

**FUZZY-BASED MODEL FOR ASSESSING
THE DIGITALIZATION LEVEL
OF CONSTRUCTION PROJECTS IN SAUDI ARABIA**

BY

YAZEED ABDULLH ALSALAMAH

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DEANSHIP OF GRADUATE STUDIES

This thesis, written by Yazeed Abdulh Alsalamah under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CONSTRUCTION ENGINEERING AND MANAGEMENT.**



Dr. Laith Al-Hadidi
Department Chairman

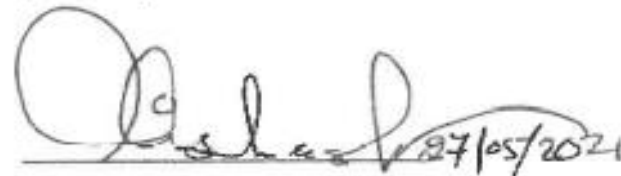


Dr. Suliman Al-Homidan
Dean, College of Graduate &
Interdisciplinary Studies

Date



Dr. Awsan Mohammed
(Advisor)



Dr. Ali Shash
(Member)



Dr. Ahmed Ghaithan
(Member)



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LIST OF ABBREVIATIONS

UTAUT: Unified Theory of Acceptance and Use of Technology

DDDM: Degree of Digitalization of Data Management Processes

DDCA: Degree of digitalization of construction Activities

DI - Digitalization Index

DA - Data Acquisition

DE - Data Entry

DN - Data Analysis

DR - Data Reporting

ABSTRACT

Full Name : [Yazeed Abdullh Alsalamah]
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Recently, digitization in the construction sector has grown, indicating an important change in how projects are planned, executed, and managed. This shift, driven by modern technologies, addresses the challenges of uncertainty in construction projects. This study proposes a fuzzy-based model to assess the digitalization level of construction projects in Saudi Arabia. The objectives are to identify digitalization activities, rank them using a model that calculates digitalization need values with six measures, and develop a fuzzy-based model that considers uncertainties in experts' judgments.

The research integrates expert insights obtained through a comprehensive survey among diverse specialists. It adopts a value-based inquiry using pessimistic, most likely, and optimistic scenarios to collect data. The Mamdani fuzzy logic system is employed, with four input variables—information acquisition, processing, evaluation, and reporting—linked to the digitalization level of construction activities (DDCA). Fuzzy rules and membership parameters connect these inputs to the DDCA metric. Findings indicate that the proposed fuzzy model effectively navigates the uncertainties in construction. High digitalization categories were identified, such as managing deviations, updating drawings, and improving waste management strategies. Activities with lower scores revealed deficiencies, while those with higher scores demonstrated the benefits of digitalization. The model closely aligned with expert opinions, demonstrating its accuracy. The proposed model was validated using a real project, showing

its effectiveness in assessing digitalization levels in construction tasks. This research provides a practical tool for construction industry stakeholders to manage the complexities of digital transformation.

ملخص الرسالة

الاسم الكامل: يزيد بن عبدالله السلامه

عنوان الرسالة: نموذج مبهم لتقييم مستوى التحول الرقمي لمشاريع البناء في المملكة العربية السعودية

التخصص: هندسة وإدارة التشييد

تاريخ الدرجة العلمية: يناير 2024

في الآونة الأخيرة، نمت الرقمنة في قطاع البناء، مما يشير إلى تغيير مهم في كيفية تخطيط المشاريع وتنفيذها وإدارتها. ويعالج هذا التحول، المدعوم بالتقنيات الحديثة، تحديات عدم اليقين في مشاريع البناء. تقترح هذه الدراسة نموذجاً غامضاً لتقييم مستوى التحول الرقمي لمشاريع البناء في المملكة العربية السعودية. وتتمثل الأهداف في تحديد أنشطة الرقمنة، وتصنيفها باستخدام نموذج يحسب قيم احتياجات الرقمنة بستة مقاييس، وتطوير نموذج قائم على الغموض يأخذ في الاعتبار أوجه عدم اليقين في أحكام الخبراء.

يتم دمج البحث رؤى الخبراء التي تم الحصول عليها من خلال مسح شامل بين المتخصصين المتنوعين. ويعتمد البحث على أساس القيمة باستخدام السيناريوهات المتشائمة والمرجحة والمتفائلة لجمع البيانات. تم استخدام نظام المنطق الغامض ممداني، مع أربعة متغيرات المدخلات - الحصول على المعلومات، ومعالجتها، وتقييمها، وإعداد التقارير - المرتبطة بمستوى الرقمنة في أنشطة البناء (DDCA). تربط القواعد المبهمة ومعلومات العضوية هذه المدخلات بمقياس (DDCA).

تشير النتائج إلى أن النموذج الغامض المقترح يتغلب بشكل فعال على الشكوك في البناء. وتم تحديد فئات الرقمنة العالية مثل إدارة التغيير وتحديث الرسومات وتحسين استراتيجيات إدارة النفايات. وكشفت الأنشطة ذات الدرجات المنخفضة عن أوجه قصور، في حين أظهرت الأنشطة ذات الدرجات الأعلى فوائد الرقمنة. يتوافق النموذج بشكل وثيق مع آراء الخبراء، مما يدل على دقته. وقد تم التحقق من صحة النموذج المقترح باستخدام مشروع حقيقي، مما يدل على فعاليته في تقييم مستويات الرقمنة في مهام البناء. يوفر هذا البحث أداة عملية لأصحاب المصلحة في صناعة البناء والتشييد لإدارة تعقيدات التحول الرقمي.

CHAPTER 1

INTRODUCTION

1.1 Research Background

The construction industry, traditionally characterized by its labor-intensive practices, has long been criticized for its slow adoption of new technologies and digital tools, resulting in lower productivity and efficiency than other sectors (Khurshid et al., 2023). Historically, construction processes have been deeply entrenched in conventional methods, with a slower uptake of technological innovations compared to industries like manufacturing or information technology. The construction industry grapples with challenges related to project coordination, communication, and data management. Traditional methods of documentation and communication are prone to inefficiencies, leading to delays and misunderstandings among project stakeholders. These challenges underscore the urgent need for innovative solutions to enhance collaboration, streamline processes, and improve overall project outcomes. One of the primary challenges impeding the digital transformation of the construction industry is the pervasive issue of uncertainty.

Construction projects are inherently complex, involving numerous variables such as site conditions, weather, and regulatory requirements. The multifaceted nature of these projects often leads to expert uncertainties that can manifest in delays, cost overruns, and quality issues (Tariq & Shujaa, 2023). The intricate interplay of these uncertainties poses a formidable obstacle to effective decision-making and project management in the construction domain. However, in recent years, there has been a growing interest in the digital transformation of construction activities to overcome these challenges. As stakeholders increasingly

acknowledge the potential transformative impact of digitalization, the construction industry is gradually pivoting towards a more technologically advanced and efficient future. Digital technologies can revolutionise managing construction projects, from design and planning to execution and maintenance (Sawhney et al., 2020). By harnessing digital tools and data-driven approaches, construction stakeholders can improve decision-making, enhance collaboration, reduce costs, and minimise risks.

Digitalization is the use of digital technologies to alter a business model and generate new revenue and value; it is the process of transitioning to a digital business (Grey & Rumpe, 2015). This paradigm shift involves tools such as Building Information Modelling (BIM) for comprehensive project representation, project management software for streamlined workflows, drones and UAVs for efficient site monitoring, and augmented reality (AR) and virtual reality (VR) for enhanced design visualisation (Khorshidi, Hosseini, & AbouRizk, 2019). Additionally, the integration of IoT devices, cloud computing, and mobile applications fosters real-time data utilisation, collaboration, and decision-making, collectively optimising construction processes and outcomes. Digitalization brings a host of advantages to the construction industry, revolutionising traditional practices.

Motivations for adopting digitalization in the construction industry include the promise of increased efficiency, reduced costs, enhanced project predictability, and improved overall project outcomes. Firstly, it significantly enhances efficiency by automating processes using tools like BIM, minimising manual efforts, and thereby saving time throughout project phases (Prasad & Egbu, 2016). Improved collaboration is another notable benefit, as digital tools facilitate seamless communication among project stakeholders, fostering better coordination and teamwork. The integration of real-time data collection and analytics ensures accurate

insights for informed decision-making, reducing errors and optimising resource allocation, leading to cost savings. Additionally, digitalization contributes to increased productivity, better risk management, and a heightened focus on sustainability. The adoption of digital technologies not only enhances safety through real-time monitoring but also improves client satisfaction by providing clearer project visualisation and transparency. Ultimately, digitalization equips construction companies with the adaptability needed to thrive in an evolving industry landscape (Parusheva, 2019). Indeed, digitalization presents an opportunity for increasing profitability, efficiency, and customer satisfaction in the construction industry.

Assessing the current digitalization degree of construction activities is essential to supporting the successful implementation of digital technologies in construction (Bajpai & Misra, 2022). This examination evaluates the extent to which digital tools and data-driven methods are employed across various project phases, including data acquisition, data entry, data analysis, and data reporting. The construction industry is known to be the least digitised in both developed and developing economies. For experts in the industry, digitalization is a priority if the sector is to remain viable in the coming decades (Bajpai & Misra, 2021). The number of initiatives seeking to remove barriers to digitalization has also increased in the last few years. Stakeholders in both the public and private spheres are keen on increasing productivity in the sector.

A study conducted by the Ministry of Housing in Saudi Arabia posits that digital transformation is today considered the pillar and the construction industry's future (Ministry of Housing, 2022). According to the study, the slow uptake of digitalization in the industry has led to issues such as time and budget overruns and cost increases because of rework. The study further argues that technologies such as 3D printing, autonomous equipment, sensors, and

drones can increase efficiency in the construction value chain. The efficacy of construction projects is determined by increased collaboration, data collection, analytics, and data-driven decision-making.

To support the shift towards digitalization, public and private stakeholders require tools to assess the progress towards digitalization in order to reduce costs and minimise risk. In addition, due to the dynamic nature of the construction project, uncertainties exist in this field at different levels. Therefore, many approaches have been used to address this problem. One of these techniques is a fuzzy approach. The architecture of a fuzzy logic system comprises four key components: the fuzzifier, rules, inference engine (intelligence), and defuzzifier. The rules section encompasses if-then conditions input by humans, serving as the decision-making mechanism for the model. Notably, recent advancements in fuzzy approaches aim to streamline and optimise the number of fuzzy rules to enhance computational efficiency (Chen et al., 2017). The fuzzification component manages the conversion of fuzzy sets from numerical inputs, with sensors measuring crisp data inputs. The fuzzy logic inference engine plays a pivotal role in matching these fuzzy inputs with predefined rules, facilitating the decision-making process within the model. This dynamic interaction between fuzzy inputs and rules contributes to the adaptability and nuanced reasoning characteristic of the fuzzy approach (Gunduz & Elsherbeny, 2021).

1.2 Problem Statement

The movement of construction companies towards digitalization requires an effective assessment of the level of digitalization in the construction industry at the project level. Today's digital requirements call for applying technologically advanced methods of assessing the level of digitalization in construction projects. Such technological tools and software are also critical

for regulatory compliance. The application of technology in construction is characterized by a wide range of innovative materials, methods, and data outputs that are difficult to track manually. It is, therefore, essential to identify tools to assess digital compliance in construction projects.

Furthermore, the dynamic nature of construction projects, influenced by factors such as unpredictable weather conditions, site complexities, and regulatory changes, introduces a level of uncertainty that traditional deterministic techniques struggle to address effectively. Deterministic approaches, which rely on fixed inputs and precise calculations, often fall short of capturing the nuanced and unpredictable aspects of construction activities. The limitations of deterministic techniques become apparent, as they lack the adaptability required to navigate the complex and evolving landscape of construction projects. The inability to account for uncertainties can lead to suboptimal decision-making, potentially resulting in delays, cost overruns, and compromised project outcomes. There is a growing recognition of the need for more sophisticated and adaptive methodologies that acknowledge and incorporate uncertainties into the assessment of project digitalization. Embracing probabilistic or fuzzy logic models, for instance, allows for a more nuanced evaluation, considering a range of potential outcomes and accommodating the inherent unpredictability of construction processes.

Developing a model for assessing the digitalization of construction projects in uncertain environments would revolutionize the construction industry for the fourth industrial revolution.

Consequently, this study will build a digitalization index that will be used to evaluate the level of digitalization on different projects. Recognizing the multifaceted nature of digital transformation within the construction industry, the digitalization index serves as a vital tool for systematically measuring the degree to which digital technologies and processes are integrated into various project facets. The digitalization index is poised to contribute to strategic decision-making processes by offering actionable insights into areas of strength and potential improvement in digital adoption across projects. Through a systematic and standardised evaluation process, the index will empower industry stakeholders, project managers, and decision-makers with a reliable benchmark to ascertain the effectiveness of digitalization initiatives and guide future investments.

1.3 Research Objectives

This research aims to develop a fuzzy-based model for assessing the digitalization level of construction projects in Saudi Arabia. This aim will be achieved through the following objectives:

1. Identify the potential activities to be digitalized at the project level related to the construction industry in Saudi Arabia.
2. Rank the identified construction activities by constructing a model to calculate the digitalization need values for each activity based on six measures that determine the acceptance of technology in construction projects.
3. Develop a fuzzy-based model to evaluate the degree of digitalization of construction projects, considering uncertainties in experts' judgments, and build an assessment tool for the digitalization of construction projects in Saudi Arabia.

1.4 Significance of the Study

The construction industry is a critical part of any economy and is essential to the fourth industrial revolution. Therefore, it is imperative to integrate technology into construction projects to reduce cost, enhance performance, ensure safety, improve quality, decrease bottlenecks, and promote sustainability. Digitalization in construction aims to help in achieving Saudi Vision 2030, which seeks to drive the country to be the most developed country in the world. The demand for speedy delivery, efficiency, quality, and client and end-user satisfaction has increased in Saudi Arabia because of an increase in infrastructure projects (Kazmi & Sodangi, 2022). The proposed model will help the contractors and stakeholders determine where digitalization can lead to improvements, resulting in increased project performance. The tool will also define the type of process required for different activities. Essentially, the developed framework from this research will help establish the correct and most appropriate technology for a construction project to ensure high performance without incurring unnecessary expenses associated with digitalization.

The fuzzy model will be leveraged to deal with uncertainties in the construction industry. This research seeks to establish a forward-thinking digitalization index that not only evaluates the current state of digitalization in construction projects but also serves as a predictive and adaptive tool, fostering informed decision-making and strategic planning. By addressing uncertainties and aligning technology choices with project needs, the digitalization index aspires to be a valuable resource for optimizing digital transformation within the construction industry. The proposed digitalization index not only serves as a quantitative measure of the digital maturity of projects but also acts as a strategic tool for predicting the specific types of technologies essential for project success.

Furthermore, construction projects have become more significant in recent years in Saudi Arabia due to the kingdom's vision to diversify the economy and boost non-oil revenues. Mega projects entail the adoption of technologies for managing a variety of activities at the project management level. Previous studies show that increased productivity and lower costs can be attained if construction companies embrace digitalization. However, no reliable tools are available for tracking the level of digitalization in construction projects. Achieving the aim of this study, which is to develop a model to assess digitalization in construction projects, would direct industry experts and scholars to construction activities and processes that are the most digitally mature, thereby speeding up the adoption rate of digitalization in the construction industry in Saudi Arabia. The proposed study seeks to fill this void by aiming to develop a comprehensive model for assessing the level of digitalization in construction projects. The significance of this endeavor lies in its potential to offer a systematic and standardized approach to evaluating the digital maturity of construction endeavors in Saudi Arabia. The absence of such tools has impeded the construction industry's ability to identify the most digitally mature activities and processes.

By bridging this gap, the study aims to provide invaluable insights to industry experts and scholars, thereby expediting the adoption of digitalization practices in the Saudi Arabian construction sector. The implications of a successful model are profound. Industry stakeholders, armed with a reliable assessment tool, can pinpoint areas within construction projects that are digitally advanced, facilitating targeted investments and strategic planning. This not only enhances project efficiency but also accelerates the overall digital transformation of the construction industry. As Saudi Arabia continues its trajectory of ambitious construction projects, the timely development of such a model becomes imperative for staying aligned with

global technological advancements and ensuring the sustainability and competitiveness of the construction sector in the Kingdom.

1.5 Scope and Limitations

The study is expected to undergo cumbersome processes, such as acquiring, importing, analyzing, and reporting data. These processes include the investigation of construction activities to be digitized. In addition, because measuring digitalization requires assessing the degree of technology use, the assessment method may become abstract. The study faces another limitation in the construction site managers that will be surveyed using the model and the unified theory of acceptance and use of technology (UTAUT) questionnaire. It would not be appropriate to assume that the challenges and activities faced in one construction location are the same in other parts of the world; therefore, the study would need to be redone in other locations for international comparison. Additionally, another limitation lies in the potentially constrained sample size, which may impact the representativeness of the study's findings.

Depending on the availability and willingness of participants, the sample size may not fully capture the diversity and complexity of the construction industry in Saudi Arabia. A larger and more diverse sample would enhance the study's external validity, providing a more comprehensive understanding of digitalization trends across various construction projects. Another limitation stems from the study's exclusive focus on the construction industry in Saudi Arabia. While this focus is essential for understanding the nuances of digitalization within the local context, it may limit the generalizability of the findings to a broader international context. Different regions may exhibit unique characteristics and challenges in digital adoption. Therefore, the study's applicability beyond the Saudi Arabian construction landscape could be constrained. Recognizing these constraints prompts considerations for future research

endeavors, such as the need for larger and more diverse samples and comparative analyses with construction industries in different global contexts.

1.6 Structure of the Thesis

This thesis is organized into the following chapters:

Chapter 1: Introduction: this chapter includes the research background, problem statement, research objectives, significance of the study, and the scope and limitations.

Chapter 2: Literature Review: a detailed literature review on studies conducted in the area of research to identify the potential construction activities to be digitized, assessment of process management activities, and a review of the use of fuzzy logic in project management and other related areas.

Chapter 3: Methodology: This chapter presents the steps that were be followed to achieve the objectives of this study.

Chapter 4: Results and Discussions: The results of the study, including those from the fuzzy model, are discussed in this chapter.

Chapter 5: Conclusion and Recommendation: The chapter includes conclusions made in the study and recommendations for experts and future research is provided in this section.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The chapter presents an overview of digitalization in construction, the use of fuzzy tools in process management, and a comprehensive list of vital construction activities, their sub-categorized processes, and their corresponding digitalization potential. Drawing from various sources, these activities include design management, quality control, material management, employee tracking, project security and safety, contract management, procurement management, risk management, and performance management. The detailed breakdown provided in this literature review lays the groundwork for subsequent chapters, emphasizing the evolving landscape of digitalization in the construction industry.

2.2 Overview of Digitalization in Construction

The digitalization of the construction industry attracted academic interest. Since the beginning of the 21st century, the growth and development of information technology (IT) and information and communication technologies (ICT) have increased in various industries, including the construction industry. At this time, scholars developed several studies to examine the extent to which construction companies and their workers were willing to adopt these new technologies into their operations.

Critical research conducted by Samuelson (2002) focused on evaluating the construction industry's preparedness for adopting IT. The research used the IT barometer as a technique to assess workers' readiness to embrace new technology. This fundamental work made a substantial contribution by offering useful insights into construction workers' mindsets and

readiness to accept IT advancements. Samuelson's study created a critical basis for following research endeavours by investigating the industry's receptivity to technological developments, affecting the direction of talks on IT adoption in the construction sector. This fundamental study laid the groundwork for a more in-depth knowledge of the obstacles and opportunities involved with incorporating technology into building methods.

Hewage et al. (2008) conducted a groundbreaking study focusing on how various stakeholders in Alberta, Canada's construction sector, perceived digitalization technologies. The technique used comprised a detailed investigation of the variables influencing acceptance, problems encountered, and possible advantages related to digitalization in the context of construction in the Alberta area. The study's main value is that it provided a thorough knowledge of how different actors, such as employees, executives, and technology suppliers, perceived and interacted with digital technologies. This localised viewpoint deepened our understanding of the dynamics of digitization in the construction sector, shedding light on the complexities and particular issues confronting players in the Alberta area.

Nourbakhsh et al. (2012) investigated the worldwide landscape of digitalization adoption among construction professionals. To do this, the approach used required expanding the investigation to more than 20 industrialised and developing nations, resulting in a solid and diversified dataset for study. This study's main value is its capacity to provide analytical viewpoints on construction workers' and engineers' readiness to adopt technology for communication and information on a worldwide scale. Nourbakhsh et al. (2012) significantly improved the comprehension of the general dynamics and challenges related to the implementation of digital tools within the construction industry by expanding the scope of

digitalization research beyond geographic regions, making a significant contribution to the global discourse on digitalization in construction.

The extensive research of Nourbakhsh et al. (2012) dove into the worldwide landscape of digitalization acceptability within the construction sector. The research provided a comprehensive perspective of construction professionals' views and preparedness to embrace information and communication technologies by expanding their investigation to over 20 industrialised and emerging nations. This broad perspective not only broadened comprehension of the many points of view but also recognised the various socioeconomic situations that impact the adoption of digital technologies. The methodology's breadth provided a complete examination, establishing the framework for detailed analyses of the international problems and prospects of digitalization.

With digital tools in construction projects gaining recognition and importance more and more, researchers discovered details of how they made construction work more efficient. Shedding light on the example, Khurshid et al. (2023) stated that the construction sector was a bit sluggish in adopting new technologies; however, once they were used, they greatly enhanced operational efficiency both in terms of the time required for a project to be completed and the quality of the work done. Therefore, this research indicated the benefits of using up-to-date digital tools for staff management and solving working processes, which ultimately brought positive end products for construction projects.

Likewise, Tariq and Shujaa (2023) highlighted the risks associated with unforeseeable issues on construction sites, including changes in weather or site conditions from unexpected changes. Such conditions could sometimes affect the progress and put the project expenses at

a higher level. Researchers claimed that a range of digital solutions could help cope with the uncertainties, giving better control. Lidelöw et al. (2023) assessed the perception and willingness of construction workers to adopt digitization in their daily work operations. Several digitization tools were evaluated for different categories of workers.

Orzeł and Wolniak (2022) analysed the influence of digitalization on the structure and creation industries, as well as the sustainability issues of remote work in Poland. The research clearly showed the remote collaboration tools, which enabled functioning without a person being physically present in any of the places, which was also an environmentally responsible step and saved carbon footprints. The proponents provided a rationale for linking digitization with sustainability via better resource management and waste minimization achieved through improved planning. Bajpai and Misra's (2022) research focused on the factors involved in the effective execution of digitalization within the construction industry. They highlighted determining factors like good leadership, strategic clarity, efficient and worthwhile training, and sufficient and robust IT. Their report implied that leadership was of great importance, as it was the leadership responsible for implementing digital initiatives, innovation culture development, and general business objectives. Additionally, it underlined the practicality of lifelong learning as well as the fact that, in the face of the ever-advancing speed of digital technologies, there was a need to continuously study and adapt.

Bajpai and Misra (2020) highlighted the significant risk factors surrounding, but not limited to, the implementation of digitization in the construction business. To explain different risks that might arise, they showed a case study as one of the presentations at the International Subsections Conference of IEEE India. These risks were too complex to be applied, including the threat of cyberattacks, reluctance to change, and the need for high initial investments. The

study highlighted the need for risk assessment in order to build a comprehensive risk management framework that would address systemic risks. Digital transformation was a topic of discussion in the so-called technological and cultural dimensions. It demanded that the culture of a company be revised in order to incorporate a strong attitude towards change and adaptation.

Marnewick and Marnewick (2022) provided new insights into the adoption of digitalization in project management and highlighted important avenues for future research as well as potential applications. The authors stressed that digital technologies were the enablers of change to make project management more efficient and effective. The key areas of impact included proper communication, resource management, and more realistic project reporting. The findings of the study were relevant to current approaches to project management, as they suggested considering the use of digital technologies for coping with the new challenges of projects. Also, it emphasised the importance of changing the organisational culture of project teams and introducing new ways of learning so that they could use digital progress opportunities. It highlighted the fact that although there were many benefits, there were also issues, including resistance to change and the need to train or prepare project managers for this new role.

Ngereja and Hussein (2021) conducted a study to understand the conditions necessary to support learning for innovation in digitalization projects from the project team members' viewpoints. The literature from their study further showed that digitalization success hinged on the availability of a learning environment that allowed for an effective team learning process in terms of knowledge generation and application. The authors identified several variables that shaped this learning process, and they included organizational culture, leadership, and resource

support for training and development. They claimed that these preconditions were necessary for supporting innovation within digital projects. Furthermore, the research mentioned obstacles that the project teams experienced in the digital space, from the direct interference of the technical environment to the proper organization of collaboration.

2.3 Use of Fuzzy Tools in Process Management

In an attempt to track construction processes, several tools were used in the construction industry. One of these tools was the fuzzy approach. Tabatabaee et al. (2021) developed a prototype risk assessment tool (PRAT) to identify and evaluate risk in building information modeling. Industrialised building system construction projects faced many risks, including lack of information, increased costs, and poor information sharing. The PRAT approach integrated a fuzzy analytic process to evaluate the data obtained from the project. The authors contended that the method prioritised risks by considering their importance and interdependencies.

The effective adoption of PRAT reduced the wastage of resources and time through systematic modular coordination. An integrated system for the IBS enabled project managers to identify risks associated with sharing and collecting information on construction projects. Sadeh et al. (2021) contended that an integrated approach reduced the cost implications of a construction project. Project managers and other stakeholders' failure to manage risk increased the project's cost. The lack of a standardised and systematic approach to risk management exacerbated this. The authors used a fuzzy logic model and a Monte Carlo simulation to identify the risks in construction projects. The plan was implemented on a commercial construction project in California. The study's findings indicated that a mitigation response

plan significantly decreased the project's cost. Project managers should use this model to forecast risk in the construction industry to reduce cost increases.

Mahdinia et al. (2021) developed a safety risk assessment approach based on a fuzzy analytic hierarchy process. Safety risks in construction projects pose a danger to the workers and cause investment losses. The fuzzy analytical hierarchy process assisted project managers in identifying the two factors of risk severity and probability. The authors developed a semi-quantitative method to evaluate the components of risk in the construction industry. For instance, incident probability was determined from hazard detection, inspection, human reliability, and incident learning (Mahdinia et al., 2021). Conversely, the severity of the incident was predicted by human injury, financial loss, and reputation damage.

As such, it could be argued that a risk assessment approach based on the fuzzy analytic model reduced the risk of occupational incidents in construction projects. Gunduz and Elsherbeny (2021) assessed the impact of contract administration on construction projects using the fuzzy logic approach. Contract components, including response time, approval process, and documentation, impacted the execution of a project. The authors proposed a new multi-dimensional fuzzy model to quantify contract administration by managers at the project level. Risks in contract administration increased the time required to complete the project. Quantifying the contract performance processes improved the tracking and implementation of the construction project. Managers should adopt the multidimensional fuzzy logic approach to improve the efficiency of contract administration processes.

Balta et al. (2021) recommended using the Bayesian Belief Network to assess the risk of tunnel projects. They discussed the types of risks that large tunnel projects faced, primarily

due to geological conditions. Therefore, they recommended using a Bayesian network-based decision support tool (BBN Tunnel) to predict delay risks in tunnel projects. The study's findings indicated that Bayesian models effectively predicted delay risks in large geological tunnel projects.

Loizou and French (2012) conducted the Monte Carlo analysis to assess the effects of uncertainties on planned project performance. The outcome of the study affirmed that Monte Carlo was one of the outstanding techniques when dealing with issues of construction projects and comprehending the matters of utility function dimensions.

Chen et al. (2017) also used the stochastic-based Monte Carlo approach to manage delay-related factors in construction projects. Two essential case studies applied the approach: a commercial construction project and a BOT highway. The study concluded that the approach was instrumental in reducing risk aversion when managing different project activities. To boost the understanding of complicated issues touching on the projects, artificial intelligence (AI) models were widely applied. The applications were increasingly embraced, not just in engineering and science but also in construction project management issues. One such application of AI was the artificial neural network that was done by El-Sawalhi, Eaton, and Rustom (2007). The model helped in the classification of the contractors into many groups. The classification was mainly targeted according to performance. Cheng and Wang (2019) used the integrated random forest algorithm to forecast and understand public partnerships in infrastructure projects. The method was handled with great accuracy when forecasting. El-Sawalhi, Eaton, and Rustom (2007) also analysed the ANN model when predicting labour productivity. The result also showed that the model was best suited to capture and forecast matters of labour productivity.

Table 1 below shows a list of construction activities at the project level that were identified based on literature surveys of previous studies. The limitation of uncertainty when evaluating the rank of activities by subject matter experts was addressed in this research by applying a fuzzy-based approach.

2.4 Vital Construction Activities

Most of the vital construction tools and activities involved are sub-categorized under the following primary processes: design management, quality control, material management, employee tracking, project security and safety, contract management, procurement management, risk management, and performance management. Some of the activities under design management include collecting and updating project details, analyzing the project's environmental impacts, and recruiting qualified artisans. The quality control process comprises several activities: updating the contract of compliance with suppliers and subcontractors and modernizing drawings, models, and document systems. The other significant processes also constitute activities tabulated in Table 1 below.

The management of construction projects is broken down into its central processes, activities, and sources in the table below. The procedures and activities shown in the table are crucial to meeting quality and safety requirements and completing the project on schedule. The collection of project information, the analysis of environmental implications, and the enhancement of waste management systems are all part of design management. Contract compliance and updating blueprints, models, and documentation systems are the responsibilities of quality control. Updating resource planning, replacing low-quality supplies on time, and providing enough storage space are all aspects of material management. Keeping tabs on staff members helps with things like compliance, education, and open lines of

communication. Prioritizing and allocating distinct tasks to artisans and keeping track of subcontractors' progress and payments are all part of scheduling work teams for projects. Assessment of risks and vulnerabilities and risk identification and analysis are at the heart of project security and risk management. Each process and action in the table is referenced from various sources that expand on the information.

Table 1: Summary of potential activities to be digitalized.

Major processes	Activities Involved	Sources
Design Management	Collecting and updating project details	
	Analysis of the environmental impacts of the project	
	Recruitment of qualified craftsmen	
	Improving waste management strategies	
	Follow-up and management of deviations	
	Shared information between companies and construction projects	Sezer et al. (2021)
	Improve the project's energy consumption.	Herrera et al. (2020)
	Creation of effective design management strategies	Savolainen et al. (2018)
	Design evaluation and project sustainability appraisal	Eze and John (2018)
		Ugwu et al. (2006)
Quality Control	Update contract compliance with suppliers and subcontractors.	
	Modernize drawings, models, and document systems.	
	Visualize pictures and use 3D models on-site.	Sezer et al. (2021)
	Project Control Assessments and Audits	Elbashir (2018)
	Creation and delivery of vital items and infrastructure	Okereke et al. (2022) Dinur et al. (2014)

Major processes	Activities Involved	Sources
Material Management	Development of acceptance and rejection strategies	
	Carry out inspections, approvals, and certifications.	
	Carry out internal product testing.	
	Create lists about material quantity.	Sezer et al. (2021)
	Update time and resource plans.	Phani et al. (2019)
	Punctual replacement of quality materials	Sivagami and
	Setting up sufficient storage space for construction materials	Anagha (2019)
	Adjusting to project scope changes	Nanaware and Saharkar (2017)
	Inventory planning, storage, and control	Soni et al. (2016)
	Ensuring the safety of the staff	
Employee Tracking	Carrying out different training programs for the employees	
	Monitoring and controlling the project's progress	
	Performance and saving of quality self-checks.	
	Follow the staff's presence and their use of protective equipment.	
	Follow up and analyze the artisans' working hours.	
	Implement problem-solving skills and communication among the workforce.	
	Develop, prioritize, and assign different roles to artisans.	
	Update time and resource plans.	Sezer et al. (2021)
	Track the subcontractor's progress and payments.	Blanco (2017)
		Calvetti et al. (2020)

Major processes	Activities Involved	Sources
	Analyze contract compliance with the suppliers and contractors. Schedule work teams for projects.	
Projects Security and Safety	Safety information and training for staff	Sezer et al. (2021)
	Hazard and security assessment activities	Purohit et al. (2018)
	Develop site mitigation methods.	Bao et al. (2019)
Contract Management	Track and update contract compliance checklists.	
	Provide updated records of all contractor and client communications.	
	Maintain a standardized communication checklist.	Blanco (2017)
Procurement Management	Product Sourcing and Purchasing	
	Digital payments	
	Smart contracts on the blockchain	Jang et al. (2021)
Risk Management	Risk Identification	
	Risk Planning	
	Risk Monitoring	
	Risk Analysis	Batson (2009)
Performance management	Provide automated dashboards created from field data	
	Monitor progress and performance across teams	
	Provide staffing updates and recent reports generated on handheld devices	Blanco (2017)

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter discusses the research methodology used to achieve the study's objectives. It is primarily focused on the development of a model for ranking specific activities and assessing the level of digitalization within construction processes. The methodology chosen employs the fuzzy approach, which is known for its ability to capture the nuances and uncertainties inherent in the construction industry, providing a nuanced perspective on the digitalization index of construction projects. Figure 1 illustrates the structured steps undertaken to gather the necessary information to address the research questions effectively. The steps implemented to achieve the objectives of this research include the identification of the construction of project activities based on a literature review and experts interviewed, construction project activity screening, ranking the identified activities, model development for assessing the degree of digitalization of activities, measuring the digitalization index, and validating the model. Each step is explained in detail in the subsequent sections.

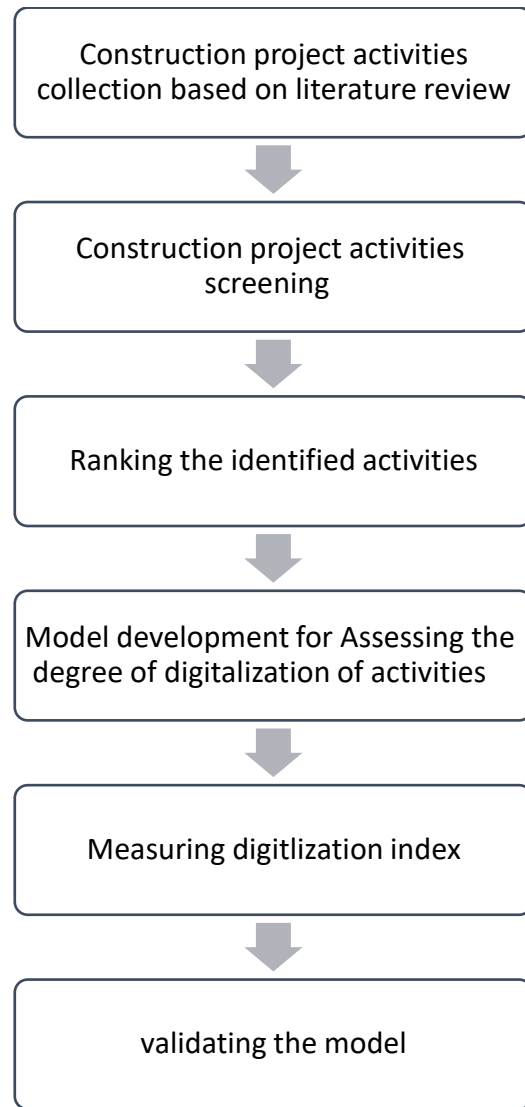


Figure 1: Research Methodology

3.2 Construction project activities identification

The first step in the study is to identify the construction activities related to the projects. In the pursuit of achieving the study's objectives, the methodology employed focused on the thorough identification of construction project activities. A comprehensive literature review was conducted to investigate the work that has been done and identify the activities related to construction projects at the project level.

The identified activities are classified into several categories, which are: design management, quality control, material management, employee tracking, project security and safety, contract management, procurement management, risk management, and performance management, as shown in Table 1.

3.3 Construction project activities screening

Based on the literature, a large number of activities have been identified. To cut down on the number of activities in the evaluation model, an initial survey was conducted. Several experts participated in a three-hour class, representing a variety of construction industry actors such as consultants, contractors, and subcontractors. Questionnaires for picking experts were divided into demographic information and digital knowledge. Experts were chosen based on industry experience, the role they hold in construction for diversity, academic qualifications, and the level of technology adoption in their projects. Individuals with extensive industry experience bring a wealth of firsthand insights into the complexities of project execution, management, and the digitalization landscape. Diversity is a key factor in the selection process, with experts representing a range of roles within the construction ecosystem, including project managers, technology specialists, construction professionals, and stakeholders. This diverse representation ensures that the digitalization index benefits from a comprehensive assessment, considering the varied viewpoints and requirements of different stakeholders involved in construction projects. Academic and research backgrounds in construction management, digital technologies, or related fields are also crucial criteria for expert selection. This ensures that the chosen experts not only bring practical experience but also possess a solid theoretical foundation, contributing to the development of a well-rounded and robust digitalization index. Experts are chosen for their proficiency in digitalization within the construction domain,

showcasing a nuanced understanding of evolving technologies such as Building Information Modeling (BIM) and activities that can be digitalized. They were given the task of describing and arguing which areas of construction should be digitalized, which require staff to be tech-savvy and have access to hardware, and which require personnel to be tech-savvy and have access to gear.

Five participants, excluding workshop organizers, representing diverse roles such as consultants, contractors, and subcontractors within the construction industry, are involved in the three-hour workshop. Participants were invited to define and argue which components of construction can be digitalized, which are easy to digitize, and which require staff to be tech-savvy and have access to hardware. The aim is also to eliminate activities that cannot be effectively digitized and incorporate any potentially missing activities.

In determining which activities to digitize based on ease of digitalization, factors such as complexity, repetitiveness, and degree of customization of existing technologies were evaluated. Certain components of construction may be easier to digitize based on their inherent complexity and repetitiveness. Tasks that involve a high degree of repetition or follow a standardized process are often more amenable to digitization. Similarly, activities closely integrated with the design and planning phases can benefit from digital tools that streamline collaboration and communication. Digitizing certain components may require staff to be tech-savvy and have access to appropriate hardware. Resource-intensive tasks, those with safety-critical implications, and activities demanding innovative approaches may necessitate skilled personnel capable of utilizing advanced technologies. Identifying such components helps tailor digitalization efforts to the technical proficiency of the workforce. Hardware plays a crucial role in enabling the effective implementation of digital tools and technologies. The workshop

results were used to reduce the number of activities in the evaluation model. Because the existing activities were deemed sufficient, no new activities were added. Table 8 shows a condensed list of potential activities.

Through these insightful interactions, the participants provided valuable input, contributing to a refined list of construction activities. The activities already present in the initial list were deemed sufficient based on the experts' perspectives. The activity screening process, guided by expert input, ensures that the identified activities align with both the industry's digitalization potential and the practical considerations of construction professionals

3.4 Ranking the identified activities

The Unified Theory of Acceptance and Use of Technology (UTAUT) was established to provide a holistic understanding of technology acceptance. The theory is a well-known model for understanding technology acceptance and adoption among users. The UTAUT determines four significant criteria that impact users' intentions towards and actual technology usage. These criteria include usefulness (U), areas that require digitalization in a project (A), challenges (CH), and ease of digitalization (E) (Venkatesh et al., 2003).

$$Total_x = \sum_{i=1}^n (U_{x,i} + A_{x,i} + CH_{x,i} + E_{x,i}) \quad (1)$$

In the current study, two additional criteria (security and safety) have been introduced based on expert input gathered during the pilot study. These new criteria expand the original UTAUT model to encompass a more comprehensive assessment of activities related to digitalization in the construction sector. The six criteria employed in this study are:

- Usefulness (U): The extent to which the digitalization of activities is perceived as beneficial and valuable in the context of a construction project.
- Areas requiring digitalization in a project (A): Identification of specific project areas that are deemed suitable and beneficial for digitalization.
- Challenges (CH): Evaluation of the obstacles and difficulties associated with the digitalization of construction project activities.
- Ease of digitalization (E): The perceived level of ease in implementing digitalization for various activities within a construction project.
- Security (S): The degree to which digitalization measures contribute to protecting the security and privacy of the overall construction project.
- Safety Enhancement (SE): The impact of digitalization on improving safety measures within the construction project.

To evaluate the activities based on the above criteria, a survey is designed and distributed to subject-matter experts. The criteria for selecting experts include specialization in digitalization and staying current with industry trends and developments. This ensures that their insights are up-to-date and relevant to the current state of the construction workforce. Also, experts need to have a substantial amount of experience in the field, ensuring a deep understanding of the various activities and their significance. A minimum of 10 years of experience can be a reasonable criterion. Experts with diverse roles within the construction industry and relevant academic qualifications, such as advanced degrees in construction management, engineering, or related fields, can bring theoretical knowledge to complement practical experience.

The construction industry in Saudi Arabia is currently not fully adopting digitalization, as there is a dependency on workers to do manual work both in the field and outside the field, such as manual processes. However, this study encountered 26 specialists who have seen and tested digitalization in construction work to optimize efficiency for different companies. The questionnaire was used to rank the construction activities. The survey is provided in Appendix I. Then, a total digitalization need value was calculated by summarizing the ranking using the following modified model:

$$Total_x = \sum_{i=1}^n (U_{x,i} + A_{x,i} + CH_{x,i} + E_{x,i} + S_{x,i} + SE_{x,i}) \quad (2)$$

Where, n represents number of respondents, and x represents each activity

3.5 Model Development for Assessing the Degree of Digitalization of Activities

This section discusses the model development for evaluating the digitalization of construction activities identified in the previous section. First, the classification of the classification of the data management process based on the degree of digitalization of activities is discussed. Then, the proposed fuzzy-based model is developed to assess the digitalization of the project activities.

3.5.1 Data Management Processes

Various descriptions have established critical categories for determining the amount of digitalization of activities. According to Boute and Van Mieghem (2020), four essential categories exist: digital, automated, innovative, and automated and intelligent. On the other hand, Kang et al. (2008) condensed digitalization into automation and integration technologies. Sezer et al. (2021) offered a sophisticated assessment with three categories: analog and manual (phase 1), digital and manual (phase 2), and digital and automated (phase 3). Using these

classifications, the research takes a holistic approach to evaluating the degree of digitalization in construction management processes. The study established a systematic categorization coinciding with the various degrees of digitalization using a fuzzy model, as explained in the following section: manual, manual to moderate, moderate to high, and high. This organized approach, the digitalization spectrum within constructing processes, provides significant insights into the industry's continuing technological transitions.

Table 2 categorizes the use of digital tools and processes in the construction industry. The level of adoption of various digital technologies is divided into four distinct categories: manual, manual to moderate, moderate to high, and high. At the initial stage (manual), all construction procedures, including data collection, input, analysis, and reporting, are carried out manually on paper. Data procedures combine manual and digital methods at the (manual to moderate) level. Some components are digitized here, but a significant percentage still requires manual intervention, indicating an intermediate stage in construction digitalization.

Significantly, moving up the scale (moderate to high), all construction activities are heavily digitized. Manual tasks are practically obsolete in this environment, with digital technologies seamlessly integrated into every data lifecycle stage, from collection to input, analysis, and reporting. This phase demonstrates an admirable amount of digital integration, demonstrating the industry's advancement. Subsequently, no manual interventions are necessary during the whole data lifespan at the high level, which denotes total digitalization. Every part is automated, from data collection to input, analysis, and reporting, showing the peak of digital transformation in construction. This classification sheds light on the various stages of digitalization within the construction industry, emphasizing the critical necessity for complete digital transformation initiatives. It highlights the industry's continued efforts to

improve project outcomes, highlighting the importance of adopting modern technological advances for construction enterprises.

Table 2: Categorization of levels of digitalization in construction (Sezer et al., 2021):

Level of categorization	Data Acquisition	Data Entry	Data Analysis	Data Reporting
Manual	Use of Paper	Use of Paper	Paper reports	Paper reports
Manual to Moderate	Manual + Digitalization	Manual and Digital analysis	Manual with digitalization	Manual with digitalization
Moderate to High	Manual and Digital procedures	Manual and Digital analytical methods	Manual and Digital analysis	Manual with digitalization
High	Fully Digitalized	Fully Digitalized	Fully Digitalized	Digitalized

3.5.2 Fuzzy Approach Development

Considering that the responses from the experts are likely to be characterized by uncertainty, it is imperative to devise a strategy for accommodating the uncertainties. The fuzzy model is a handy tool for tackling uncertainties associated with survey results. Ultimately, it guarantees the reliability of information obtained from survey procedures. The fuzzy model's inputs were responses from the participants for the degree of data management processes (very low, low, moderate, high, very high) for each data management process, while its outputs were the degree of digitalization for an activity. Since the assessment of data management processes was initially deduced from responses, their associated degree of uncertainty was minimized using the fuzzy model. One of its key advantages is that it requires

a relatively small amount of data to run its analysis. Five steps were followed to apply the fuzzy approach to a model efficiently, and they include the following:

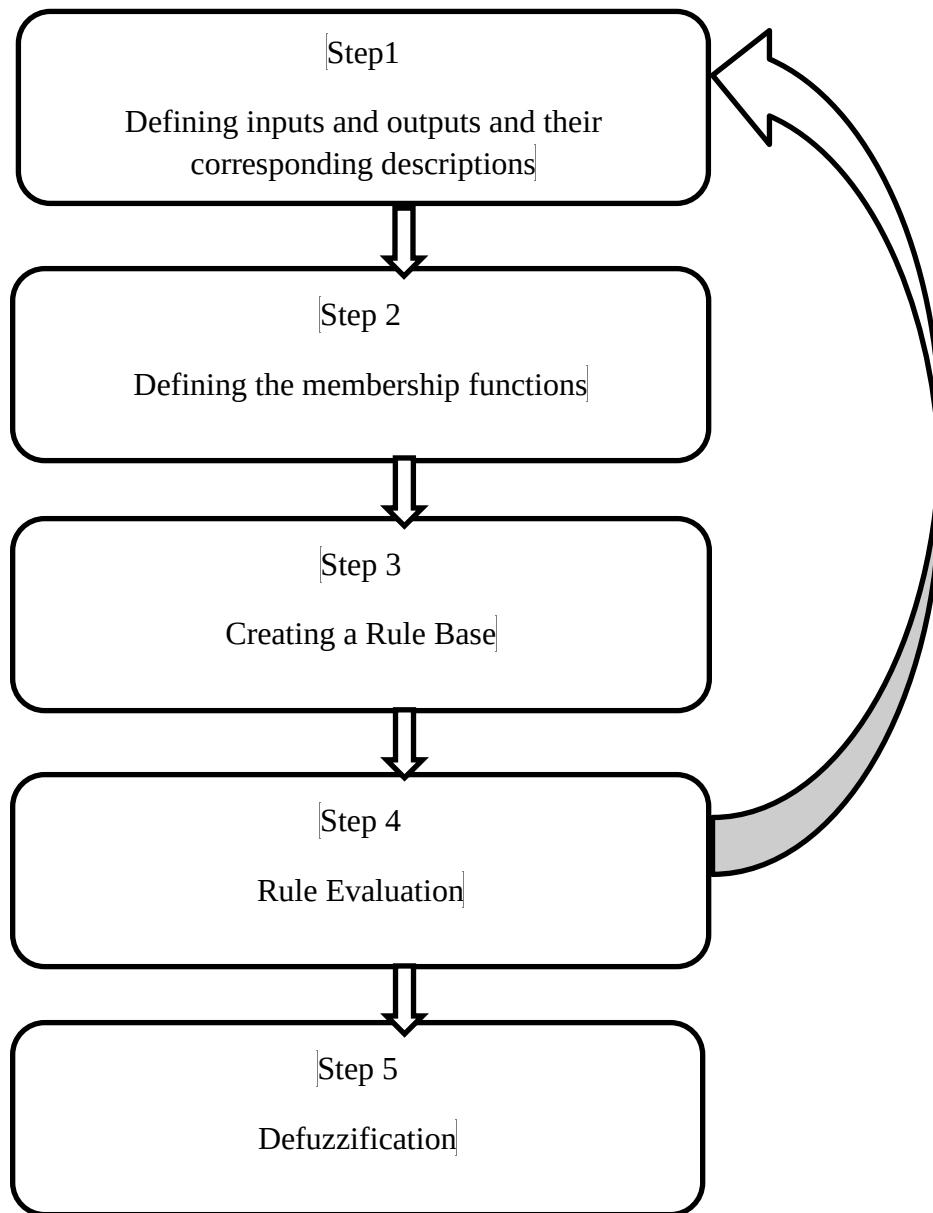


Figure 2: Logic flowchart

- The first step defines the fuzzy model's inputs and outputs. Based on the study's desired objectives, the responses from the participants were the inputs, while the outputs were the degree of digitalization of construction activities. The descriptors provided additional information about each of the inputs and outputs.
- The second step aimed to determine the fuzzy membership function accompanying each input variable. Membership functions were curves defining the mapping relationship between each point in the input space and the membership value or degree of membership between 0 and 1. Previous studies showed the utilization of triangular shapes for a fuzzy set, which transfers the linguistic variables that are identified by a judgment of experts using the below equation:

•

$$\mu_M(x) = \begin{cases} 0, & x < a \text{ or } x > c \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b < x \leq c \end{cases} \quad (3)$$

Where $\mu_M(x)$ is linear membership function; and M is fuzzy numbers (a,b,c) (Dubois & Prade, 2021)

In this study, five membership functions were utilized: Very low (1 = [0,0,2.5]), Low (2 = [0,2.5,5]), Moderate (3 = [2.5,5,7.5]), High (4 = [5,7.5,10]), Very high (5 = [7.5,10,10]). Tables (3-7) were developed to show Linguistic variables. Data management processes membership functions, Linguistic variables, and output membership functions.

- In Step 3, once the membership functions and variables were determined, the rule base for the fuzzy model was created based on the descriptors defined in the first step. Previous studies showed that the fuzzy rule-based system is a fuzzy logic technique when historical information is unavailable. Mamdani fuzzy rules were employed, and from the second questionnaire, the input and output data obtained from experts were used to construct the fuzzy rules.

- The rules were evaluated to ascertain their strengths in the rule evaluation step. Multiple combinations of each of the rules were tried.
- In the final step, the most appropriate demulsifying methods were selected and used to obtain the mean of the maximum. Different methods were considered, including the center of gravity, the center of sums, and the center of the area.

Table 3: Linguistic variables and data acquisition membership functions

Rating	Fuzzy number
Very low	(0,0,2.5)
Low	(0,2.5,5)
Moderate	(2.5,5,7.5)
High	(5,7.5,10)
Very high	(7.5,10,10)

Table 4: Linguistic variables and data entry membership functions

Rating	Fuzzy number
Very low	(0,0,2.5)
Low	(0,2.5,5)
Moderate	(2.5,5,7.5)
High	(5,7.5,10)
Very high	(7.5,10,10)

Table 5: Linguistic variables and data analysis membership functions

Level	Fuzzy Number Range
Manual	(0,0,5)
Manual to Moderate	(0,2.5,7.5)
Moderate to High	(2.5,5,10)
High	(5,7.5,10)
Very high	(7.5,10,10)

Table 6: Linguistic variables and data reporting membership functions

Rating	Fuzzy number
Very low	(0,0,2.5)
Low	(0,2.5,5)
Moderate	(2.5,5,7.5)
High	(5,7.5,10)
Very high	(7.5,10,10)

Table 7: Linguistic variables and output membership functions

Rating	Fuzzy number
Very low	(0,0,25)
Low	(0,25,50)
Moderate	(25,50,75)
High	(50,75,100)
Very High	(75,100,100)

Furthermore, fuzzy analysis includes four input parameters: data acquisition, data entry, analysis, and reporting. The degree of digitalization of data management processes is used as an input variable. Each data management process is assigned a 10-point scale evaluation based on the degree of digitalization (from fully manual to fully digitalized). Fuzzy rules (IF-THEN) are applied to assess the input variables. The input variables are the data management processes (data acquisition, data entry, data analysis, and data reporting), which are leveled based on their degree of digitalization into five levels (very low, low, moderate, high, and very high). The fuzzy DDCA value outputs are divided into five classes (deficient, low, moderate, high, and very high). The fuzzy rules were developed using MATLAB to generate all possible fuzzy rules.

The fuzzy method has proven to be a beneficial tool in dealing with uncertainties in survey findings, as it gives a means to accommodate the inherent uncertainty that is connected with expert replies. Significantly, the fuzzy approach provides a way to accommodate the inherent uncertainty. The fuzzy model has several benefits, one of which is its capacity to lessen the degree of uncertainty associated with the findings of surveys. Another benefit is that its analysis can be carried out with only a small quantity of data, making it a more cost-efficient choice. In addition, fuzzy logic may be utilized to solve various issues, not simply data management procedures. For instance, it has been well utilized in anticipating climate change's consequences on the available water supplies.

The versatility of the fuzzy approach is one of its primary advantages, as it enables the use of various membership functions and defuzzification methods depending on the specifics of the issue being investigated, which is one of the strategy's primary strengths. Because of its adaptability, the fuzzy model may be tailored to unique requirements and adjusted to produce the best possible outcomes. In addition, the fuzzy approach may be readily integrated with other methods, such as neural networks, to increase its performance further.

Although there are numerous advantages to using a fuzzy approach, there are also some drawbacks. One of these limitations is that it places a significant amount of reliance on the knowledge of specialists, which may add subjectivity and prejudice to the study. In addition, the interpretation of fuzzy findings might be problematic because it can be tricky to translate language variables into accurate numerical values, possibly making the interpretation of fuzzy results difficult. It is necessary to ensure that experts have explicit knowledge of the survey questions and that the fuzzy model is appropriately calibrated to limit the effects of these problems.

3.6 Measuring Digitalization Index

Accurately assessing the degree of digitalization requires that uncertainty in experts' assessments of the data management process be given adequate attention when utilizing the fuzzy approach. Since data management processes can be conducted at different degrees of digitalization, the objective of this section is to determine the digitalization index of construction projects. A construction site's data management processes include data acquisition, data entry, data analysis, and reporting. We then attempt to assess the degree to which these processes have been digitalized using the developed fuzzy model. The Degree of Digitalization of a Construction Activity (*DDCA*) is the sum of the four Degrees of Digitalization of the Data Management Processes (*DDDMP*). A project's digitalization index is the sum of *DDCA* as summarized by the following equation (Sezer et al., 2021):

$$\text{Digitalization Index} = \sum_{i=1}^m DDCA_i \quad (4)$$

Where, *m* represents the number of activities in total

3.7 Model Validation

Ensuring the reliability and efficacy of the fuzzy model for evaluating the degree of digitalization in construction activities required a thorough validation process. The proposed model is validated against real projects. The evaluation process involves expert assessment and empirical data analysis. The study consulted professionals with experience and educational background in digitalization and construction through interviews and questionnaires. Their knowledge was essential in assessing the model's criteria and design critically. The model was improved by considering the insightful criticism of respondents, ensuring it now accurately reflected the complexities of actual construction procedures and the ever-changing nature of

digitalization. This cooperative effort strengthened the model's relevance and dependability in determining the degree of digitalization.

Expert assessment plays a pivotal role in validating the fuzzy model, leveraging the insights of seasoned professionals within the construction domain. Subject matter specialists, well-versed in both digitalization trends and industry intricacies, were engaged to evaluate the model's appropriateness and relevance. Their expertise provided a qualitative layer to the validation process, offering valuable perspectives on the model's alignment with real-world scenarios, its ability to capture nuanced construction dynamics, and its practical utility in decision-making contexts.

The collaboration with experts ensured that the fuzzy model was grounded in industry knowledge and reflective of the complexities inherent in construction activities. In-depth analysis of empirical data derived from real-world construction projects. Actual data points related to digitalization levels, project outcomes, and other relevant variables were utilized to validate the model's predictions. Through rigorous empirical testing, the fuzzy model's performance was cross-verified against observed results, allowing for a comprehensive evaluation of its effectiveness in different construction contexts. This data-driven validation not only substantiated the model's reliability but also highlighted its adaptability to diverse scenarios and project characteristics.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter provides and discusses the results of this study, focusing on applying the Mamdani fuzzy logic system to assess the degree of digitalization of construction activities (DDCA) in construction projects. The research methodology comprised surveying experts for data, using 3-point estimates for input data, and employing the defuzzification centroid algorithm. The findings and comparison between expert data and model outputs, as well as the study's implications and insights, are also discussed. The details and results of this research are presented in the subsequent sections.

4.2 Pilot Study Analysis

In this study, the first step is to screen the activities identified from the literature review by conducting a structured interview with subject matter experts. Five participants, representing diverse roles such as consultants, contractors, and subcontractors within the construction industry, are involved in a three-hour workshop. Participants were invited to define and argue which components of construction can be digitalized, which are easy to digitize, and which require staff to be tech-savvy and have access to hardware. The aim is also to eliminate activities that cannot be effectively digitized and incorporate any potentially missing activities.

Experts were chosen based on industry experience, the role they hold in construction for diversity, academic qualifications, and the level of technology adoption in their projects. Individuals with extensive industry experience bring a wealth of firsthand insights into the

complexities of project execution, management, and the digitalization landscape. Diversity is a key factor in the selection process, with experts representing a range of roles within the construction ecosystem, including project managers, technology specialists, construction professionals, and stakeholders. This diverse representation ensures that the digitalization index benefits from a comprehensive assessment, considering the varied viewpoints and requirements of different stakeholders involved in construction projects. Academic and research backgrounds in construction management, digital technologies, or related fields are also crucial criteria for expert selection. This ensures that the chosen experts not only bring practical experience but also possess a solid theoretical foundation, contributing to the development of a well-rounded and robust digitalization index. The outcome of this step is shown in Table 8. One activity related to assessing the productivity of equipment operations has been added. The table lists the potential activities that can be digitalized based on expert opinion and literature.

Table 8: Reduced list of potential activities to digitalize and Categorization of levels of digitalization in construction

Activities
Collect and update project communications and documents
Evaluate the environmental impacts of the project
Review design documents
Improve waste management strategies
Follow-up and management of deviations
Improve the project's energy consumption
Update contract compliance with suppliers and subcontractors
Update drawings, models, and document systems
Visualize pictures and use 3D models on-site
Create a material quantities list

Activities

Carry out inspections, approvals, and certifications
Create and update project deliverables
Punctual replacement of quality materials
Set up sufficient storage space for construction materials
Carrying out different training programs for the employees
Monitoring and controlling the project cost and progress
Follow the staff's presence and human resources reports
Assess the productivity of equipment operations
Monitor safety and mitigate the risk of unforeseen site conditions
Implement problem-solving skills and communication among the workforce
Update time and resource plans
Track the subcontractor's progress and payments
Manage project risks/hazards

4.3 Construction Activities Ranking Analysis

To rank the activities in terms of digitalization, a survey is designed. Targeted participants with experience in various disciplines, such as architects, engineers, and project executives, were invited to rank the construction activities in terms of digitalization. The poll was presented to 30 respondents, and 26 completed the questionnaire, yielding an 87% response rate to participate in the research. In terms of expertise, 30.77% of the participants are managers of projects, 50.00% are engineers, 11.54% have experience in managerial duties, and 7.69% mentioned other responsibilities in the construction business. In the context of years of expertise in construction management and engineering, 61.54% have a minimum of five years, 19.23% possess 5 to 10 years, and the remainder have varied degrees of experience from 11 to more than 20 years. With respect to the experience of respondents in digitalization, the

results show that 48% have a very good experience, 36% have a good experience, 12% have moderate experience, and 4% have poor experience. Regarding educational background, 65.38% of respondents have a bachelor's degree, 30.77% have a post-graduate degree, and 3.85% have elementary school diplomas or comparable qualifications, as shown in Table 9.

Table 9: Respondent's bio result

Variable	Category	N	F	%
Field of experience	High Management	26	3	11.54%
	Project Manager		8	30.77%
	Engineer		13	50.00%
	Other (please specify)		2	7.69%
Years of experience in construction engineering and management	Less than 5	26	16	61.54%
	5 – 10 years		5	19.23%
	11 – 15 years		3	11.54%
	16 – 20 years		1	3.85%
	Over 20 years		1	3.85%
Educational Level	High or lower	26	1	3.85%
	Diploma		0	0.00%
	Bachelor's Degree		17	65.38%
	Post-graduate degree		8	30.77%
	Very poor		0	0.00%
	Poor		1	4.00%
Digitalization Experience	Moderate	25	3	12.00%
	Good		9	36.00%
	Very Good		12	48.00%

The quality and dependability of data acquired from participants are crucial to the achievement of any research undertaking. Within the scope of this research, it is duly recognized that the respondents' educational backgrounds and industry experience have a significant influence on the strength and reliability of our conclusions. Concerning the educational backgrounds of the participants, our survey included individuals with a wide range of academic degrees, such as architecture, engineering, project management, and other experts in the construction industry. The diverse perspectives provided a complete understanding of digitalization in the construction industry, enabling a thorough assessment of how educational experiences influence individuals' inclinations toward digital tools and procedures.

The impact of the experts' experiences on the assessment of digitalization activities is remarkable. Their experience helps assess what can be digitalized and what cannot. They can provide best practices for adopting digitalization, contributing to a successful digital transformation. The respondents' educational backgrounds and industry experience have an impact on the assessment of digitalization in the construction industry. The survey, inclusive of individuals with diverse degrees in architecture, engineering, and project management, sought to capture varied perspectives. Engineering and project management professionals exhibited a preference for digitalization in technical processes, while architects preferred digital design tools. The segmentation facilitated nuanced insights into the influence of education on digitalization priorities. Additionally, the extensive industry experience of respondents, spanning decades and diverse roles, contributed invaluable insights into prevailing digitalization trends. The combination of educational diversity and rich professional

backgrounds enriched the findings, presenting a holistic view of digitalization in the construction sector.

After the crucial information was collected from the questionnaire, a model was developed, which involved identifying the activities to digitize based on the literature review, interviews, and questionnaire responses. Experts' motivations for selecting specific activities included what activities were helpful in digitalization (U), for which activities areas were required to be digitalized in a project (A), what the challenges were for activities digitalization (CH) (such as IT infrastructure and education), what activities were easy to digitalize (E), for which activities digitalization would support project security (S), and for which activities digitalization would support safety enhancement (SE) based on a 5-point Likert scale, where 1 indicates strongly disagree and 5 indicates strongly agree.

Equation 2 calculated each potential activity's capability to digitize construction projects based on the Modified Unified Theory of Acceptance and Use of Technology (UTAUT). The computation established a relationship between dependent variables (intention to use technology) and independent variables (usefulness (U), areas that required digitalization in a project (A), challenges (CH), ease to digitalize (E), project security (S), and safety enhancement (SE).

The core strength once the digitalization of construction is applied and implemented is the ability to follow up and check on the progress of the project, updating the drawings, models, and documents to reflect the progress and the improvements of the project. While maintaining the integrity of the work environment by managing the staff and the reports of the field work,

digitalizing and not focusing on manual paperwork aids in preserving clean energy, thus reducing serious environmental impact and waste.

On the other hand, there are several activities that are considered low-risk. First and foremost, the ability to train fieldworkers, who are the majority of old-fashioned workers, to carry out a new and improved way of performing by being able to monitor the safety and integrity of the quality of work. Another low activity is the ability to monitor the safety of the information and mitigate unexpected and unforeseen site conditions, such as weather changes. Also, the ability to track subcontractor progress and payments, punctual replacement of quality materials, and assess the productivity of equipment operations have limitations in software availability.

Table 10: Results of expert ranking of activities

Activities	U	A	CH	E	S	SE	Total	N	RII	Ranks
Follow-up and management of deviations	21	19	15	16	23	15	109	26	0.699	1
Update drawings, models, and document systems	20	19	10	15	19	16	99	26	0.635	2
Improve the project's energy consumption	19	18	14	15	15	17	98	26	0.628	3
Improve waste management strategies	17	15	11	17	15	21	96	26	0.615	4
Follow the staff's presence and workforce reports	16	17	14	16	18	15	96	26	0.615	5
Collect and update project communications and documents	19	14	13	15	13	21	95	26	0.609	6
Update contract compliance with suppliers and subcontractors	19	19	10	14	17	16	95	26	0.609	7

Activities	U	A	CH	E	S	SE	Total	N	RII	Ranks
Carry out inspections, approvals, and certifications	18	17	13	14	19	14	95	26	0.609	8
Update time and resource plans	15	20	13	17	19	11	95	26	0.609	9
Create a material quantities list	14	16	11	17	17	19	94	26	0.603	10
Implement problem-solving skills and communication among the workforce	15	19	12	13	19	16	94	26	0.603	11
Review design documents	19	20	10	13	15	16	93	26	0.596	12
Monitoring and controlling the project cost and progress	13	19	14	14	18	13	91	26	0.583	13
Manage project risks/hazards	14	16	11	16	17	16	90	26	0.577	14
Evaluate the environmental impacts of the project	18	18	10	14	12	17	89	26	0.571	15
Visualize pictures and use 3D models on-site	17	15	13	12	17	15	89	26	0.571	16
Set up sufficient storage space for construction materials	15	15	10	16	18	14	88	26	0.564	17
Create and update project deliverables	15	15	10	15	20	11	86	26	0.551	18
Monitor safety information and mitigate the risk of unforeseen site conditions	15	13	10	15	17	15	85	26	0.545	19
Track the subcontractor's progress and payments	14	16	11	14	19	10	84	26	0.538	20
Punctual replacement of quality materials	13	14	9	12	15	13	76	26	0.487	21
Carrying out different training programs for the employees	12	14	7	12	17	13	75	26	0.481	22

Activities	U	A	CH	E	S	SE	Total	N	RII	Ranks
Assess the productivity of equipment operations	13	8	13	10	16	11	71	26	0.455	23

4.4 Reliability Analysis

A Cronbach's alpha study was performed to analyze the internal coherence and dependability of the survey data. This analysis assesses the degree to which an assortment of elements (in this case, survey responses) are associated with accurately estimating the fundamental idea (digitalization degree). For each activity, Cronbach's alpha coefficient was calculated for the scores of data acquisition (DA), data entry (DE), data analysis (DN), and data reporting (DR).

A study used something called Cronbach's alpha to check how reliable and consistent survey data about digitalization in construction activities was based on Table 11. They looked at different activities like data acquisition, data entry, data analysis, and data reporting. The scores for these activities were listed in Table 12. Higher scores in this table mean better consistency. The study also mentioned something called variance, which measures how spread out the scores are. The comments in the table give an idea of how reliable each activity is. The total variance for all activities together was calculated. The result showed a high alpha value of 0.896961, meaning the survey questions did a good job reflecting what people think about digitalization in construction.

Table 11: Cronbach's Alpha Analysis

Cronbach's Alpha score	Level of reliability
0.0 – 0.20	Less reliable
>0.20 – 0.40	Rather reliable
>0.40 – 0.60	Quite reliable
>0.60 – 0.80	Reliable
>0.80 – 1.00	Very reliable

The coefficient value was high, with an alpha of 0.896961, suggesting that the replies were internally consistent. The result indicates that the questionnaire questions precisely reflected respondents' thoughts on digitalization throughout construction activities. It is acceptable.

Table 12: Test table for Cronbach's analysis

	Activity 1	Activity 2	Activity 3	Activity 4	Activity 5	TOTAL
DA	6.46	7.04	6.84	7.17	6.43	33.94
DE	5.3	4.35	6.18	5.94	5.83	27.6
DN	5.78	7.14	6.76	7.76	7.32	34.76
DR	6.65	6.44	6.7	7.66	7.24	34.69
variance	0.387825	1.687358	0.089333	0.698492	0.5019	11.91409
Comment	Rather reliable	very reliable	Less reliable	Quite Reliable	Reliable	
sum of individual variances:					3.364908	
alpha:					0.896961	

4.5 Configuration of Fuzzy Model

The main purpose of this research is to develop a fuzzy model for assessing the digitalization of activities identified in the previous section. This section describes the steps for configuring the fuzzy model using the MATLAB software. The model was tested using the subsequent procedures utilize a fuzzy command on the command line to import the requisite FIS (Fuzzy Inference System) file into MATLAB. Subsequently, integrate the file in the manner illustrated in Figure3.

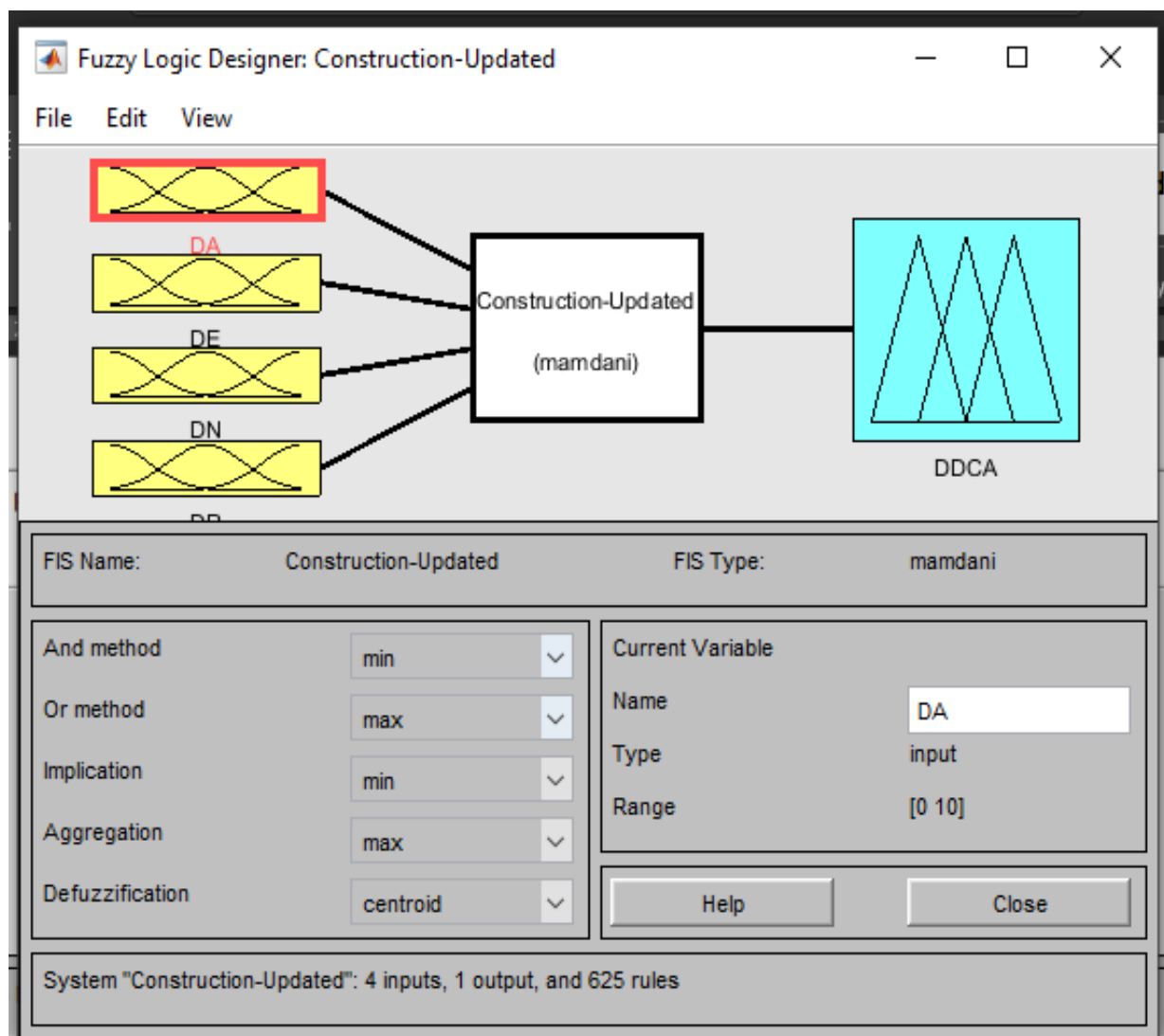


Figure 3: Imported FIS File Displayed in the MATLAB Window

1. Define input variables: The range and name of the input variables are specified in the definition. The range denotes the magnitude by which the inputs are evaluated.
2. Define the output variable: The output variable's name and range are explicitly specified. The range denotes the rating scale by which the output is assessed.
3. Define the Functions of Membership:
4. In addition to defining the number of membership functions, the properties of each function (name, type, and parameter) are also specified.
5. Erratically defined rule base:
6. Based on the input and output variables and their respective membership functions, the rule base is established.
7. Modify the input for the model following the inputted figures to obtain distinct DDCA results.
8. Click the surface icon to generate a plot of the result, which can then be compared to the expert information depicted in Figure 4.

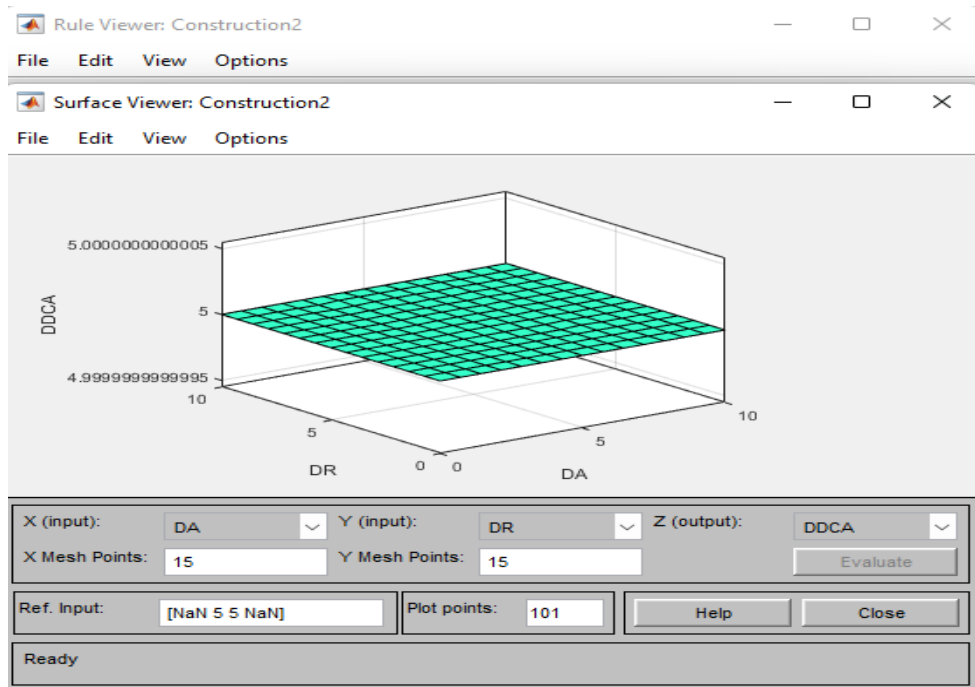


Figure 4: How to plot the input information and the result

4.6 Execution of the Fuzzy Model

The execution of the fuzzy model is detailed below, by providing insights into codes, components, and functionality:

1. An explanation of the system's definition:

- The designation of the system is "Construction."
- The inference can be classified as of the 'Mamdani' type.
- The version number of the system is 2.0.
- NumInputs: Four input variables are declared by the system.
- The system declares a single output variable named NumOutputs.
- The system is comprised of 625 defined fuzzy rules (NumRules).

- The evaluation of principles is conducted utilizing the theming AND operator.
- OrMethod: The thermal OR operator is utilized by the rule evaluation method.
- ImpMethod (i): The implication technique utilized in rule evaluation is denoted by "min."
- The aggregation technique max is implemented to evaluate rules.
- The 'centroid' defuzzification method is utilized for defuzzification.
- Defined Input Variables: The four input variables, symbolized in Figures 5, 6, 7, and 8, are 'DA' (Information Acquisition), 'DE' (Information processing), 'DN' (Information evaluation), and 'DR' (Information reporting).
- Each input variable is assigned a range of 0 to 10.
- Each input variable is accompanied by the type of membership function ('trim' denotes a triangular membership function) and five membership parameters.

Figure 5 contains information obtained from the fuzzy model about the input variable DA that relates to information acquisition in construction activities.

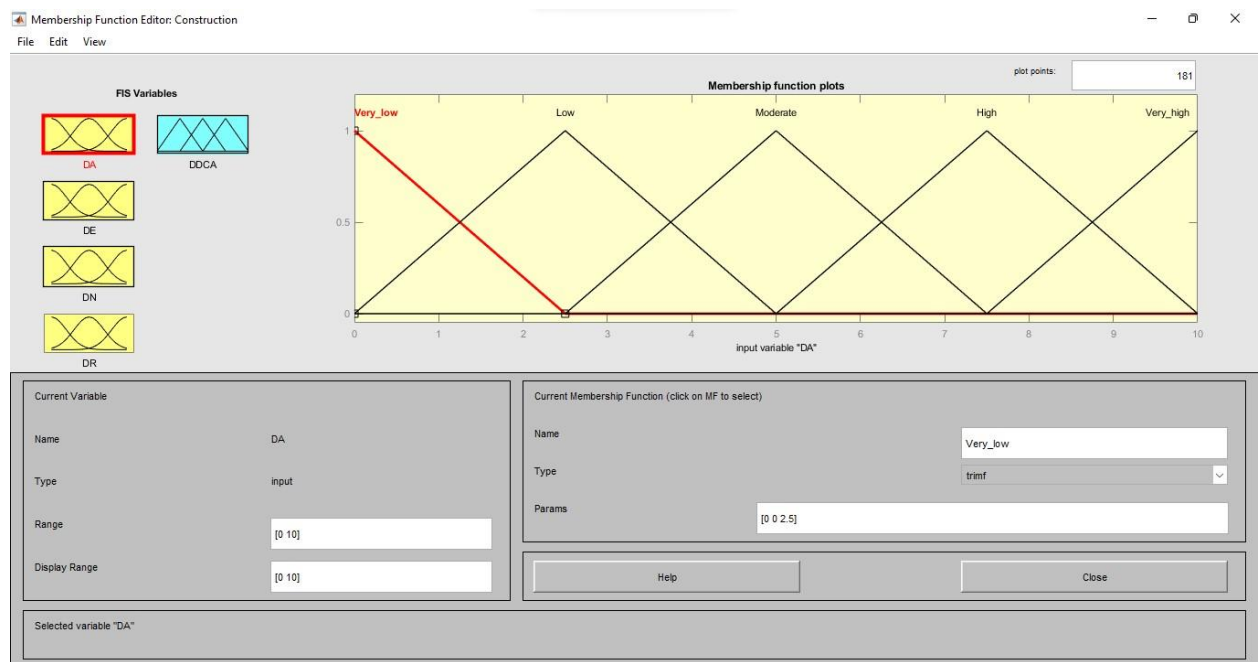


Figure 5: Data Acquisition input

Figure 6 contains information obtained from the fuzzy model about the input variable DE that relates to information processing in construction activities.

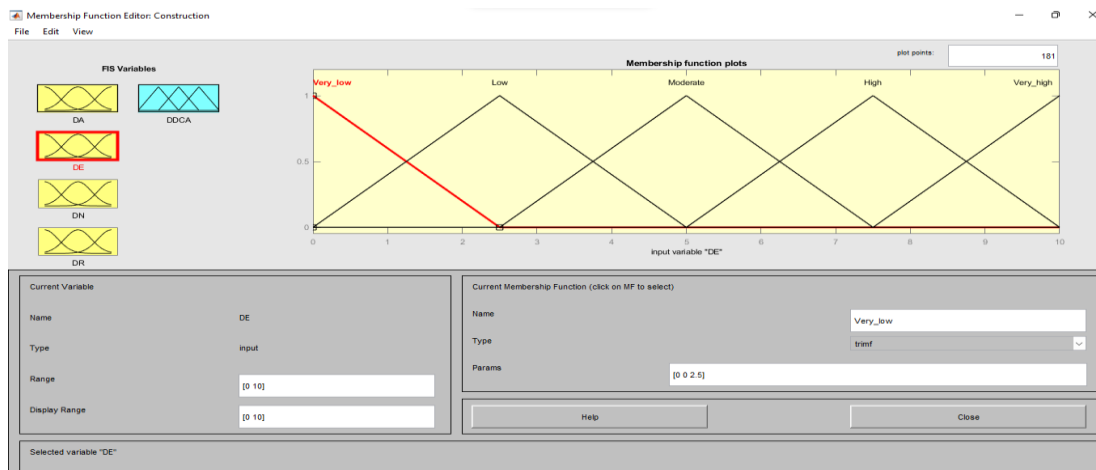


Figure 6: Data entry input

Figure 7 contains information obtained from the fuzzy model about input variable DN that relates to data evaluation in construction activities.

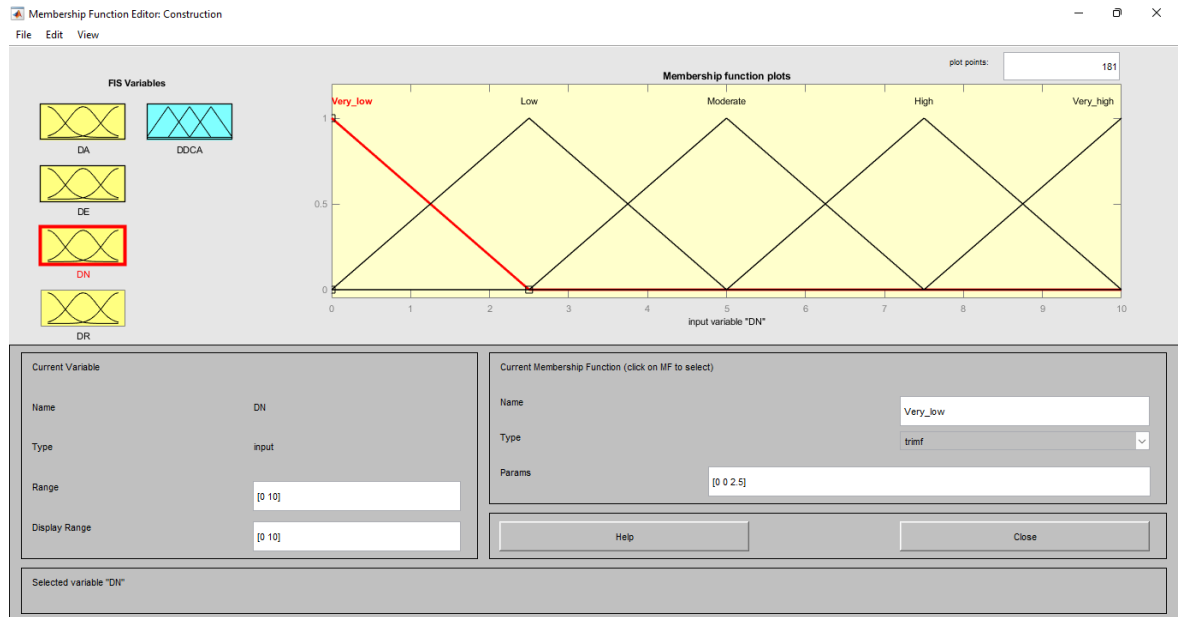


Figure 7: Data analysis input

Figure 8 contains information obtained from the fuzzy model about the input variable DR that relates to information reporting in construction activities.

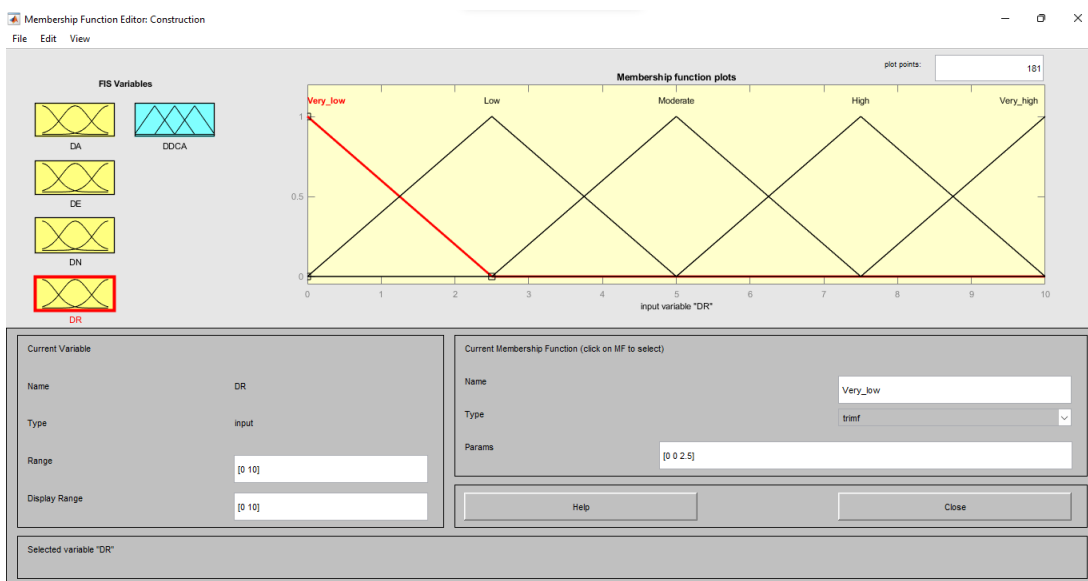


Figure 8: Data reporting input

2. The sole output variable specified in Figure 9 is 'DDCA' (Degree of digitalization of construction activities).

- The range of the output variable is delineated as 0 to 10.
- The output variable contains three membership parameters, each accompanied by its corresponding membership function type ('trim') and parameters.

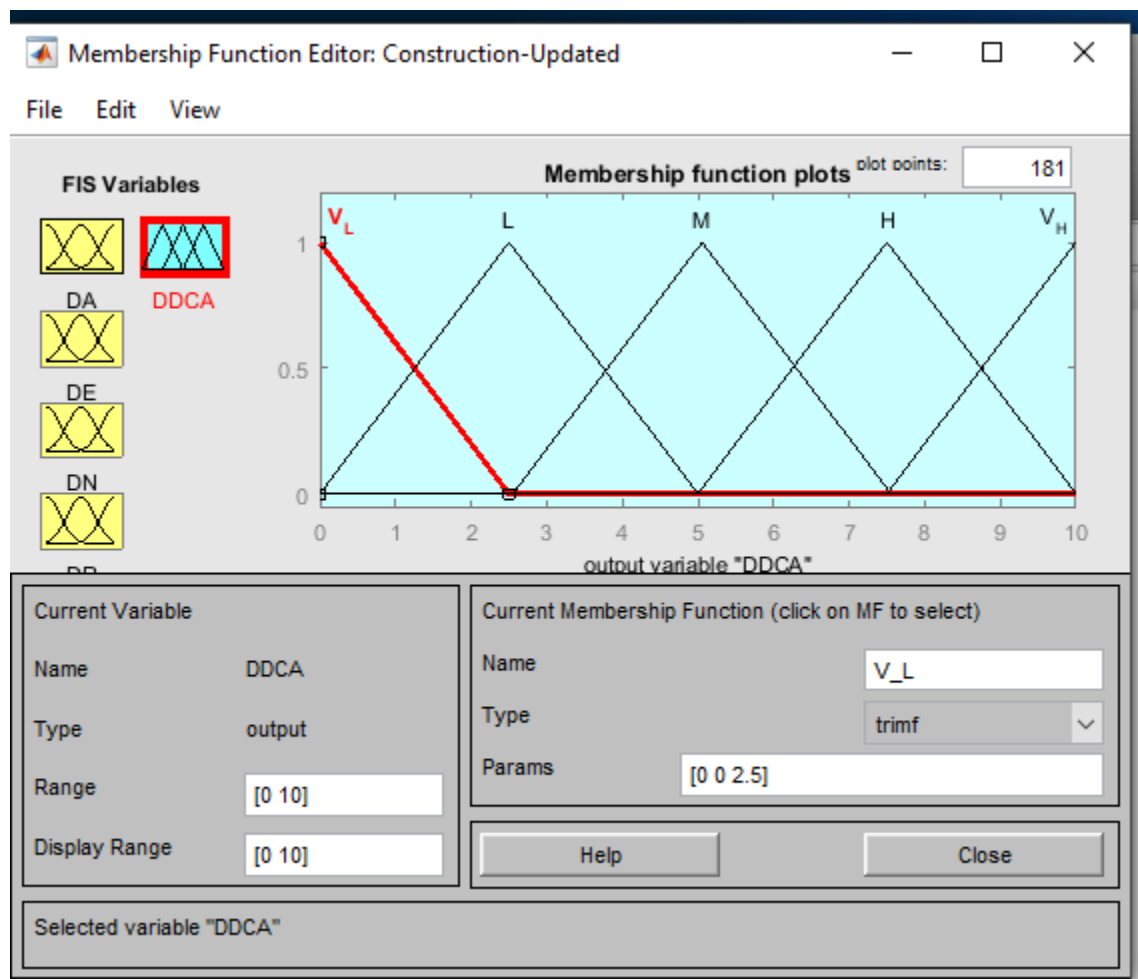


Figure 9: Activity 1 DDCA Output

3. As illustrated in Figure 10, a set of 65 fuzzy rules is devised to define the relationship between the output variable and the input parameters.

Four input values, one output value, and the rule's weight comprise each rule.

"Input1 Input2 Input3 Input4 Output1 (Weight): OutputValue" is the structure of the rules.

The rule of 625 stipulates that the range of values for the four input parameters of the fuzzy model (DA = data acquisition, DE = data entry, DN = data analysis, and DR = data reporting) must be from extremely low to extremely high. This results in 625 rules, each of which represents a unique combination of input levels and membership functions. There are 625 rules in the fuzzy model due to the fact that each of the four input parameters has five membership functions.

As defined by these criteria, a particular output (DDCA—Degree of Digitalization of Construction Activity) is produced in accordance with the exact combination of input levels. To illustrate a simplified rendition of a single rule, the output DDCA is ascertained by the specified consequence (e.g., moderate, denoted as M) when the inputs consist of the following: very low (VL.) DA, low (L) DE, moderate (M), and high (H) DN, as shown in Figure 10.

By considering numerous input combinations and their corresponding fuzzy output levels (VL, L, M, H, and VH), the fuzzy model is capable of conducting a comprehensive evaluation of the extent to which each activity has undergone digitalization. Fuzzy models are utilized to assess the degree of digitalization in construction tasks due to their capability of capturing intricate input-output interactions.

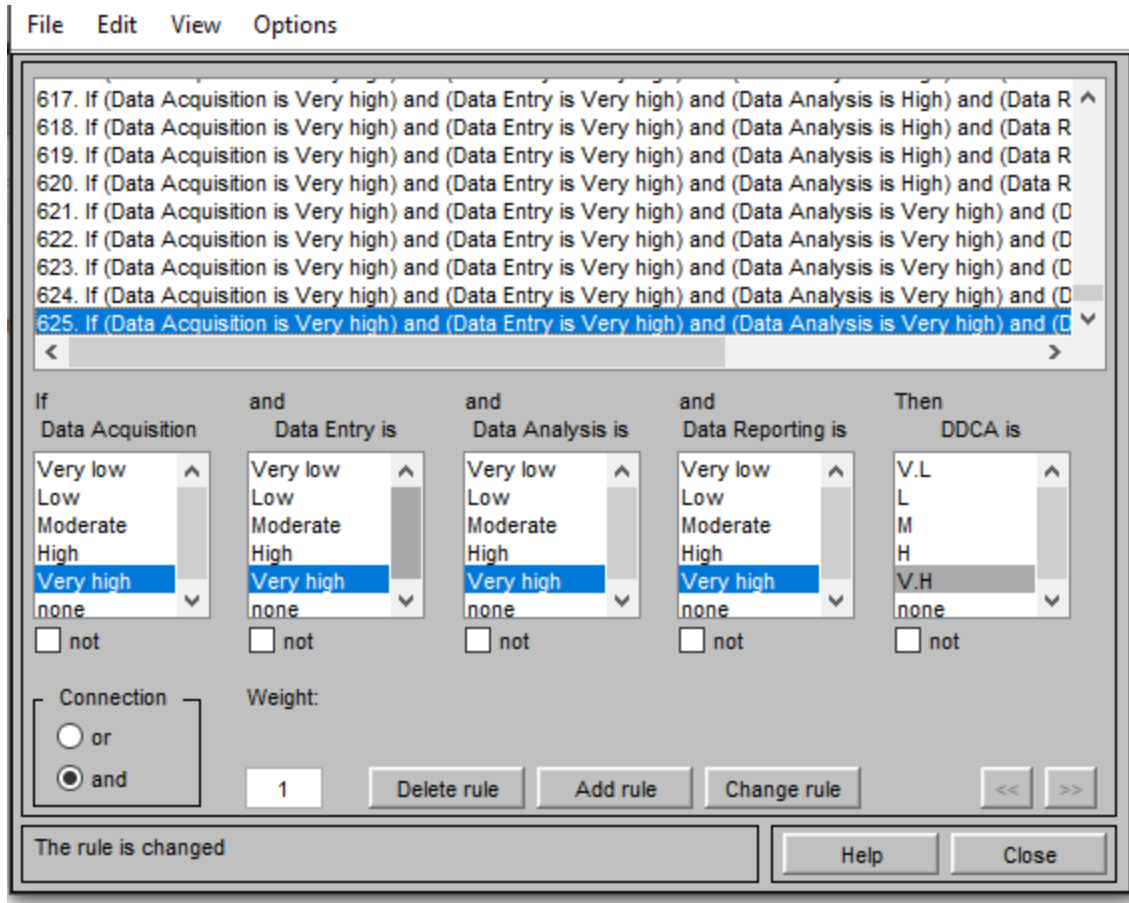


Figure 10: Rule manipulation process

For digitalization, the code implements a fuzzy logic system for the construction industry with four input parameters and one output parameter. The centroid approach is utilized to evaluate rules and de-fuzz output by applying membership parameters, rules, and inference settings to fuzz inputs. The code facilitates design-related decision-making through the utilization of membership parameters and principles.

4.7 The Defuzzification Centroid For 3-Point

The defuzzification centroid for 3-point scenarios plays a pivotal role in converting fuzzy outputs into a precise, crisp value. In this study, the weighted average approach was adopted for defuzzification, a method well-established in the literature for its effectiveness.

Defuzzification is the method of turning fuzzy outputs into a singular or crisp output value. This technique can be carried out using any of the numerous defuzzification approaches. The max or mean-max membership concepts, the centroid approach, and the weighted average method are common defuzzification strategies. This study employed the weighted average approach to output membership functions, as exhibited in Figure 11. In his research, Ahmadian (2001) posits that the weighted average approach determines the crisp output value, y , by adding the sum of each weighting function's (μy) multiplication with the maximum value of its corresponding membership value, y , and dividing it by the total of the weighting functions.

Defuzzified value (Ahmadian, 2001) is given by:

$$(y^*) = \Sigma (\mu y * \hat{y}) / \Sigma \mu y \quad (5)$$

Where, y^* is the crisp output value, μy is the membership function corresponding to the output fuzzy set, $\hat{y}$ is the representative value of the output fuzzy set.

However, appropriate representative values for each output are; Pessimistic Value = 0, Most Likely Value = 5, and Optimistic Value = 10

This approach underscores the significance of weighted contributions in generating the crisp output value, providing a robust and practical methodology for handling uncertainty in 3-point defuzzification scenarios. The calculated Defuzzified values serve as actionable indicators, facilitating informed decision-making in situations characterized by varying degrees of uncertainty.

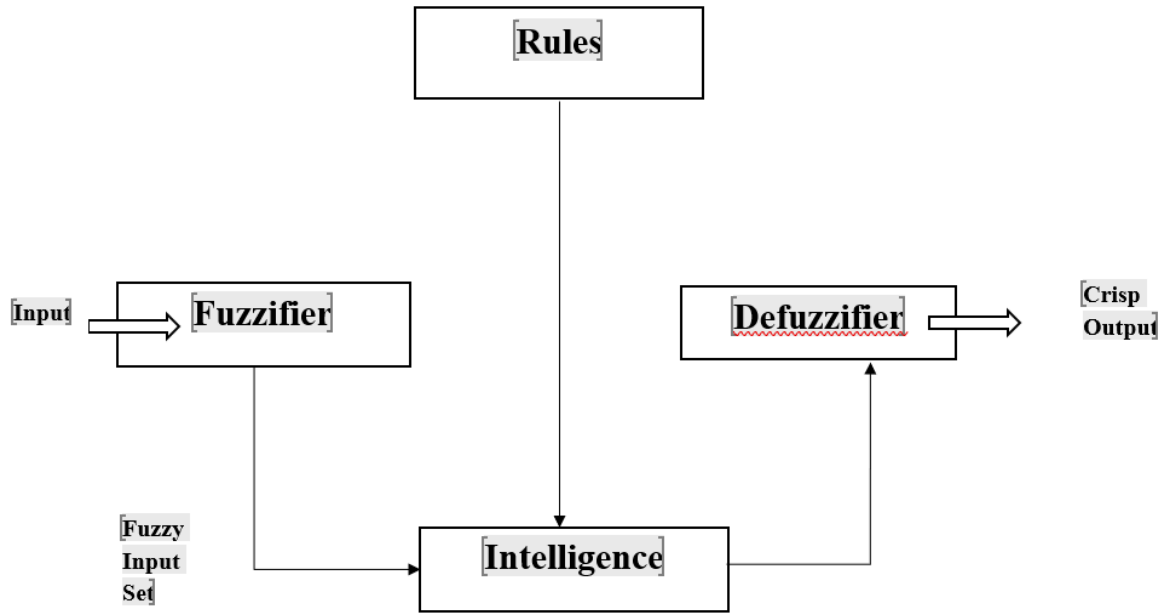


Figure 11: Membership functions work on fuzzy sets of variables

4.8 Levels of Digitalization and DDCA Output for Various Activities

Each activity demands a given level of digitalization in data acquisition, data entry, data analysis, and data reporting. It is therefore wise to break down each activity to find out how each phase varies from the other in terms of digitalization levels. This helps in pinpointing the phases that require more digitalization effort to realize a balanced digitalization. This data is critical for comprehending the present digital environment and pinpointing areas for improvement in construction management activities. The degree of digitalization was assessed using expert data and a fuzzy model, suggesting the fuzzy model's robustness in measuring digitalization levels.

4.8.1 Activity 1: Follow-up and Management of Deviations

Based on expert data, the defuzzified centroid metrics for Activity 1 reveal a high degree of digitalization in data collection and reporting, showing efficient integration of digital instruments. Data analysis suggests significant digital adoption, while data entry shows a balanced approach. These findings illustrate the construction industry's digital transformation progress, emphasizing the importance of data-driven choices and increased efficiency. Regular evaluations of the fuzzy logic model will provide correct assessments and contribute to the sector's continuous digital evolution.

In Activity 1, the defuzzified centroid technique and the MATLAB fuzzy model both produced findings that were quite distinct from one another. The defuzzified centroid technique provided a value of 6.08, while the MATLAB fuzzy model yielded a somewhat lower result at 6.02. The result can be seen below in Figure 12 and Table 13. Although there is a 0.06 percentage point discrepancy between the two techniques, they invariably point to a significant amount of digitalization in the business. This tiny deviation is still well within the bounds of what is considered acceptable, providing more evidence that the fuzzy logic model used for determining the level of digitalization in construction activities is coherent and compelling.

Table 13: Answers provided by the experts for activity 1

Digitalization Level		DDCA Output		
(Expert Data)		(Fuzzy Model)	Expert DDCA	Disparity
DA	6.46	6.02	6.08	0.06
DE	5.3			
DN	5.78			
DR	6.65			

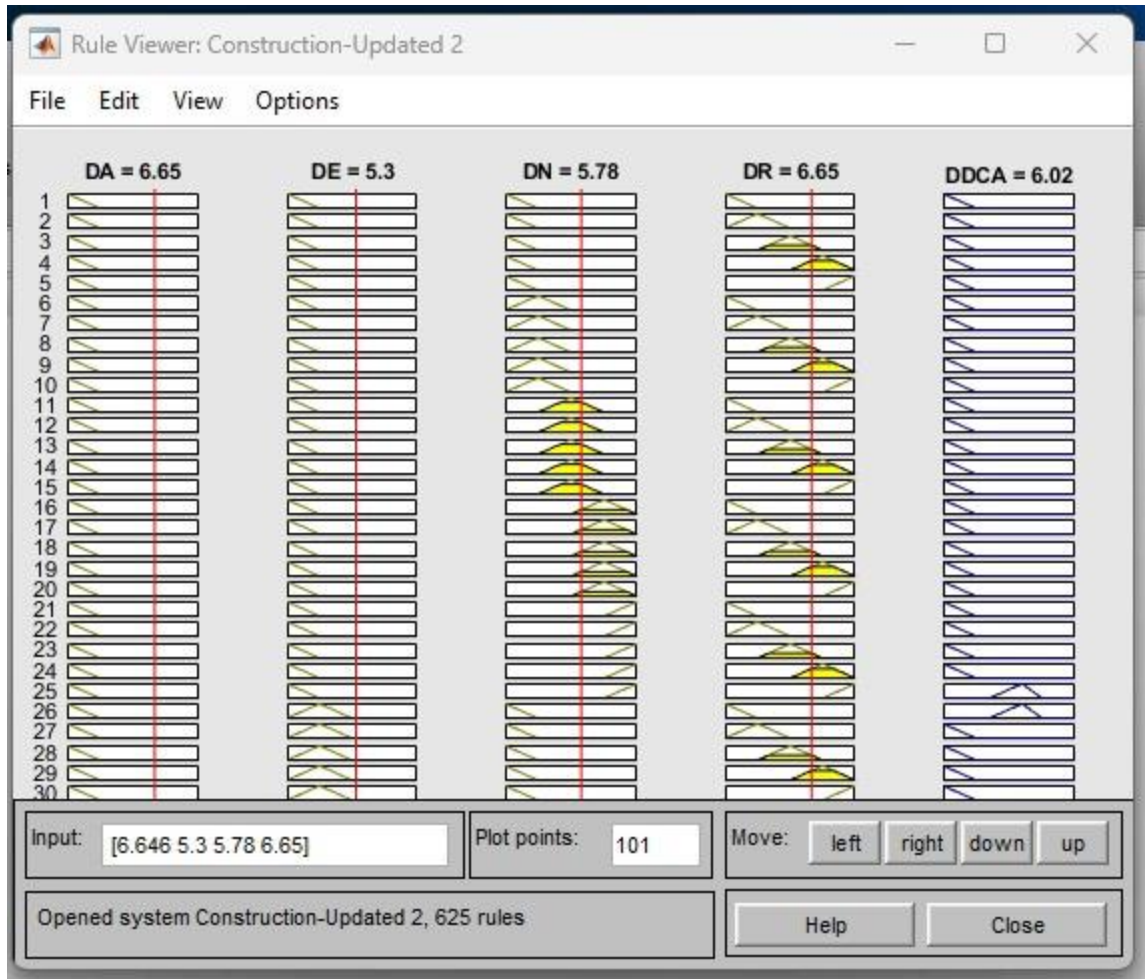


Figure 12: Input-Output Mapping in MATLAB Fuzzy Model for Activity

4.8.2 Activity 2: Update Drawings, Models, and Document Systems

Data Acquisition (DA) has an average score of 7.04, Data Entry (DE) has an average score of 4.35, Data Analysis (DN) has an average score of 7.14, and Data Reporting (DR) has an average score of 6.44 for Activity 2. These results show that Activity 2 has an elevated degree of digital adoption and use in the data acquisition and analysis processes. However, there appears to be potential for development in the data entry element of the digitalization process. Furthermore, data reporting is substantially digitalized, allowing additional digitalization efforts. Addressing the areas for improvement will help Activity 2, which

optimizes construction management processes, achieve a more balanced and thorough digitalization.

The degree of digitalization for Activity 2 was assessed using expert data and a fuzzy model, yielding DDCA values of 6.61 and 6.19, respectively. The marginal discrepancy of 0.42 between the two results indicates a tight agreement, suggesting the fuzzy model's robustness in measuring digitalization levels, as manifested by Figure 13 and Table 14. The synchronization of expert assessments with model outputs improves the general accuracy of the research outcomes. The fuzzy logic technique helps capture the intricacies of digitalization in construction processes, allowing for a measurable measure of digital adoption. As a result, the combination of expert knowledge and the fuzzy model provides a thorough grasp of the degree of digitalization in Activity 2.

Table 14: Answers provided by the experts for activity 2

Digitalization Level		DDCA Output		
(Expert Data)		(Fuzzy Model)	Expert DDCA	Disparity
DA	7.04	6.19	6.61	0.42
DE	4.35			
DN	7.14			
DR	6.44			

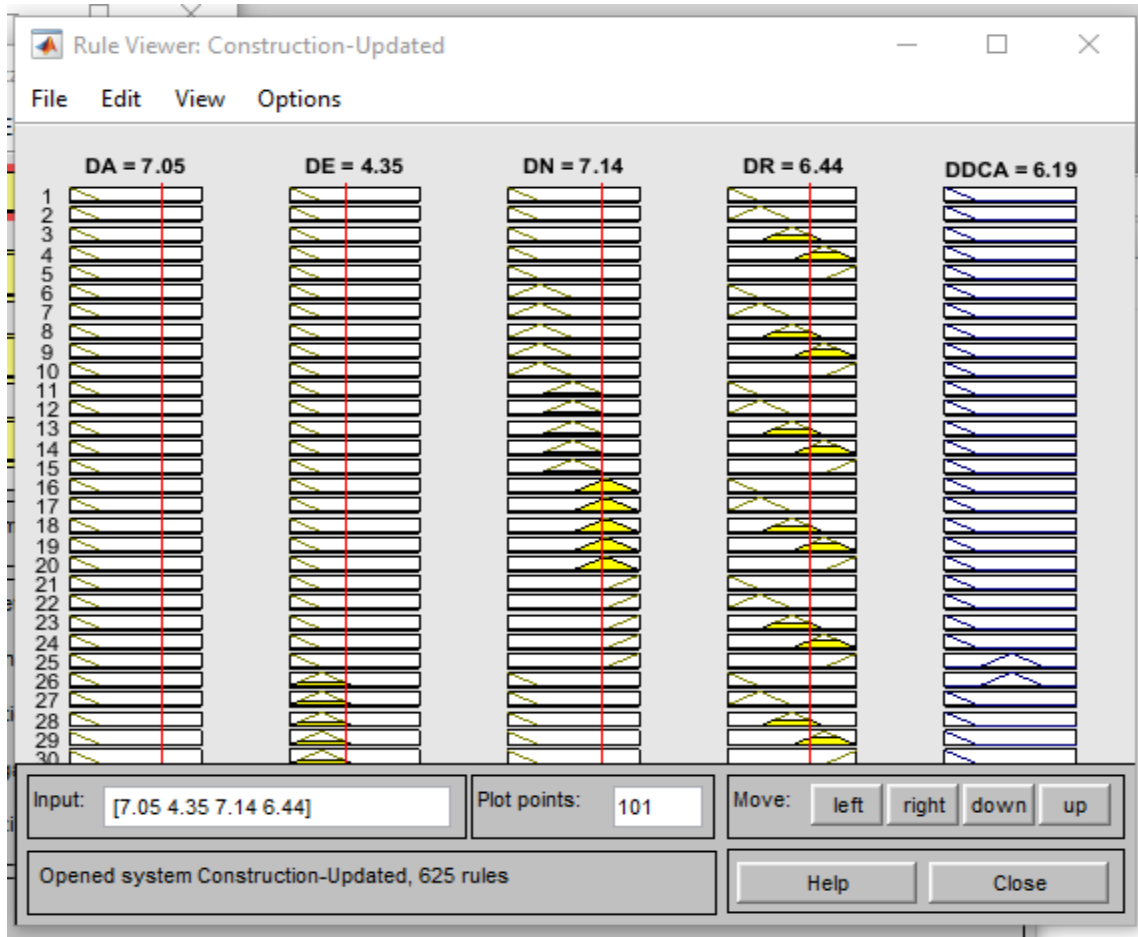


Figure 13: Input-Output Mapping in MATLAB Fuzzy Model for Activity 2

4.8.3 Activity 3: Improve the Project's Energy Consumption

Based on expert data, the defuzzified centroid for Activity 3 yields the following estimated parameters: DA = 6.84, DE = 6.18, DN = 6.76, and DR = 6.70. Each category that was scored indicates a high level of digitalization across all elements of data management, implying that digital tools and procedures are deeply embedded in the data collection, entry, analysis, and reporting operations. The generally balanced results across the four characteristics in Activity 3 indicate a holistic adoption of digital processes, indicating a mature level of digitalization. These findings illustrate the construction industry's progressive nature,

embracing technology to streamline data-related jobs and improve general effectiveness and decision-making procedures.

The expert-based defuzzified centroid technique generated a score of 6.90, whereas the fuzzy model data for DDCA output from Activity 3 yielded a value of 7.01. In line with our earlier assessments, these data highlight the activity's high level of digitalization. It is still clear that the fuzzy logic model and the expert-based method of evaluating the stages of digitalization are closely aligned. Both methods consistently show that Activity 3's construction activities substantially use digital tools and procedures. Figure 14 and Table 15 illustrate how closely the fuzzy model's output matches the expert data, supporting the model's cautious estimate. These results demonstrate the accuracy of our evaluation techniques and provide crucial information on Activity 3's digitalization environment in the construction industry.

Table 15: Answers provided by the experts for activity 3

Digitalization Level		DDCA Output		
(Expert Data)		(Fuzzy Model)	Expert DDCA	Disparity
DA	6.84			
DE	6.18			
DN	6.76			
DR	6.70	7.01	6.90	0.11



Figure 14: MATLAB Fuzzy model activity three inputs and outputs

4.8.4 Activity 4: Improve Waste Management Strategies

Based on expert data, the defuzzified centroid for Activity 4 gives intriguing insights regarding the degree of digitalization in various aspects. Data acquisition (DA) has a comparatively high rating of 7.17, indicating that digital tools were heavily integrated during this phase. Data entry (DE) comes in second with a score of 5.94, showing an average degree of digitalization in data entry procedures. Data Analysis (DN) has a rating of 7.76, showing widespread use of digital data analysis technologies. Finally, data reporting (DR) scores a high of 7.66, indicating that digital reporting techniques have been prevalent in this activity. The

constant high ratings across the four characteristics indicate that Activity 4 was well-digitized. This data is critical for comprehending the present digital environment and pinpointing areas for improvement in construction management activities.

The study meticulously compared the defuzzified centroid outputs for Activity 4, utilizing expert data (6.94) and the fuzzy model's analysis (6.61), as shown in Table 16 and Figure 15. The slight difference of 0.33 between these two findings indicates that the fuzzy model, as opposed to the expert-derived data, is more optimistic about the level of digitalization within this activity. This surprising variation does not lessen the main finding, which is that Activity 4 has a high level of digitalization, consistent with the general trend of digital integration in the construction industry.

Table 16: Answers provided by the experts for activity 4

Digitalization Level (Expert Data)		DDCA Output (Fuzzy Model)		
			Expert DDCA	Disparity
DA	7.17			
DE	5.94			
DN	7.76			
DR	7.66	6.61	6.94	0.33

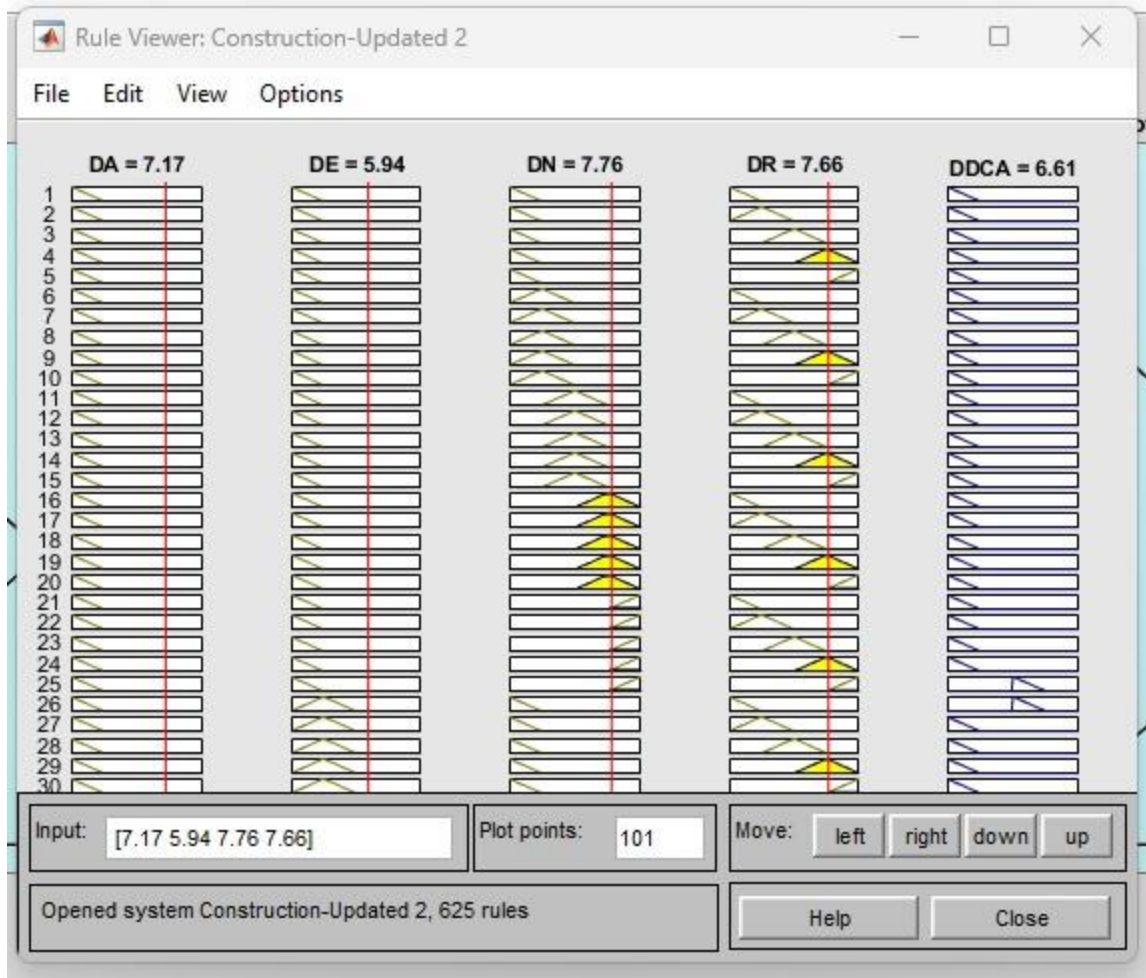


Figure 15: MATLAB Fuzzy model activity four inputs and outputs

4.8.5 Activity 5: Follow the Staff's Presence and Workforce Reports

Based on expert data, the defuzzified centroid for Activity 5 was DA = 6.43, DE = 5.83, DN = 7.32, and DR = 7.24. These findings suggest a reasonably high level of digitalization in the data collection (DA) and data entry (DE) elements, with scores above 5 indicating a leaning toward an elevated level of digitalization. Furthermore, the data analysis (DN) and data reporting (DR) elements received even better marks, indicating a significant integration of digital tools in these operations. These findings highlight the widespread use of digital technology and approach in Activity 5, which improves productivity based on data decision-

making procedures. The study also demonstrates the use of the fuzzy logic technique in determining and assessing the degree of digitalization in different construction operations, offering helpful information for the sector's digital revolution.

A detailed examination of Activity 5's DDCA output indicated a significant variance between the expert-derived data, which provided a DDCA of 6.29, and the results obtained by the fuzzy model, which indicated a higher DDCA output of 6.57, as shown in Figure 16 and Table 17. This significant variation of 0.28 points highlights the complex nature of digitalization assessment within this specific industry. It encourages a more in-depth investigation of the underlying variables causing this disparity, such as the intricacies of data-gathering methodologies and the complexity of digitalization assessment in construction.

Table 17: Answers provided by the experts for activity 5

Digitalization Level (Expert Data)		DDCA Output (Fuzzy Model)	Expert DDCA	Disparity
DA	6.43			
DE	5.83			
DN	7.32			
DR	7.24	6.57	6.29	0.28

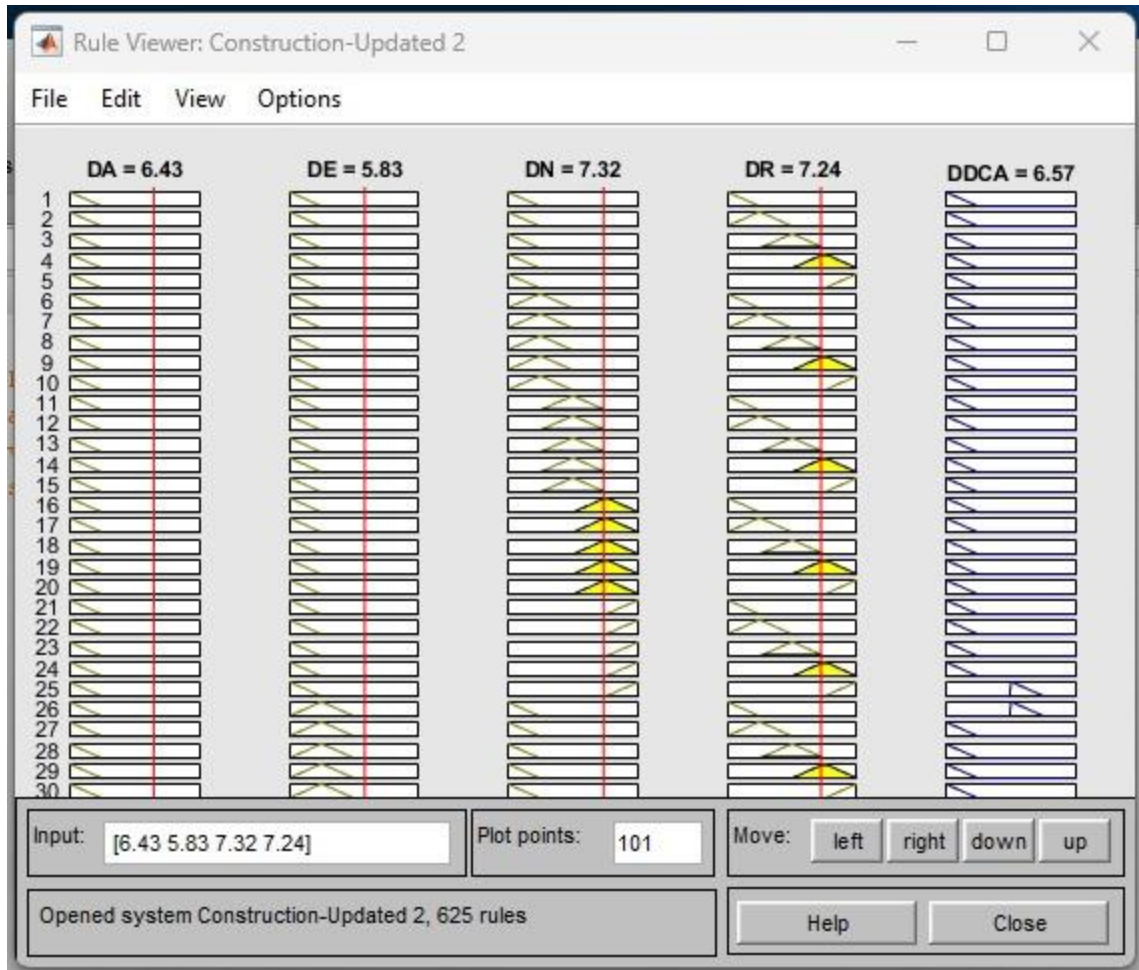


Figure 16: MATLAB Fuzzy model activity four inputs and outputs

4.9 Model Outputs and Expert Data Comparison

4.9.1 Comprehension of Fuzzy Logic

The study employs fuzzy logic, a mathematical structure capable of dealing with ambiguous and imprecise knowledge, to analyze the degree of digitalization in construction management activities. Fuzzy logic is appropriate for situations in which classic binary logic fails to convey the intricacies of real life. Membership functions define the degree to which each component belongs to a set and are at the foundation of fuzzy logic. These utilities make it easier to interpret imprecise or confusing data. A fuzzy inference framework, an approach to

reasoning that translates the input parameters to output parameters, is employed in the model's development. The system comprises rules written in fuzzy logic expressions that allow output value deductions due to input parameters.

The Mamdani model, a form of fuzzy inference framework, is critical in this study. It uses linguistic parameters and rules for if-then to derive inferences about the output parameter based on the input variables. Membership functions, vital elements of fuzzy logic, grant degrees of membership to set items. Depending on the task's requirements, these functions might assume numerous forms, such as triangle-shaped, trapezoidal, Gaussian, or sigmoidal. Properly selecting the membership functions ensures the model's efficiency in assessing the degree of digitalization in construction.

4.9.2 Model Design Decision

Fuzzy logic, characterized by its capacity to handle the complexities of real-world settings, extends traditional binary logic by offering measures of truth and untruth along a continuum. We use the Mamdani fuzzy inference system in this work, which is a powerful tool for obtaining conclusions about the degree of digitalization based on input parameters (data acquisition, data entry, analysis, and reporting). This method enables the development of a more dynamic model to describe the amount of digitalization in construction management activities, incorporating nuances that binary logic may ignore. The study employs a classification technique in our model that adds clarity and simplicity to our survey results. This classification system has four levels, each denoting the degree of digitalization within construction management activities.

The "manual" level represents tasks with low digital integration, mainly relying on traditional, non-digital methods. "Manual to Moderate" activities are found slightly further along the digital spectrum. These include some digital integration but rely mainly on manual methods. We meet "moderate to high" tasks as we progress up the digitalization ladder. These operations demonstrate a high level of digitalization, indicating a significant shift toward sophisticated digital integration. Finally, we arrive at the "high" category, designated for activities that ultimately embrace digitalization, with advanced digital instruments and procedures deeply embedded in their operations.

4.9.3 Results Summary

Activity 1 exemplifies the rapid digitalization of the construction industry. The comprehensive assessment ranks it in the High Digitalization Category, demonstrating a deep integration of digital tools and processes. Data collection (DA=6.46) and reporting (DR=6.65), in particular, are excellent instances of this digital revolution, demonstrating a high level of digitalization. Furthermore, data analysis (DN=5.78) supports this trend, indicating widespread digital usage. Meanwhile, data entry (DE=5.3) finds a sensible compromise between manual and digital approaches. These findings highlight the construction industry's constant pursuit of digital transformation. They stress the importance of data-driven choices and increased operational efficiency. Notably, the defuzzified centroid approach (6.08) and the MATLAB fuzzy model (6.02) converge consistently.

Activity 2 falls into the Moderate to High Digitalization Category, suggesting a significant level of digital integration. Data acquisition (DA=7.04) and data analysis (DN=7.14) show a high level of digital adoption and vital digitalization. However, data input (DE=4.35) indicates room for progress, and data reporting (DR=6.44) shows significant

digitalization with places for improvement. The fuzzy model yields a DDCA value of 6.19, underscoring the difficulty of accurately quantifying digitalization. These findings provide actionable insights for tailored digitalization plans in the construction industry, intending to increase efficiency and competitiveness.

As indicated by expert data, Activity 3 displays a high level of digitalization across all facets of data management. The defuzzified centroid metrics, which include DA=6.84, DE=6.18, DN=6.76, and DR=6.70, show high incorporation of digital tools throughout data collection, entry, analysis, and reporting. This equitable performance across the four classifications reflects Activity 3's mature and holistic embrace of digital processes. These findings highlight the construction industry's forward-thinking attitude to utilizing technology to improve efficiency and decision-making. The expert-based defuzzified centroid score of 6.90 corresponds to the fuzzy model's DDCA result of 7.01, confirming the activity's high level of digitalization. Table 18 depicts the fuzzy model's close alignment with expert data, demonstrating the model's correctness. Activity 4 is highly computerized, with expert data giving surprising insights. The significant integration of digital technologies during data acquisition (DA) results in a high grade of 7.17. Data entry (DE) has an average degree of digitalization, with a score of 5.94. Additionally, data analysis (DN) is a widespread use of digital technology, with a grade of 7.76. Digital reporting techniques are also standard in data reporting (DR), with a high score of 7.66. These constant high ratings across all four qualities demonstrate that Activity 4 has been well-digitized. When the expert-derived defuzzified centroid score of 6.94 is compared to the fuzzy model's analytical score of 6.61, the difference of 0.33 highlights the high level of digitalization within this activity. Table 18 displays this alignment visually, illustrating the industry's tendency toward digital integration.

As evidenced by expert data with variables DA=6.43 and DE=5.83, Activity 5 demonstrates a reasonably high level of digitalization, notably in data collecting (DA) and data entry (DE) elements. Furthermore, with ratings of 7.32 and 7.24, respectively, data analysis (DN) and data reporting (DR) demonstrate even deeper digital integration. These findings highlight the broad usage of digital technologies and methodologies in Activity 5, which aims to boost productivity through data-driven decision-making. However, as shown in Table 18, a considerable difference of 0.28 points exists between the expert-derived DDCA of 6.29 and the fuzzy model's output of 6.57, highlighting the complexity of digitalization evaluation in this business. This discrepancy necessitates more inquiry into the underlying elements influencing assessment precision, such as data collection procedures and digitalization complexity.

Table 18: Summary of Digitalization Levels and DDCA Output Disparities for Different Activities

Activity	Digitalization Level	DDCA Output		
	(Expert Data)	(Fuzzy Model)	Expert DDCA	Disparity
Activity 1	DA=6.46, DE=5.3, DN=5.78, DR=6.65	6.02	6.08	0.06
Activity 2	DA=7.04, DE=4.35, DN=7.14, DR=6.44	6.19	6.61	0.42
Activity 3	DA=6.84, DE=6.18, DN=6.76, DR=6.70	7.01	6.90	0.11
Activity 4	DA=7.17, DE=5.94, DN=7.76, DR=7.66	6.61	6.94	0.33
Activity 5	DA=6.43, DE=5.83, DN=7.32, DR=7.24	6.57	6.29	0.28

4.9.4 Verification of the Degree of Digitalization of Construction Activities

Using information from a construction and rehabilitation project at Ras Tanura, Saudi Arabia. The project team consists of a project manager, engineers, and IT specialists with experience ranging from 5 to 15 years. A case study will be undertaken to demonstrate how the digitalization evaluation model is applied. In the case study, the level of digitalization in a construction project will be evaluated, and areas where digitalization can be strengthened will be identified. Figure 17 shows the method that is implemented to calculate the project digitalization index.

A comprehensive verification approach (expert answers and MATLAB fuzzy model results were compared) was carried out to thoroughly test the precision of the DDCA computed by the model. This procedure included several phases to validate the model's accuracy in assessing the degree of digitalization of construction activities per the methodology. The Matlab fuzzy model proved to be an effective instrument for precise digitalization assessment. This model was used to methodically compute the DDCA levels for each activity based on insights from expert-provided ratings. This crucial step verified that the DDCA ratings were theoretical and firmly based on expert data, boosting the trustworthiness of the research results.

Digitalization tools play a crucial role in various aspects of project management and improvement initiatives. The tools mentioned are categorized based on their functions in different phases of digitalization, including data acquisition, data entry, data analysis, and data reporting. Autonomous project updates, 3D laser scanning, and drones Enable high-precision data acquisition from physical sites, providing accurate representations for project planning and execution, and aiding in project updates and monitoring. 5D modeling, augmented reality, descriptive and diagnostic analysis, and predictive Analytics Tools Utilize tools like BIM

software, smart sensors, and IoT for digital data entry, analysis, and forecasting to enhance efficiency and accuracy, which enables real-time contributions and updates to construction project activities by team members, fostering collaboration. Dashboard and Visualization Tools generate automated reports on project updates, providing for real-time reporting of construction activities, which facilitates informed decision-making.

These digitalization tools collectively contribute to streamlining project processes, improving accuracy, enhancing collaboration, and optimizing resource usage at the project level. However, the digitalization score has low values across different aspects, indicating areas for further improvement in the digital transformation journey in this construction project.

Typically, expert answers and MATLAB fuzzy model results were compared. Activity 1 matched with follow-up and deviation management: This activity rigorously monitored deviations from scheduled project operations. Expert assessments revealed a moderate level of digitalization in data acquisition (DA = 55%) and a low level in data entry (DE = 30%). Additionally, almost moderate digital adoption was observed in data analysis (DN = 45%), and the data reporting process (DR = 60%) demonstrated above-average digitalization. Activity 2 entailed the modification of drawings, models, and document systems. Experts evaluated the critical activity of upgrading project drawings, models, and documenting systems.

This study revealed moderate digitalization throughout every parameter: data acquisition (35%), data entry (25%), data analysis (40%), and data reporting (30%). Additionally, Activity 3 signified an improvement in the project's energy consumption. The focus of this activity on improving energy consumption efficiency resulted in low digitalization scores in data acquisition (DA = 33%) and data entry (DE = 35%). Furthermore, data analysis

(DN = 40%) revealed almost average adoption, while data reporting (DR = 35%) demonstrated low digitalization. Subsequently, improvement of waste management techniques was denoted by Activity 4. Experts emphasized strong digital adoption in data acquisition (DA = 37%) to improve waste management techniques.

Data entry (DE = 30%) progressively showed low digitalization, while data analysis (DN = 50%) showed moderate. Simultaneously, data reporting (DR = 45%) demonstrated almost average digitalization. Activity 5 entailed the presence of staff and the workforce report. This activity focused on monitoring personnel presence and compiling workforce reports. Experts observed inconsiderable digitalization in data acquisition (DA = 36%), indicating an abundance of manual aspects (DE = 25%), above-average digital adoption in data analysis (DN = 55%), and moderate digitalization in data reporting (DR = 50%).

After aggregating the DDCA scores for each activity using the Matlab fuzzy model, the resulting total produced the Digitalization Index (DI) value for the construction project. In this case, the DI of 14.2 was calculated by adding the various DDCA scores. This index number represents the total degree of digitalization of the project across multiple data management components. It encapsulates the degree to which technology and digital tools have been incorporated into project processes, offering a clear numerical indicator of the project's digital transformation. The following scaling of the DI added another level of clarity, putting the value into a specified range for easier comparison and interpretation. The DI scaling to improve its interpretability utilized the formula: $(DI / 50) * 100$. This scaling method not only standardized the DI to a range of 0 to 100, but it also gave a logical categorization of the project's level of digitalization. As a result, the scaled DI of 28.4% revealed a low level of digitalization within the construction management procedure due to limited utilization of digitalization tools. This

scaled value enabled a clear and logical evaluation of the project's level of digital adoption, allowing for a more relevant comparison and comprehension of its digitalization path.

A critical verification phase emerged two days after the initial assessment, with a follow-up interview with three industry experts. The goal was to examine the estimated Digitalization Index (DI) and confirm its alignment with established categorizations, confirming the model's correctness. The qualitative insights of the experts were compared to the DI, which was scaled adequately to interpretative ranges (manual to moderate). This comparison confirmed that the model appropriately embraced the project's level of digitalization. The approach demonstrated the index's dependability and the model's ability to reflect real-world digitalization circumstances.

Five activities with critical input have been assessed for their incorporation of digital technologies. Urban residential development projects, like those in Riyadh, are the focus of this brief overview. For example, Activity 1 demonstrated this by utilizing drones and IoT devices to gather real-time data for monitoring construction progress and resource management. This approach resulted in a DDCA score of 2.79 for the technology input, indicating its robustness. The application enables aerial monitoring and surveying, resulting in high-resolution imagery and 3D mapping information. In real time, IOT sensors were used to monitor equipment, materials, and labor, resulting in improved logistics and resource distribution. The second type of activity revolves around information processing. Sophisticated software was used to update project plans in real-time based on the collected data. This approach achieved 3.38 DDCA, indicating a high level of digitalization. The digital platform used amalgamated data from various sources to facilitate scheduling optimization and clash detection, allowing for easy communication of plan amendments among stakeholders.

Activity 3 forecasted potential future bottlenecks, delays, and resource shortages, but it received a low ranking of 0.902 in the DDCA due to its early adoption of innovation. By looking at past project data and current site conditions, predictive models figure out how defenses will stop likely weaknesses. This is done by predicting the risks that these predictive supplies are based on. Activity 4 used dashboards to communicate with stakeholders about the project's information, resulting in a 0.902 DDCA. These visual analytics tools would present progress updates and insights in a very lucid way, thus allowing the project to obtain key performance indices. Activity 5 was characterized by comprehensive digital tools for overall project management and execution, giving it an advantage in achieving 2.79 DDCA in the project. Digital collaboration platforms, mobile apps for field teams, and integrated software suites for schedule, cost control, and quality assurance are all within its scope. Using Matlab's fuzzy model to add up the scores for the DDCA activities, we obtained a total score of 10.8. This created a Digitalization Index (DI) for the project, which helped experts figure out the qualitative ranking of digitalization levels from manual to moderate.

Activity 1 covered the best use of drones and IoT devices in data collection and resource management for the Riyadh Commercial Infrastructure Upgrade project, achieving a high DDCA score of 5.43 points. Drones worked on inspection and site survey, while IOT sensors followed up on material, equipment, and worker location. Activity 2, on the other hand, utilized machine learning algorithms to transfer information and update the project plan. It achieved a total of 5.02 DDCA. The AI models analyzed data flows, identified patterns, and identified dependencies. As a result, an efficiency modification plan is recommended. Activities 3 and 4 were concerned with the evaluation of information and equally reporting, although they got a bit lower DDCA scores of 4.0, indicating that there still needs to be some

form of digitalization. Activity 5 provided a summary of the digital tools needed for easy overall management, resulting in a DDCA score of 5.43 through the use of integrated platforms for communication, documentation, and decision support. In this exercise, the digitization index totaled 23.9. Qualitative experts plotted Matlab's fuzzy model and found that it falls within the digitalization range of moderate to high.

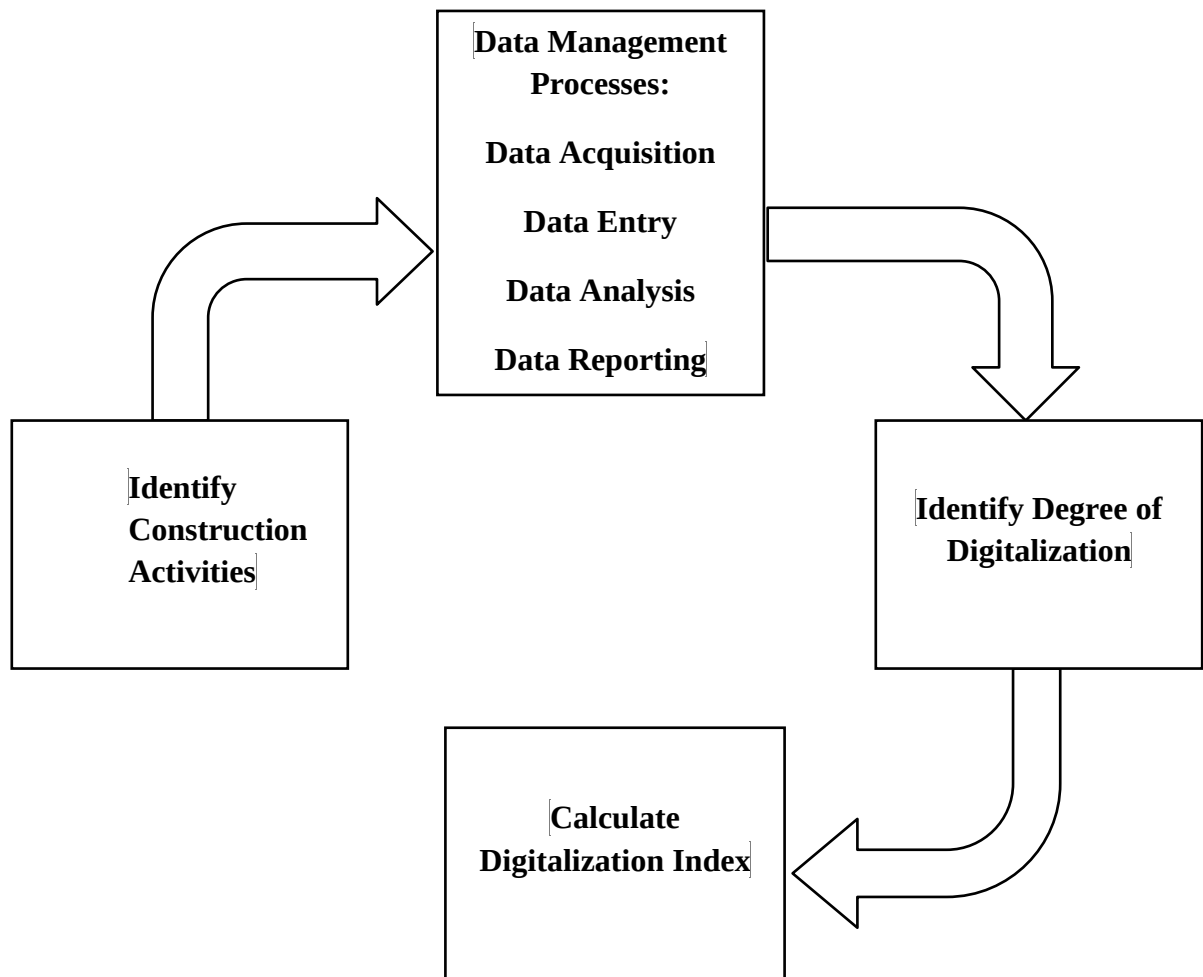


Figure 17: Model to evaluate the level of digitalization in construction projects

4.10 Summary of the Research

The construction sector is undergoing tremendous change as a result of the fast integration of digital technologies and techniques. The objectives of this study were to identify potential activities that can be digitalized, rank the identified construction activities based on six measures that determine the acceptance of technology in construction projects, and develop a fuzzy model to evaluate the degree of digitalization in construction, considering uncertainties in expert judgments in Saudi Arabia. This study provided a thorough assessment of the levels of digitalization in various construction activities, employing a Mamdani fuzzy logic framework to calculate the Degree of Digitalization of Construction Activities (DDCA). This study shed light on the extent to which digitalization has entered the construction sector by evaluating four main data management facets, namely data acquisition (DA), data entry (DE), data analysis (DN), and data reporting (DR).

The six measures for determining acceptance of technology were derived from UTAUT, a theory developed by Venkatesh et al. The study developed a fuzzy model that was used to determine the degree of digitalization in construction activities. The fuzzy model was developed to address uncertainties in the construction industry. A comprehensive literature review was done to identify digitalization efforts in Saudi Arabia and determine activities that can be digitalized in the construction industry. Expert interviews were conducted, and questionnaires were filled out to rank construction activities based on their ability to be digitalized. The fuzzy model was leveraged to calculate the level of digitalization. Expert opinion ranks were compared to the outputs of the fuzzy model to validate the model. The limitations of the study included the sample size of 26 experts and the focus on one location, limiting the generalizability of the research findings.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The findings of this study indicate notable variations in the ranks of activities, as determined by the digitalization index, which incorporates factors such as usefulness (U), areas requiring digitalization in a project (A), challenges (CH), ease of digitalization (E), security (S), and safety enhancement (SE). The ranks of the top five activities were elevated due to their exceptional performance in crucial digitalization parameters, as shown in Table 10. On the contrary, activities that are scored lower have deficiencies in specific areas of digitalization. The comparatively lower scores seen in domains such as ease of use and favorable circumstances underscore potential obstacles or constraints that may arise while implementing digital solutions. These operations may not effectively leverage digital tools, leading to diminished rankings. The significant disparity in rankings highlights the crucial significance of digitalization within the construction industry. The activities that demonstrate superior performance highlight the advantages of a robust implementation of digitalization, including enhanced efficiency and competitiveness. Essentially, activities that are ranked lower may require further support or modifications to improve their efforts in digitalization.

This study shows a broad digitalization environment within the construction industry, with activities ranging from low to high categories. Activity 1 is an example of the industry's rapid digitalization, with high degrees of digitalization in data gathering and reporting. Activity 2 is classified as moderate to high digitalization, suggesting strong digital integration but with opportunity for improvement in data entry. Activity 3 demonstrates a high level of

digitalization across all aspects of data management, demonstrating a forward-thinking attitude toward technology adoption. Activity 4 is notable for being highly automated, with consistently high ratings across all four attributes. Activity 5 has a high level of digitalization, notably in data analysis and reporting.

The study emphasizes the difficulty of effectively assessing digitalization. Disparities between expert-provided DDCA and fuzzy model outputs highlight the assessment's complexities. These differences range from 0.06 to 0.42 points and highlight the importance of continuing research into the underlying issues influencing assessment precision, such as data collection techniques and digitalization complexity. A case study was done to test the correctness of the DDCA model, demonstrating the model's efficacy in determining the extent of digitalization in a construction project. The resulting Digitalization Index (DI) summarizes the level of digitalization across several data management components. Scaling the DI from 0 to 100 improves interpretability, with a scaled DI of 28.4% resulting in a low level of digitalization in the construction management procedure. A follow-up discussion with an industry expert confirmed the model's accuracy, boosting its dependability in representing real-world digitalization scenarios.

The study's findings provide useful advice for steering the Saudi construction industry toward a successful digital transformation. First and foremost, there is an urgent need to invest in the development of digital skills. To bridge the digital divide evident across various building operations, thorough training and upskilling initiatives are required. These initiatives will enable the workforce to effectively leverage the potential of digital tools and technology, ensuring their ability to manage the developing construction landscape. Furthermore, it is critical to promote collaborative digital platforms. These tools can help project teams

communicate and share data more effectively, resulting in better cooperation and efficiency. Adopting such technology can improve collaboration among various stakeholders, ultimately contributing to the success of construction projects.

Using digitalization tools in building projects improves efficiency, accuracy, and overall success. Here are strong reasons for stakeholders to use digitization in construction: Digital technologies simplify construction procedures, eliminating manual labor and decreasing delays. Automation of operations like data input, documentation, and project tracking speeds up project completion, saving time and resources. CAD software, 3D scanning technologies, and BIM tools enhance the precision of architectural and engineering drawings. This avoids design errors and provides construction teams with accurate information, saving rework and expenses. Digitalization tools like IoT sensors and powerful analytics software enable real-time data on energy use, deviations, and waste management. This allows project managers to make educated decisions quickly, handle issues as they arise, and avoid future delays. Data-driven insights from digital tools enable better resource allocation and optimization. Digitalization identifies inefficiencies and cost reductions in various areas, including energy usage, workforce management, and material procurement.

Digital tools enable smooth communication and collaboration among project stakeholders, such as architects, engineers, project managers, and contractors. This leads to better coordination, less confusion, and a more effective workflow across the project lifetime. Digitalization tools promote sustainability and environmental responsibility by improving energy use, waste management, and resource usage. This not only complies with environmental standards but also builds the project's reputation as environmentally friendly. Digital technologies promote proactive risk management by identifying potential difficulties

early on in the project. Using tools like deviation tracking and trend analysis helps quickly resolve deviations from project plans, lowering the risk of costly errors and delays. LoT sensors provide real-time monitoring of building sites to ensure compliance with safety rules. This proactive approach to safety reduces the chance of accidents and improves job site security. Digitalization helps building projects keep up with technological improvements. This adaptability not only secures the project's future but also establishes stakeholders as industry leaders, recruiters, and clients. Digital tools provide thorough reports and visualizations for stakeholders to understand project performance. Transparency builds trust among clients, investors, and regulators, boosting the project's legitimacy.

Construction enterprises that use digitalization obtain a competitive advantage in the market. Digitalization is crucial for obtaining new business and maintaining a strong market position, as clients place a higher value on technologically advanced solutions. Digital tools provide effective project lifecycle management, from design to construction and maintenance. This holistic strategy extends the benefits of digitalization beyond the building period, promoting project success and sustainability. Digitalization tools offer numerous benefits for building projects, including increased productivity, accuracy, collaboration, sustainability, and overall success. Convincing stakeholders to adopt digitalization is a strategic step to remain competitive, agile, and future-ready in the construction business.

5.2 Recommendations

The recommendations are based on the results of the study, the fuzzy model, and expert opinions. The recommendations are meant for construction industry experts in Saudi Arabia who are interested in leveraging digital technologies in construction activities. The study was done using various experts in different parts of construction project development, and therefore

the results can be applied by any expert who is involved in the activities of the study to enable digitalization. This study has major consequences for the construction sector, policymakers, and stakeholders. It emphasizes the significance of data-driven decision-making and greater operational efficiency in construction. Construction organizations can increase their competitiveness and efficiency by identifying areas for digitalization enhancement. Furthermore, the research helps to close a gap in methods for analyzing the extent of digitalization in construction projects, giving vital guidance for the industry's digital transition. Finally, this study makes an important addition to understanding and analyzing the levels of digitalization in building processes. It provides a solid framework for quantifying digitalization, but with some caveats. As the construction sector embraces digital transformation, the findings of this study can help stakeholders make informed decisions, increase efficiency, and ensure long-term success in the face of global problems.

Benchmarking and best practices should be actively promoted as well. Construction firms should conduct benchmarking activities to compare their digitalization efforts to industry best practices. This not only aids in the identification of areas for improvement, but it also promotes knowledge sharing among industry peers. Companies can speed their digitalization journeys by learning from successful instances. The integrity and quality of data utilized in construction activities are critical. As a result, it is critical to build strong data governance structures and quality assurance methods. Making educated decisions based on digital insights requires ensuring the quality and dependability of the data. Customized digitalization strategies are required. Rather than taking a blanket approach, construction firms should devise strategies tailored to the unique needs and challenges of each building operation. This personalization enables a more targeted and efficient digitalization endeavor. Continuous monitoring and

assessment are important components of digitalization success. Organizations can make timely adjustments and enhancements by implementing procedures for ongoing review of digitalization activities. It ensures that the digitalization journey stays on track with changing goals and industry developments.

Another important suggestion is to collaborate with technology providers and entrepreneurs. Construction companies can get cutting-edge solutions tailored to their specific needs by aggressively seeking relationships with digital innovators. These collaborations have the potential to foster industrial innovation. Policymakers and regulatory agencies are critical to advancing digitalization efforts. They should foster an environment conducive to digitalization in the building industry. This entails creating clear norms and standards for digital data management as well as encouraging industry-wide adoption of digital practices. Research and development should remain a priority. Interdisciplinary study can result in the creation of cutting-edge tools and procedures for assessing digitalization levels and enhancing construction processes. In order to drive digital transformation, organizations must embrace innovation and research. International benchmarking can provide useful information. Engaging with counterparts in other countries provides a broader view of the levels and practices of digitalization. Comparing and learning from global counterparts can help inform local strategies. Collaboration between the public and private sectors is needed for a coordinated approach to digitalization.

Joint ventures between public and commercial partners can fund research, prototype digital solutions, and allow the sharing of best practices. This type of partnership has the potential to expedite the adoption of digital technology in the construction industry. Finally, environmental and sustainability concerns must be factored into digitalization efforts.

Construction activities with digital technologies have the potential to have a lower environmental impact. As a result, sustainability should be a key component of the digitalization strategy. Incorporating these guidelines into the digitalization strategy of the construction industry will lead to enhanced efficiency, productivity, and competitiveness. Adopting these recommendations would assist players in navigating the intricacies of digitalization, paving the path for a more innovative and sustainable Saudi construction sector.

The research has successfully identified a diverse range of construction activities in Saudi Arabia with significant potential for digitalization, showcasing the varied digital landscape within the industry. Through the construction of a comprehensive model that incorporates six key measures of technology acceptance, the study has effectively ranked these activities. The top-ranked activities exhibit strong digital integration and excel in critical digitalization parameters. Moreover, the development of a robust fuzzy-based assessment model, which accounts for uncertainties in expert judgments, provides a more accurate representation of the digitalization landscape in Saudi Arabian construction projects.

The study's recommendations for follow-up and management of deviations emphasize the importance of streamlining tracking, analysis, and corrective action implementation. Utilizing tools such as IoT sensors, RFID technology, and advanced analytics software can enhance the efficiency of deviation management, benefiting project managers and quality control teams. Additionally, the call to update drawings, models, and document systems focuses on enhancing the accuracy and accessibility of project documentation. Implementing 3D scanning technology, CAD software, BIM software, and document management systems can significantly improve the documentation processes, benefiting design teams, architects, and project managers. The study also highlights the need to optimize energy use and

sustainability in construction projects. Recommendations for using IoT energy sensors, energy management software, AI-powered analytics tools, and sustainability reporting tools target sustainability coordinators and project managers, emphasizing the importance of environmentally conscious construction practices.

Furthermore, the research suggests strategies to improve waste management, advocating for effective waste tracking, reduction, and recycling processes. Utilizing IoT waste sensors, waste management software, AI-powered analytics tools, and sustainability reporting tools can enhance waste management strategies, benefiting site managers and environmental compliance teams. The prioritization of projects based on the top 5 activities identified in the study is proposed as an effective approach to resource allocation, aiming to enhance overall project success. The study also promotes the use of fuzzy tools for uncertainty management, highlighting their effectiveness in informed decision-making and improved project outcomes.

5.3 Future Research

It is critical to highlight the study's limitations, which include potential biases in expert data and the need for additional research to strengthen the assessment model. Limitations in geographic location can be addressed by replicating the study in other areas to enable generalizability of the results. Future initiatives could include broadening the study to include a wider range of building operations and investigating additional factors influencing digitalization. Comparative studies across different global regions were conducted to assess the adoption and impact of digitalization in construction. Explore regional variations in technological implementation, regulatory frameworks, and industry readiness for digital transformation. Continuous monitoring and adaptation of the evaluation model are required to keep up with the construction industry's growing digital ecosystem.

Recommendations for future research include the expansion of digitalization activities to identify a broader range of construction activities, increasing the sample size of experts and construction projects to enhance model robustness, exploring alternative assessment tools and methodologies, and replicating the research in various geographic locations to ensure the generalizability of findings.

In conclusion, this research provides valuable insights and actionable recommendations for stakeholders in the Saudi Arabian construction industry to leverage digitalization, improve project management, and contribute to sustainable and efficient construction practices. Adopting the suggested strategies and considering future research directions will further propel the industry towards a more technologically advanced and environmentally responsible future.

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Appendix

Data Collection Forms

Questionnaire 1

Part 1: Demographic Information (Tick appropriately)

1. Field of Experience

☐ High Management ☐ Project Manager ☐ Engineer ☐ Other

2. Years of experience in construction engineering and management

☐ Less than 5 ☐ 5 – 10 years ☐ 11 – 15 years ☐ 16 – 20 years ☐ Over 20 years

3. Education level

☐ High or lower ☐ Diploma ☐ Bachelor's Degree ☐ Post-graduate degree

Part 2: Digital Knowledge

4. How would you describe your Internet knowledge

☐ Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good

5. How would you describe your Computer knowledge

☐ Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good

6. How frequently do you use the Internet per day

☐ Do not use ☐ Rarely ☐ Moderately ☐ Frequently ☐ Very Frequently

Part 3: UTAUT Model

7. This Section is organized into Six columns as follows: usefulness, areas that require digitalization in a project, challenges, ease to digitalize, projects security, safety enhancement. Based on a rating scale of 1 -5, where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree, please rate each activity (in row) for each criterion (In column).

Activities	U	A	CH	E	S	SE
Collect and update project communications and documents						
Evaluate the environmental impacts of the project						
Review design documents						
Improve waste management strategies						
Follow-up and management of deviations						
Improve the projects energy consumption						
Update contract compliance with suppliers and subcontractors						
Update drawings, models, and document systems						
Visualize pictures and use 3D models on site						
Create material quantities list						
Carry out inspections, approvals, and certifications						
Create and update project deliverables						
Punctual replacement of quality materials						
Set up sufficient storage space for construction materials						
Carrying out different training programs for the employees						
Monitoring and controlling of the project cost and progress						
Follow the staff's presence and manpower reports						
Assess the productivity of equipment operations						
Monitor safety and mitigate the risk of unforeseen site conditions						
Implement problem-solving skills and communication among the workforces						
Update time and resource plans						

Activities	U	A	CH	E	S	SE
Track the subcontractor's progress and payments						
Manage project risks/hazards						

Your cooperation is highly appreciated. Thank you for your time and participation

Questionnaire 2

Please rate the degree of digitalization (range from 0% to 100%) of the following processes for managing data for each Activity and its associated project activities on a scale of 1 to 10. Give a rating of 1 for entirely manual processes and a 10 for entirely digital processes. A rating system should also be provided based on the worst-case scenario, the most likely estimate, and the best-case scenario for each data management process and Activity.

Data Management Processes	Scenario	Rate
Data Acquisition	Pessimistic	
	Most likely	
	Optimistic	
Data Entry	Pessimistic	
	Most likely	
	Optimistic	
Data Analysis	Pessimistic	
	Most likely	
	Optimistic	
Data Reporting	Pessimistic	
	Most likely	
	Optimistic	

Q 2. Please assess the overall level of digitalization of Activity 1 on a scale of 1 to 10.

Pessimistic	
Most likely	
Optimistic	

Snippets

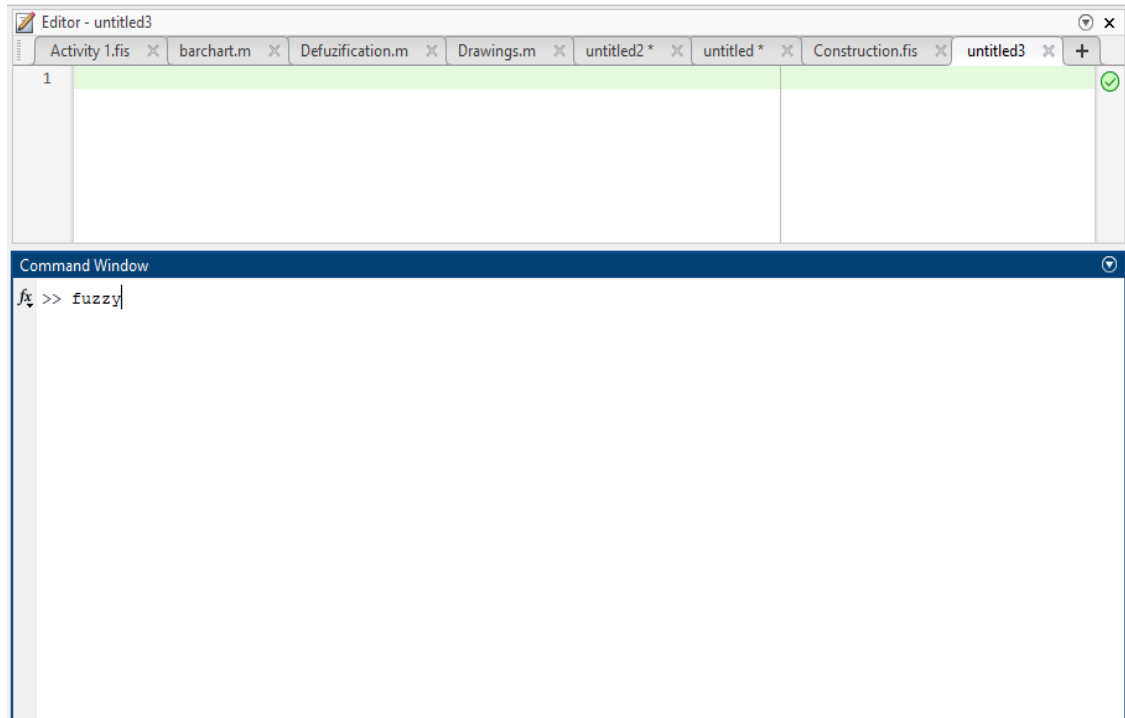


Figure 18: Terminal Execution of fuzzy command

Fuzzy Inference System (FIS) entails all the necessary information that is aimed at describing the fuzzy logic controller. It contains such information as fuzzy rules, type of fuzzy logic, control inputs. etc.

```

24 [Input2]
25 Name='DE'
26 Range=[0 10]
27 NumMFs=5

Construction.fis
28 MF1='Very_low':trimf',[0 0 2.5]
29 MF2='Low':trimf',[0 2.5 5]
30 MF3='Moderate':trimf',[2.5 5 7.5]
31 MF4='High':trimf',[5 7.5 10]
32 MF5='Very_high':trimf',[7.5 10 10]
33
34 [Input3]
35 Name='DR'
36 Range=[0 10]
37 NumMFs=5
38 MF1='Very_low':trimf',[0 0 2.5]
39 MF2='Low':trimf',[0 2.5 5]
40 MF3='Moderate':trimf',[2.5 5 7.5]
41 MF4='High':trimf',[5 7.5 10]
42 MF5='Very_high':trimf',[7.5 10 10]
43
44 [Input4]
45 Name='PR'
46 Range=[0 10]
47 NumMFs=5
48 MF1='Very_low':trimf',[0 0 2.5]
49 MF2='Moderate':trimf',[2.5 5 7.5]
50 MF3='Very_high':trimf',[7.5 10 10]
51 MF4='Low':trimf',[0 2.5 5]
52 MF5='High':trimf',[5 7.5 10]
53
54 [Output1]
55 Name='ODCA'
56 Range=[0 10]
57 NumMFs=3
58 MF1='Pessimistic':trimf',[0 2.5 5]
59 MF2='Optimistic':trimf',[5 7.5 10]
60 MF3='Most_likely':trimf',[2.5 5 7.5]
61
62 [Rules]
63 3 3 2 4, 1 (1) : 1
64 3 3 3 2, 3 (1) : 1
65 4 3 4 3, 2 (1) : 1
66 1 3 1 4, 1 (1) : 1
67 3 3 3 5, 3 (1) : 1
68 5 3 5 3, 2 (1) : 1
69 2 3 2 1, 1 (1) : 1
70 3 3 3 2, 3 (1) : 1
71 5 5 5 5, 2 (1) : 1
72 1 3 1 1, 1 (1) : 1
73 3 2 3 2, 3 (1) : 1

```

Figure 19: Code snippet illustration

Code representing a fuzzy logic system for the construction industry using the Mamdani type inference.

Sent invitation

،، تحية طيبة

هذا الاستبيان جزء من رسالة ماجستير تم إعدادها في جامعة الملك فهد للبترول والمعادن. الهدف الرئيسي من هذه الدراسة هو تطوير نموذج لتقييم مستوى الرقمنة لمشاريع البناء في المملكة العربية السعودية.

تجربة الاستبيان تستغرق 5-7 دقائق.

شكرا لمشارككم

Dear Respondent,

Thank you for agreeing to participate in this survey. This study is part of a Master Thesis at the Construction and Engineering Management program of King Fahd University of Petroleum and Minerals. The aim of this research is to develop a fuzzy based model for assessing the digitalization level of construction projects in Saudi Arabia.

Survey time: 5-7 minutes

Thank you once again for your participation.

Figure 20: Invitation Email for Questionnaire 1

Sent invitation

From: elision.sigh-0e@icloud.com via SurveyMonkey

Date: Saturday, April 29, 2023 12:44 AM

Sent to: 27 recipients

Subject: We want your opinion

Message:

Assessing Digitalization of Construction Project in Saudi Arabia

We're conducting a survey and your input would be appreciated. Click the button below to start the survey.
Thank you for your participation!

Figure 21: Invitation Email for Questionnaire 2

Vitae

Name : YAZEED ABDULLH ALSALAMAH |

Nationality : SAUDI |

Date of Birth : 9/2/1987 |

Email : YALSALAMAH@LIVE.COM |

Address : 3426 ZAID AD DAILAMI, RIYADH, SAUDI ARABIA |

Academic Background : CIVIL ENGINEERING |

Professional Certifications :

- PMP | Project Management Institute (PMI)
- CMRP | Society for Maintenance and Reliability Professionals (SMRP)
- Engineering Accreditation (EA) | Saudi Council of Engineers (SCE)

Courses :

- Structural Analysis and Design using SAP-2000
- Project Risk Management
- Construction Management