maturity models identified in the literature were pruned and the model elements were categorised using ontology development methodology. Ontology is a *"formal and explicit specification of a shared (shared) conceptualization"*[14]. The steps of this methodology are described in detail in [13]. These steps led to the creation of the C4M families and elements.

2.4 Justification

To justify the integrity and applicability of the model to the environment, a qualitative case study was conducted in four steps: (1) designing the case study protocol, (2) conducting the case study, (3) analysing the evidence, and (4) developing the conclusion [15]. 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 terms of digitalisation compared to other market players.

During the second phase of the case study, two interviews were conducted. Firstly, the CEO of the company explained the main steps taken in their digital transformation journey. Secondly, the C4M elements were discussed in detail to assess the importance of each model element on a scale of 0 to 5. In the subsequent round of the case study, the Chief Technology Officer (CTO) was interviewed. During the analysis phase, we prepared the interview transcripts and created a matrix in Microsoft Excel to justify the model. The matrix had rows representing categories, families and elements (C4M elements) and the two columns (CEO and CTO) were filled with the data collected from the transcripts. During this phase, our main objective was to identify correlations between different processes and determine the drivers of digital transformation. Thus we created the process map of the case study and analysed the steps in detail. Based on the results, we drew conclusions, and considerations for future research.

3 Maturity Model

C4M has six main pillars: Technology Management and Business Applications [7,16], Culture and People Management [7,16–20], Collaboration and Communication [17], Technology for Automation [17,18], Innovation [17] and Change Management and Processes [7,16–18]. Technology for Automation category encompasses the use of industry-specific robotics [21–23], Building Information Modelling (BIM) and Digital Twin, Internet of Things (IoT) and sensing systems [21–23], and data-driven technologies [21,23] to enhance construction projects and production efficiency. The model is presented in more detail by [13]. Figure 1 illustrates the C4M and the Technology for Automation category in detail.

Figure 1 C4M Technology for Automation's families

4 Case study

The company operates with a team of 30 employees at its headquarter, with an additional 40 employees working in production and construction. The core team comprises individuals from various fields, including finance, logistics and procurement, sales, design, project management, CEO, ESG Manager (Innovation Manager), marketing, and software development. The company follows a matrix organizational structure. It is important to note that nearly one-third of the headquarters' employees work in software development.

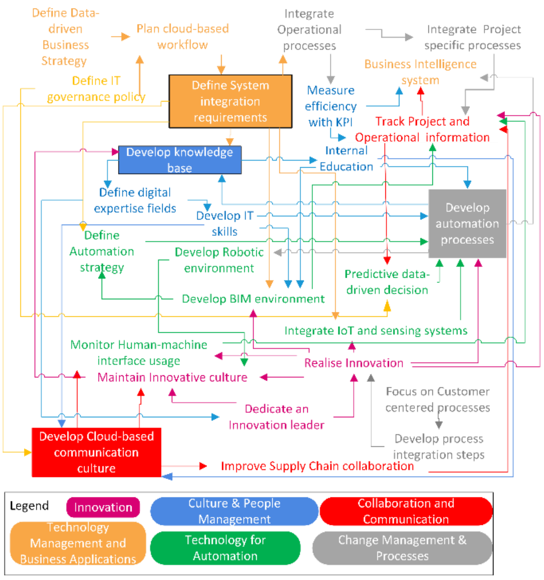

Figure 2 The digital transformation process map

The strategic goal of the digital transformation journey was threefold: (1) automatic façade design, (2) production plan automation, and (3) predictive decision-making based on project data. The interviews revealed four development phases. Phase 1 involves developing a general IT infrastructure, Phase 2 includes creating a knowledge base which was used to educate employees about internal processes, Phase 3 focuses on system integration, and Phase 4 involves system scale-up and AI development based on data. The purpose of the case study was to test the relevance and existence of each category of the C4M, based on the company's digital transformation journey.

A process map in the context of C4M elaborated from the case study outlines the key steps involved in the digital transformation represented in Figure 2. This process map is introduced in the following paragraphs.

4.1 Technology Management and Business Applications

This category refers to the systematic coordination and application of technology to achieve its strategic goals and objectives [13]. This category examines how effectively integrated digital technologies can support the company's digital processes.

The journey towards digital transformation begins with defining a data-driven business strategy. During the system development process, the focus was on creating an IT framework, including both software and hardware, that enables data-driven operations. Specifically, the goal was to convert Excel sheets to an SQL database management system. The requirements for this can be defined by the IT governance policy, which also guides predictive data-driven decision-making. Cybersecurity should be included in this policy as it is becoming an increasingly important concern in the construction industry, particularly as core processes are digitised [24]. However, the case study did not reveal any particular focus on this area. Therefore, we did not include it in the process map.

"The biggest challenge was to build the system from the ground up to be able to apply data science "(CEO)

The importance of facilitating data-driven operations is underscored by the development of a cloud-based workflow management system that is compatible with existing software. These cloud-based workflows were later extended from core operational processes to project-related design and construction processes.

System integration and interoperability are significant challenges in digitisation, which require to rationalize the IT portfolio for efficiency. System integration refers to the process of combining individual component subsystems into a unified system to achieve its desired functionality effectively [25]. Defining system integration requirements is essential for the effective deployment of integrated systems. This task involves evaluating the compatibility and capacity of the hardware infrastructure, establishing testing criteria, selecting appropriate software, and validating integration to ensure system reliability. It is essential that functional requirements are clearly specified and that a cost-benefit analysis is carried out to assess the financial implications. Additionally, scrutinising the software data structure is necessary to enable seamless data flow. This systematic approach establishes clear integration requirements for successful operation.

During this process, nearly 100 construction-specific software programs were tested. Although individual software solutions have their advantages, the company decided to develop its own system called Dijkstra due to the lack of a comprehensive solution.

4.2 Culture and People Management

This category refers to maintaining a positive and productive work environment to drive organizational performance, with a focus on performance management, training and development, and employee engagement [13]. This category assesses the effectiveness of knowledge management within an organisation. It includes whether employees have the confidence and knowledge to use digital technologies effectively in the corporate environment.

The process map presents a thorough method for improving organisational capabilities through a systematic approach. It starts by establishing system integration requirements as guidelines for the knowledge base. Then, a knowledge base is developed, which includes technological instructions and case studies, to lay the foundation for digital expertise. Defining digital expertise fields and developing IT skills further empowers employees to navigate the digital landscape. Internal education initiatives, such as training sessions and onboarding programs, help ensure alignment with company processes and technologies.

The integration of operational processes streamlines workflow and enhances organizational efficiency. This integration aims to consolidate various activities within the organization, promoting cohesion and synergy. Subsequently, the implementation of a Key Performance Indicator (KPI) system enables the continuous measurement of employee efficiency. This system captures designers' hourly tasks, providing valuable insights for controlling and project pricing. The generated data facilitates pricing negotiations and automates invoicing processes, contributing to improved decision-making and resource allocation within the organization. A Business Intelligence (BI) system leverages this data for visualizing financial reports and project progress. Challenges were raised in defining KPIs for construction field workers, particularly in measuring their soft skills.

4.3 Technology for Automation

The Technology for Automation category assesses the use of several technologies, including data-driven technologies, robotics, BIM and Digital Twin, and IoT and sensing systems. The process flow diagram shows the close relationship between automation technologies and system integration requirements, which are defined in parallel.

4.3.1 BIM and Digital Twin

The design of the automation strategy is heavily influenced by the BIM environment, and the creation of an appropriate enterprise BIM environment is based on the system integration requirements. Special emphasis should be placed on ensuring interoperability among software. For instance, contractors often need to extract quantitative data from customer-provided IFC format and transfer it to Excel. To process the data, supplementary software is required, such as Revit, ArchiCAD, or even Inventor for certain manufacturers, which enables direct transmission of the data to production. Speckle's approach offers a viable way to address these data communication issues. Furthermore, the BIM ecosystem necessitates ongoing development of relevant IT expertise and internal training on software processes. If the data flow within the established ecosystem is continuous, it can provide real-time input data for data analytics. This data enables the company to track and measure project information.

The company utilises software such as Revit, ArchiCAD, Grasshopper, and Speckle to create project plans at Level of Development (LoD) 500, which represents the As-Built Stage of Modelling. This includes model elements with precise size, shape, location, quantity, and orientation for fabrication and assembly processes at the shop drawing level, with technical data connected to the modelled elements. Constant training and development have resulted in a high level of software usage, which has significantly improved its quality. The interviews identified barriers within the BIM and Digital Twin domain that are hindering the company's progress and the demonstration of BIM's added value. Firstly, Clients are increasingly requesting more extensive documentation from contractors, while not having the same expectations for their as-built BIM models. This is due to the contractors' far more advanced level of expertise in BIM compared to theirs. Secondly, there are data interchangeability issues due to challenges in software interoperability, especially between Revit and ArchiCAD. Finally, contractors may face additional challenges due to the large amount of data generated by designers.

These challenges resulted in the decision to integrate the Industry Foundation Class (IFC) model into the self-developed Dijkstra platform using Speckle's solution. Figure 3 shows how this viewer enables the team to update and track the project through the model, visualising the state of each façade component.

Figure 3 Dijkstra platform and project tracking

4.3.2 Data-driven technologies

The development of a data-driven technology ecosystem is a sequential process. First, the data structure for analytical purposes must be designed, taking into account system integration requirements and guidelines from IT governance policies. It is crucial to consistently gather data by monitoring both project and organizational operations to preserve effectiveness.

To meet the requirements of data-driven technologies, the company focused on building the appropriate data structure. This structure would enable the system to be used for data analysis and BI reporting in the future. To achieve this, the company linked an SQL database to the SharePoint system and then to the Dijkstra interface.

The company is now developing an AI chatbot called Mici, which will integrate existing databases through the Dijkstra interface and extract information from background databases through human communication.

Recent research has identified three potential directions for data mining: data mining for intelligence, digitalization, and automation [26]. The company has identified two of these directions; and has developed three goals from an AI perspective:

- The purpose of this project is to use data mining techniques to access internal company SQL data and provide Project Managers with relevant information and knowledge.
- Additionally, the project includes the development of an AI chatbot to aid designers in documenting their design process and translating it into ArchiCAD.
- The project also involves developing a system for generating data to facilitate communication with the platform, recording data via mobile phone, and managing the platform.

The study of how employees view these technologies highlighted the need for thorough training programs. If employees do not receive adequate feedback from AI, there is a possibility that they may return to using traditional job methods. The CEO highlighted that the internal IT staff has substantial concerns about future job loss due to AI.

4.3.3 Human-machine interfaces and Wearable devices

Cloud-based workflows and communication culture support the usage of human-machine interfaces. However, complete enterprise integration requires continuous monitoring of technology usage to track and record project data.

In the early stages of digital transformation, the company focused on prioritising mobile devices to ensure data availability across various workspaces and construction sites. Their mobile application was then updated to allow for microphone-based data entry, which was found to be more efficient than on-site typing. Furthermore, the company developed VR and AR areas to facilitate model visualisation. Continuous education is necessary to support the use of these devices for constant monitoring. Management control also influences the level of usage.

4.3.4 IoT and Sensing System

The integration of Internet of Things (IoT) and sensor systems is another key aspect that can facilitate real-time data collection in automated processes. This integration is a key aspect as it defines the ability of the robotic environment and its software to integrate with pre-existing systems.

4.3.5 Robotics

Establishing a robotic manufacturing environment requires several preparatory stages. It is crucial to align the automation strategy, including the development of robotics, with the system integration requirements. The ongoing evolution of existing automated processes facilitates the development of a robotic environment.

In the field of robotics, the company prioritised the development and automation of production processes. They emphasized that the effectiveness of robotics depends on the user's expertise, thus the need for continuous training for welders operating Computerised Numerical Control (CNC) machines. These machines are used in computerized manufacturing, where pre-programmed software and code control the movement of production equipment. The CEO highlighted the growing importance of sustainability in automation and robotics. This includes the development of machines capable of managing waste produced within factories and on projects.

4.4 Change Management and Processes

This category refers to the degree of alignment between organizational and digital processes that enable the company to promptly and efficiently address customer requirements, as well as to integrate or introduce new processes [13].

Defining system integration requirements precedes the integration of corporate processes, enabling the extension of efficiently functioning operational processes to project-specific workflows. The development of automated processes emerges as a key element on the process map, and is driven by the automation strategy. IoT and sensor data contribute to seamless automated processes and continuous data flow. Additionally, support for development efforts across multiple domains is required, including internal training initiatives and continuous improvement of IT skills.

4.5 Collaboration and communication

Collaboration and communication cover how the organisation works, interacts, and cooperates within its physical, and digital environment and throughout its supply chain [13]. This category measures the effectiveness of workers in sharing information within and across organizations through digital technologies. Both the digital system and the staff are responsible for tracking project and operational information. Project-specific digital processes should be properly integrated to support automated processes and the automatic flow of data. The cloud-based collaboration culture supports the use of a human-machine interface, allowing workers to capture the necessary data via mobile phones. Cloud collaboration also facilitates collaboration in the supply chain, which can contribute to the tracking of project information.

Internal communication was improved by eliminating WhatsApp and Viber-based communication, which has enhanced efficiency in cloud-based communication and allowed for better tracking of project information and changes. Supply chain collaboration aims to improve efficiency. The company implemented a supplier database to monitor pricing and effectiveness, enabling the Procurement and Project Manager teams to handle 70% of their work during offer preparation.

4.6 Innovation

This category assesses the corporate culture, leadership approach, and feasibility of innovation to promote the development and execution of new ideas, services, technologies, or procedures [13]. The Innovation Manager facilitates the ongoing implementation and maintenance of innovation. This is achieved through the triangle of knowledge base, technology, and process automation, which ensures a culture of innovation.

The Innovation Manager is responsible for maintaining a sustainable and innovative environment and ensuring ongoing reporting. With a comprehensive understanding of both manufacturing and IT processes, she is able to support the launch and implementation of innovation projects to keep employees motivated to innovate.

5 Findings

During the interview, the initial model element relevance importance was rated on a scale from 0 to 5 by the CEO. The mean value of the element's importance under the six main categories is shown in Figure 4.

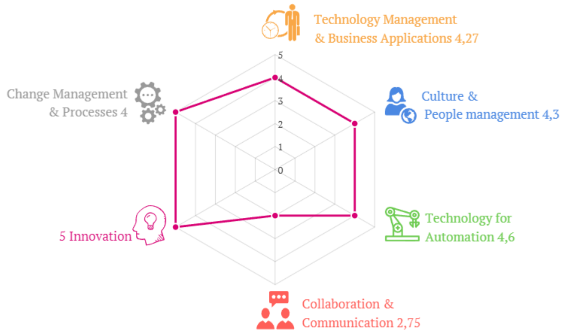

Figure 4 The importance of the C4M categories

The results indicate that, among the items assumed in our model, several elements in the Collaboration and Communication category were not considered significant by the CEO. It is important to note that the company did not prioritize soft skills, as presented in the case study.

We aimed to use the case study to explore which processes and areas were more prominent within each category. Figure 5 constructed based on the process map presented in Chapter 4, shows the number of predecessors and successors for each process element, with the size of the bubbles representing the number of categories a process is linked to. The term 'predecessor' refers to the previous process step as defined in the process map. For example, the process element 'Measure efficiency by KPI' has one predecessor (Integrate Operational processes in Change Management and Processes category) and two successors (Track Project and Operational Information in Collaboration and Communication category, and BI System in Technology Management and Business Application category). The number of connected categories summarises the categories of the predecessors and successors, therefore it is three. The figure leads to the following conclusions: (1) the development of the automation process was related to all categories, (2) Systems Integration, Knowledge Management, and Cloud-based Systems were related to four categories. From the location of these four processes on the grid, it can be concluded that (3) System integration was the most important initial element in the digital transformation, as most of the successors were related to it. (4) Knowledge management and cloud collaboration were both preceded and followed by a similar number of processes, indicating their importance in establishing and sustaining progress. (5) The development of automation processes had the majority of the preceding processes. Consequently, several preventive steps need to be taken before process automation can take place.

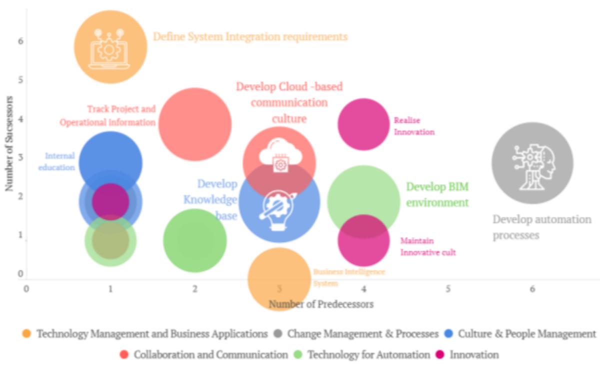

Figure 5 Visualisation of the process map results

6 Summary and conclusion

The purpose of this case study was to provide a justification for the developed C4M in terms of model categories with a qualitative case study. The company perspective demonstrated that all six categories of the model are equally important. However, our results indicate that the innovation category is the least important compared to the other five categories. This conclusion was drawn from the process map, which showed that innovation can be identified as the integration of industry-specific technology. The case study identified three main drivers of digital transformation for this company: cloud-based systems, knowledge management, and system integration leading to automated processes.

The objective of the C4M was to conceptualise and quantify C4 in construction business activities and make them measurable over time. The case study revealed that the model accurately represents the company's digital maturity aspects however further development is needed to measure these aspects over time. Our research will continue to verify the underlying elements of each category and to develop for each category indicator level.

In summary, this research has presented a detailed case study of the C4M that will significantly contribute to guiding researchers and developing businesses. The results indicate that digital transformation was primarily driven by cloud-based systems, knowledge management, and system integration to drive further the digital processes (achieve higher level of automation) that are connected between design, production and construction phases through system integration with human resource capabilities.

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