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A REVIEW OF DIGITALLY MANUFACTURED EARTHEN STRUCTURES WITHIN THE CONTEXT OF CONSTRUCTION 4.0

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By

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January 2025

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ABSTRACT

A REVIEW OF DIGITALLY MANUFACTURED EARTHEN STRUCTURES WITHIN THE CONTEXT OF CONSTRUCTION 4.0

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Earth is among the most ancient construction materials utilized globally for times. While locally produced building materials provide several environmental benefits, attaining optimal efficiency regarding construction time, cost, and quality in urban settings remains difficult. Contemporary natural building materials have begun to reshape the construction sector with the help of technological developments. In the era of Construction 4.0 and sustainable development goals, digital fabrication and mass customization are changing local construction. Low-carbon materials such as soil have replaced contemporary building materials with high embodied energy. Therefore, understanding the impact of these technologies on earth-based construction techniques can guide future design and construction processes. The history, development process, footprints of current local practices, and the future of digital manufacturing technologies used for earth-based materials are examined in the context of Construction 4.0 core values. This thesis study examines local and innovative digital production techniques with earth-based materials and presents an evaluation of these within the scope of Construction 4.0 core values. It is expected that the thesis research will contribute to the construction sector by presenting a comparison of digital and robotic production techniques of earth-based materials in terms of material, technique, and labour in accordance with the Construction 4.0 core values in order to increase their usage areas in the construction sector.

Keywords: Construction 4.0, Construction Technology, Digital Fabrication, Earth-Based Materials, Industry 4.0

ÖZET

DİJİTAL OLARAK ÜRETİLEN TOPRAK YAPILARININ İNŞAAT 4.0 BAĞLAMINDA İNCELENMESİ

İsmet SAYIN

Mimarlık Anabilim Dalı Yüksek Lisans

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Toprak, küresel olarak kullanılan en eski inşaat malzemeleri arasındadır. Yerel olarak üretilen inşaat malzemeleri çeşitli çevresel faydalar sağlarken, kentsel ortamlarda inşaat süresi, maliyeti ve kalitesi açısından optimum verimliliğe ulaşmak zor olmaya devam etmektedir. Çağdaş doğal yapı malzemeleri, teknolojik gelişmelerin yardımıyla inşaat sektörünü yeniden şekillendirmeye başlamıştır. İnşaat 4.0 ve sürdürülebilir kalkınma hedefleri çağında, dijital üretim ve kitlesel özelleştirme yerel inşaatı değiştirmektedir. Toprak gibi düşük karbonlu malzemeler, yüksek somutlaştırılmış enerjiye sahip çağdaş yapı malzemelerinin yerini almıştır. Bu nedenle, bu teknolojilerin dünya tabanlı inşaat teknikleri üzerindeki etkisini anlamak gelecekteki tasarım ve inşaat süreçlerine rehberlik edebilir. Dünya tabanlı malzemeler için kullanılan dijital üretim teknolojilerinin tarihi, gelişim süreci, mevcut yerel uygulamaların ayak izleri ve geleceği, İnşaat 4.0 temel değerleri bağlamında incelenmektedir. Bu tez çalışması, toprak bazlı malzemelerle yerel ve yenilikçi dijital üretim tekniklerini inceleyerek, bunların inşaat 4.0 temel değerleri kapsamında bir değerlendirmesini sunmaktadır. Araştırmanın, inşaat sektöründeki kullanım alanlarının artırılması için İnşaat 4.0 temel değerlerine uygun olarak toprak bazlı malzemelerin dijital ve robotik üretim tekniklerinin malzeme, teknik ve işgücü bağlamında karşılaştırılmasını sunarak inşaat sektörüne katkı sağlaması beklenmektedir.

Anahtar kelimeler: İnşaat 4.0, Yapım Teknolojisi, Dijital Üretim, Toprak Tabanlı Malzemeler, Endüstri 4.0

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TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 PROBLEM AND RESEARCH QUESTION	2
1.2 LITERATURE REVIEW	3
1.3 MOTIVATION & OBJECTIVES	6
1.4 SCOPE AND CONTEXT	6
1.5 RESEARCH DESIGN AND METHODS	7
2. EARTH-BASED MATERIALS IN CONSTRUCTION	10
2.1 ADOBE	15
2.2 COB.....	17
2.3 RAMMED EARTH	18
3. DIGITAL AND ROBOTIC FABRICATION IN CONSTRUCTION.....	20
3.1 DIGITAL FABRICATION.....	24
3.1.1 Additive	26
3.1.2 Subtractive.....	28
3.1.3 Formative	30
3.2 ROBOTIC FABRICATION.....	31
4. INDUSTRY 4.0 AND CONSTRUCTION 4.0.....	36
4.1 INDUSTRY 4.0.....	37
4.2 CONSTRUCTION 4.0.....	38
4.3 CONSTRUCTION 4.0 TECHNOLOGIES.....	41
4.4 CORE VALUES OF CONSTRUCTION 4.0	47
4.4.1 Sustainability.....	49
4.4.2 Efficiency.....	53
4.4.3 Flexibility	54
4.4.4 Connectivity.....	56
4.4.5 Safety.....	58
4.4.6 Innovation.....	60
4.4.7 Data-Driven Decision Making.....	62
5. A REVIEW OF DIGITALLY MANUFACTURED EARTHEN STRUCTURES	64
5.1 PROPOSED APPROACH.....	64
5.2 DIGITAL AND ROBOTIC FABRICATION CASES PRODUCED WITH EARTH-BASED MATERIALS	66
5.3 FINDINGS AND DISCUSSION.....	74
5.4 OVERALL ASSESSMENT.....	85
6. CONCLUSIONS AND FUTURE PROSPECTS.....	94
6.1 CONCLUSIONS	94
6.2 SOCIETAL IMPACT AND CONTRIBUTION TO GLOBAL SUSTAINABILITY	98
6.3 FUTURE PROSPECTS	100
7. BIBLIOGRAPHY	102

LIST OF FIGURES

Figure 2.1 World map illustrating the worldwide use of earth construction (Auroville Earth Institute, 2023)	10
Figure 2.2 Composition of an earth (Auroville Earth Institute, 2023)	11
Figure 2.3 Twelve major strategies are connected to the earth's four phases (Auroville Earth Institute, 2023).	14
Figure 2.4 Earth-Based Materials Classification (adapted from Hamard et al. (2016) and Keefe (2005))	15
Figure 2.5 Production Methods of Adobe (Made In Earth Collective, 2017)	16
Figure 3.1 Timeline of Fabrication (Produced by The Author).....	23
Figure 3.2 Basic types of industrial robots (Ramb, 2023)	32
Figure 3.3 3D printing robot (Romeo, n.d.).....	33
Figure 4.1 The Transition from Industry 1.0 to 4.0. Adapted from (Da Xu et. al., 2018 & Yin et.al., 2017)	37
Figure 4.2 The evaluation of Construction 4.0 (Produced by The Author).....	39
Figure 5.1 Gaia Project (Chiusoli, 2024).....	68
Figure 5.2 Mud Frontiers Project (Mud Frontiers RAEL SAN FRATELLO, n.d.)	69
Figure 5.3 Printed Stairs Project (Say, 2024)	70
Figure 5.4 Clay Rotunda Project (Gramazio Kohler Research, n.d.)	71
Figure 5.5 Digital Soil Project (Mitterberger & Derme, 2020)	72
Figure 5.6 Terramia Project (Reed, 2019)	73

LIST OF TABLES

Table 3.1 Additive Fabrication Tools*	27
Table 3.2 Subtractive Fabrication Tools*	29
Table 3.3 Formative Fabrication Tools*	30
Table 4.1 Core Values of Construction 4.0	48
Table 5.1 Classification of Cases According to Materials, Equipment, and Techniques	74
Table 5.2 Gaia Project	76
Table 5.3 Mud Frontiers Project	77
Table 5.4 Printed Stairs Project	80
Table 5.5 Clay Rotunda Project	81
Table 5.6 Digital Soil Project	83
Table 5.7 Terramia Project	84
Table 5.8 Materials Assessment of The Projects According to C4.0 Core Values	86
Table 5.9 Technique Assessment of The Projects According to C4.0 Core Values	87
Table 5.10 Labor Assessment of The Projects According to C4.0 Core Values	88
Table 5.11 Overall Assessment of The Projects	89

LIST OF ABBREVIATIONS

ADF	Adaptive Design and Fabrication
AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
BC	Before Christ
BDA	Big Data and Analytics
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Methodology
CAAD	Computer-Aided Architecture Design
CAD	Computer-Aided Design
CEP	Circular Economy Principle
CNC	Computer Numerically Controlled
CPS	Cyber-Physical Systems
CPPS	Cyber-Physical Production Systems
CTS	Cost and Time Savings
C4.0	Construction 4.0
DTT	Digital Twin Technology
EE	Energy Efficiency
EEAS	Economic and Environmental Accounting System
EIA	Environmental Impact Assessment
EIR	Environmental Impact Reduction
ELM	Ethical Sourcing and Low-Impact Materials
ENIAC	Electronic Numerical Integrator and Computer
FFF	Fused Filament Fabrication
ICT	Information and Communications Technologies
IOT	Internet of Things
ISO	International Organization for Standardization
IWS	Improved Worker Safety
I.4.0	Industry 4.0
LEED	Leadership in Energy and Environmental Design

MC	Mass Customization
MFA	Material Flow Analysis
MR	Mixed Reality
OMC	Optimum Moisture Content
PA	Predictive Analytics
PO	Process Optimization
PRC	Parametric Robot Control
RAI	Robotics and AI Integration
RMF	Real-Time Monitoring and Feedback
SCRA	Selective Compliance Assembly Robot Arm
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Stereolithography
UAV	Unnamed Aerial Vehicle
VR	Virtual Reality
3DP	3D Printing

Chapter 1

Introduction

In hot, dry, and regions with temperate climates earth-based construction materials are the most frequent. Minke (2005) reports that one-third of the world's population lives in clay buildings, mostly in poor nations. Industrial materials and processes like brick, concrete, and steel have struggled to satisfy growing countries' housing demands. However, the earth is the most plentiful natural building material. The construction industry is moving towards digitally controlled manufacturing processes that can meet building form efficiency and complexity (De Soto et al., 2018). Construction has employed "digital manufacturing" since the 1980s. Modern enterprises are adopting additive manufacturing technologies like 3D printing and robotic production, according to Kolarevic (2001). The construction industry is exploring digital manufacturing procedures for major structures and components to capitalize on these advantages (Agustí-Juan & Habert, 2016). Digital prototypes of full-scale building components, furnishings, and buildings are shown at several museums and galleries worldwide. According to Walasek and Barszcz (2017), several colleges and firms quickly develop 3D printing technologies to manufacture full-size structures. However, construction technology uptake has been far slower than projected. Technology is a tool that meets people's social, cultural, economic, and environmental needs. Most definitions emphasize that technology is information, and one of its components is knowledge. Due to its characteristics, the construction sector is essential in industrialized and developing economies (Barberio et al., 2023). In the construction sector, technology is defined as the product output produced by the use of tools, materials, methods, procedures, information inputs, processes, and management systems, i.e. (Scherer et al., 2023). In addition, technological progress, automation, and integration give a chance to increase the quality of design and construction, as well as to increase efficiency (Hamzeh et al., 2021).

However, the construction sector has increasingly adopted automation and modern technologies. According to Lasi et al. (2014), the construction sector, one of the most important in the economy, should adopt new technology for project management, productivity, and value chain development. Industry 4.0 has recently gained attention to improve digitalization and automation in the manufacturing sector, creating a digital value chain across the full product life cycle. Recognizing and appropriately addressing the fundamental barriers inherent to construction projects that hinder incorporating new technology is critical. Hossain and Nadeem (2019) stated that the construction sector's strategic position is transforming, with technological innovation becoming the fourth dimension of competitiveness, alongside time, cost, and quality. The influence of novel materials and methodologies on the building industry is determined by the responsiveness of current production resources to the requirements for volume and quality.

Initially, construction was based on practical expertise. More is science-based; with the development of new and superior construction materials, application technical developments have expanded the impact of developments in construction. In parallel with the developments in material science, the production technology for construction and building materials has advanced significantly. Traditional earth-based materials are finding new applications in architecture. Such materials are chosen by both individual architects and architectural groups. However, material science has also made significant progress in classical materials. As a result of digitalization, new materials, production processes, and application techniques have been developed. Furthermore, conventional materials have been refined (Srivatsan & Sudarshan, 2015).

1.1 Problem and Research Question

The construction industry is transitioning to digital and automated methods, known as Construction 4.0 (C4.0), which seek to enhance efficiency, sustainability, and flexibility. Earth-based materials, known for their sustainability and low cost, are increasingly being investigated as potential materials for digitally generated buildings. However, incorporating these materials into C4.0 presents difficulties regarding standards, material behavior, structural performance, and scalability. Gomaa et al. (2022) state that although concrete, timber, and masonry building methods are evolving because of advancements in

digital manufacturing techniques like 3D printing and robotic fabrication, earthen construction remains one of the least examined approaches. On the other hand, there is much interest in utilizing earth-based materials for digital and robotic fabrication processes; however, there haven't been many extensive assessments and evaluations of existing uses and problems.

The main research question of the thesis is " How do digital manufacturing technologies contribute to the construction of earthen structures in the context of Construction 4.0?". In order to answer this main question, the following sub-questions have been addressed in the chapters of this research:

- What are the material properties of the earth make it suitable for construction?
- What are the constraints and capacities of vernacular and digital manufacturing methods using earth-based materials?
- What digital manufacturing techniques are presently employed to produce earthen structures?
- How do digital fabrication methods improve the efficiency and precision of earth-based construction?
- In what ways do digitally fabricated earthen structures contribute to sustainability goals in alignment with Construction 4.0 principles?

1.2 Literature Review

Construction with earth-based materials has attracted much attention due to its low environmental impact in recent years. Nevertheless, its progress is constrained due to its low rate of manufacturing. New developments have been achieved to improve the design of earth-based material mixes and processing processes (Mohan, 2024). There are studies on the construction and manufacturing of earth using traditional production

techniques. While some of the studies focus on traditional production techniques and innovative projects produced with digital production techniques, others focus on the concept of construction 4.0. However, research examining digital projects produced with earth-based materials according to the fundamental values of Construction 4.0 and finding solutions according to the results are limited. Some of the studies in the literature investigating the traditional use of earthen construction materials such as adobe, cob, and rammed-earth, digital fabrication, and the concept of construction 4.0 are described below.

Tunalı (2015) states that adobe has historically been the primary building material in military, ecclesiastical, and civil architecture worldwide, especially in Mesopotamia. Since its inception, humanity has required specific minerals to survive. The Neolithic era was a significant revolution in which humans learned to domesticate, cultivate, and construct dwellings. Since the beginning, Adobe has been used as a construction material and is still commonly used in many different locations.

Information on how to enhance the cob production process and how to work on it properly for peaceful and sustainable conservation is provided by Quagliarini et al. (2010). Raw earth structures can be called sustainable because of their low environmental effect, superior thermal and hygrometric performance, sound insulation, and possibly low cost. A mechanical mixing machine, used to make burnt bricks, might improve cob output. This saves time and money. Furthermore, cob bricks may be used to construct a one-story wall immediately after manufacturing, even if they are still wet. This applies to both tinkering with ancient cob architectures and building new ones.

Dabaieh (2014) provides an overview of rammed earth buildings from their historical context to their current use. Rammed Earth is a natural building technology that has been utilized for thousands of years on all continents. It offers several advantages, including being a low-tech, inexpensive building approach.

Weissenböck (2015) considers employing manufacturing tools in the design process, where the final shape is neither preset nor simulated digitally before materialization. This research uses robotic production as an evolutionary design process to examine digital design and manufacturing. A new way of thinking about architectural design and execution is made possible by this "design-fabrication" or "design-factory" approach, which also

frees up creativity and permits the investigation of novel geometries and aesthetics. In the domains of robotics, digital design, and digital manufacturing, this article investigates material properties. It makes the design of robotic production dynamic.

Digital fabrication methods and technology are increasingly becoming a necessary component of modern product manufacture. Potential applications for large-scale procedures are developing as the use of 3D printing grows. Agusti-Juan and Habert (2016) argue that combining computational design and robotic production has demonstrated the ability to broaden architectural design. Taking contemporary architectural advancements into account, it looks into the potential benefits and environmental effects of digital output in the construction industry. The research emphasized the significance of material-efficient design in digitally created buildings to attain significant ecological advantages. The insights gained from this research should be used to develop standards that will assist designers in making more sustainable decisions when implementing digital fabrication in architecture and construction.

Casini (2021) analyzes an increasing array of successful innovation initiatives to demonstrate how the construction sector may be reformed to enhance efficiency while confronting emerging global concerns such as resource depletion, climate change, and population expansion. Artificial intelligence and machine learning are among them, as are standardized, modularized, or prefabricated products and components such as fully autonomous on-site robotic 3D printing; generative design, augmented reality, drone use, and lifecycle building information modelling (BIM); and imaginative and innovative building materials, techniques, and technologies. Known as Construction 4.0, this innovative method of construction may make use of the new prospects brought about by the digital revolution. The advantages this transition will have for the economy, the environment, and society at large make it noteworthy in addition to the sector's efficiency, which has stagnated over the previous 80 years and expanded far more slowly than the manufacturing sector and industry.

The deficiency in these studies is that they do not establish a complete connection between earth-based materials and the core values of Construction 4.0. These studies focus on the technical details of earth-based material and generally on its vernacular use. Most of the research does not consider using innovative materials while examining the details

of earthen construction materials. As a result, the materials emphasized in these studies and the innovations in the construction sector have not been evaluated in a single context. The research closes a gap in the literature by establishing a relationship between earth-based projects produced with digital fabrication and the core values of construction 4.0.

1.3 Motivation & Objectives

The movement toward more sustainable, low-carbon alternatives is encouraged by the high environmental costs and sustainable implications of the most common building materials used in the construction sector, such as steel and concrete. Locally obtained and biodegradable earth-based components provide a sustainable solution. In this way, C4.0 refers to a wave of digital innovation in construction that uses cutting-edge technology such as automation, the Internet of Things, robots, and data-driven decision-making to boost output, effectiveness, and quality. With the help of these cutting-edge digital technologies, earth materials that were previously labour-intensive and inaccurate in their application may now be modified for use in contemporary buildings. By assessing them in light of the fundamental principles of Construction 4.0, the research aims to revive the usage of earthen construction materials made by conventional methods and expand their contemporary applications. The thesis's objective is to provide a thorough analysis of digital manufacturing techniques tailored for earth-based materials to assess their technical prowess, constraints, and building potential. In line with the fundamental principles of Construction 4.0, the suggested evaluation seeks to advance the stagnant earthen usage.

Using the concept of Industry and Construction 4.0, this thesis evaluates the existing status of construction-related technologies (Industry and Construction 4.0) and the construction of earth-based materials with vernacular and digital fabrication techniques. This creates an outline for adding new technology to construction projects. The framework will help a construction organization grasp its many automation and digitization target sets.

1.4 Scope and Context

Within the scope of the study, the focus is on the evaluation of earth-based materials produced by digital fabrication within the framework of construction 4.0. It aims to

critically analyze and evaluate the role of digitally manufactured earthen structures within the framework of Construction 4.0. The scope of the thesis is limited to the evaluation of sustainable materials such as earth produced with digital and robotic fabrication techniques due to their accessibility, according to the core values of construction 4.0. Although not many digital fabrication projects are made with earthenware building materials, the research does not include all earth-based construction cases produced by digital fabrication. The research is constrained by its emphasis on six initiatives utilising digital and robotic production with earth-based materials. The study seeks to investigate their capacity to tackle modern challenges in the construction sector, such as cost-effectiveness, material sustainability, and swift implementation, while conforming to the overarching objectives of Construction 4.0 to transform construction methodologies through innovation, digitalization, and enhanced environmental performance.

Earth materials have historically been appreciated for their minimal environmental impact, thermal insulation, and affordability. The emergence of digital manufacturing processes has revived interest in using soil as a construction material, especially in areas where sustainable, low-cost housing is in demand. Furthermore, in the context of C4.0, the construction sector is shifting towards more automated, data-driven, and sustainable practices. This movement stems from the fundamental principles of Construction 4.0, which emphasize using innovative technology to increase efficiency, eliminate waste, and limit the environmental impact of construction. The context of the study consists of current digital and robotic manufacturing projects with earth-based materials worldwide. This research operates in this context by investigating the potential of digitally produced earth structures, aiming to bridge the gap between the local and contemporary use of earth construction, the data-driven methodologies of Construction 4.0.

1.5 Research Design and Methods

Case studies can be used in qualitative research. These qualitative methodologies gathered during case studies aid in understanding and discovering concepts and relationships derived from data and analysis. The data collection and analysis process seek to comprehend, characterize, and investigate processes within a subject of study. Within the information gained from the literature, research is not only evaluated but also

broadened with case studies that are descriptive and exploratory. According to Yin (2017), a descriptive case study describes a phenomenon, whereas an exploratory case study identifies research topics or processes for further study. Case studies are precious in this study of utilizing digital fabrication techniques with earthen construction materials in Construction 4.0 since the difficulties and definitions that produce complexity and variety in present practices have not been appropriately identified. In conclusion, this research adopts an interpretative research approach to critically analyse digitally manufactured earthen structures within the framework of Construction 4.0. Interpretative research is particularly suited to understanding complex and context-specific phenomena, as it allows the researcher to uncover the subjective meanings and interactions underlying emerging technologies in construction processes. Meaning-making activities are at the heart of scientific discovery in interpretive research, also known as qualitative research. Additionally, interpretative researchers aim to acknowledge that human conduct is located inside a specific culture and history rather than searching for generalizable laws (Arnett, 2007). Interpretive researchers use social dynamics and people's sharing of meaning to try to comprehend the investigated phenomena. For instance, they depend on their relationships, communication, language, and the overall ambiance of the situation under study (Klein & Myers, 1999).

To perform a thorough evaluation and analysis of digital fabrication processes for earthen buildings, this research uses qualitative methods that focus on identifying the key features or attributes that contribute to the success of each project without relying on numerical scoring or weighting. The research emphasizes gathering and synthesizing current information rather than producing new empirical data because this discipline remains relatively new. To develop a thorough grasp of the research, the research would primarily include a case study analysis with an interpretative research approach. It will concentrate on earth materials made via digital fabrication, looking at the material's technical procedures and how they fit with the core values of Construction 4.0. The chosen qualitative research methods and design are aligned with the interpretative approach, allowing for a holistic and context-sensitive exploration of digitally manufactured earthen structures within the broader framework of Construction 4.0. Combining case studies, document analysis, and thematic analysis, this research aims to provide meaningful

insights into the transformative potential of digital manufacturing technologies in sustainable construction practices.

The research design of this study is guided by an interpretive paradigm that emphasizes understanding complex phenomena through qualitative research. This design is suitable for investigating the role and implications of digitally produced earthen structures within the evolving framework of C4.0. Earthen construction material, digital and robotic fabrication production techniques in the construction sector, and core values of construction 4.0 were examined through qualitative research methodology in traditional and contemporary construction materials. The identified case studies were determined to have overarching themes regarding material, technique, and labour against this background. The identified themes were interpreted about the analytical and experimental case studies of construction 4.0 core values. As an interpretive study, the research aims to explore the relationships between digital fabrication technologies, material applications, and core values of C4.0 outcomes while revealing the broader socio-technical dimensions of innovation in construction. The research adopts a qualitative exploratory design that provides a flexible and systematic approach to investigating emerging technologies.

Chapter 2

Earth-Based Materials in Construction

People have used raw earth to build homes throughout history. Every continent and almost every country has a diverse earthen-building history. People have used the earth as construction material in places such as Tibet's roof of the world, Peru's Andes, Egypt's banks of the Nile, and China's verdant valleys. Around 1.7 billion people are predicted to live in earthen homes globally, including at least 20% of the population in cities and suburbs and almost 50% of the population in developing countries (Minke, 2013). Figure 2.1 depicts the global application of earth construction.

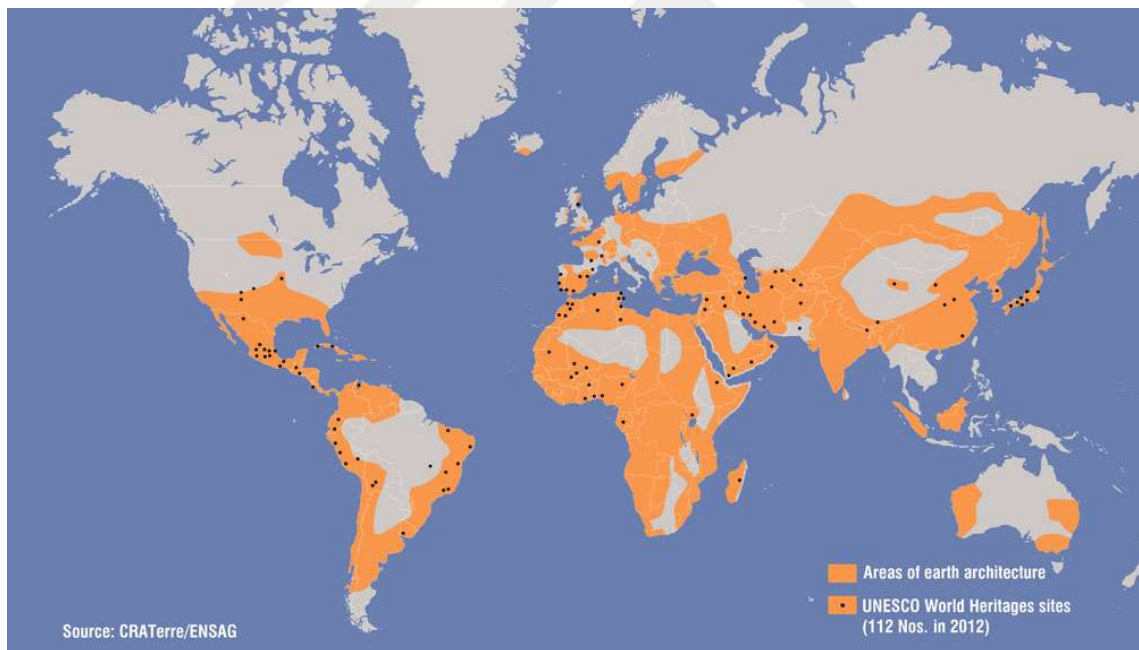


Figure 2.1 World map illustrating the worldwide use of earth construction (Auroville Earth Institute, 2023)

The Ramesseum, which is approximately 3,300 years old and was constructed around 1300 BC, is the earliest extant earthen structure in the world. This structure, which is still accessible on the west bank of the Nile River opposite Luxor, Egypt, was constructed in the ancient city of Thebes using sun-dried masonry adobe (Almeida &

Vasco, 2019). Its survival and architectural features make it a significant example of early earth-based construction (Minke, 2013). The Tabo Monastery in India, which was constructed in the Spiti Valley in 996, has withstood the Himalayan winters and is also constructed of adobe. Its resilience in extreme climatic conditions and its architectural design make it a noteworthy example of earth-based construction (Auroville Earth Institute, 2023). Throughout the globe, individuals have employed earth as a building material in societies with varying cultures, social structures, and construction practices. They employed this material in various methods to accommodate the soil and climatic conditions of the region in which they were constructed. However, Minke (2013) argued that by the end of the 19th century, the knowledge and skills of earth architects had largely disappeared. Constructing with earth was considered a marginal discipline until the latter half of the 20th century. However, Egyptian architect Hassan Fathy significantly influenced the revival of earth construction in the mid-20th century. In recent decades, scientific research has revived earth architecture and construction due to the growing global awareness of sustainable development (Auroville Earth Institute, 2023). Humans have successfully converted this amorphous, weighty, and dark substance into a more functional and lightweight building material on a global scale (Minke, 2013). Fabbri et al. (2021) argued that this transformation has generated novel opportunities for the construction of structures that are tailored to the unique characteristics of the earth's material and the local conditions.

Despite the perception that silt and clay lack stability in aqueous environments, well-treated and consistently maintained earthen constructions have proven their durability. Various physical, chemical, and biological processes, influenced by biological and climatic factors, along with flora and fauna, have converted rock into earth (Xavier et al., 2024). In Figure 2.2, earth comprises gravel, sand, silt, and clay binders, similar to the composition of concrete. This enduring quality of earth-based materials should instill confidence in their reliability.

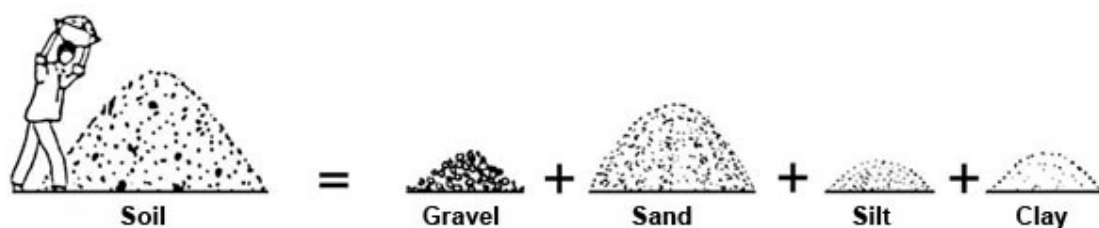


Figure 2.2 Composition of an earth (Auroville Earth Institute, 2023)

There are several ways to characterize the makeup of Earth's artificial and natural components. The chemical, mineral, and rock composition of Earth materials define these components. Atoms combine to make minerals, which form rocks. Understanding atom, mineral, and rock interactions helps explain Earth's materials and behaviours (Hefferan & O'Brien, 2010). Many situations employ mineral terminology. A cereal box describes its ingredients as minerals. Minerals include oil and gas. All of these mineral definitions are arbitrary. Wenk and Bulakh (2004) list about 3500 minerals with distinct chemical and crystal properties. Mineraloids are natural solid minerals without the aforesaid features. Typical examples include volcanic glass coal and other organic sedimentary rocks. In addition, rocks include mineral crystals or mineraloids. Many identical crystals form a monomineralic rock. Examples include volcanic rock dunite, which may contain totally olivine crystals, and sedimentary rock quartz sandstone, which is quartz grains bonded together by quartz cement. Granite contains quartz, potassium feldspar, plagioclase, hornblende, biotite, and others. One of the main characteristics of rocks is their mineral content. Distinctive rock textures and shapes are also important. The vast quantity of minerals in nature, their formation circumstances, and their rates of combination all contribute to the production of aggregates with diverse textures.

Earth-based materials, being the oldest and most widely used construction materials, have evolved and been utilised in various building civilisations worldwide (Aubert, 2019). Their adaptability to different climates and regions and their versatility in construction make them one of the most readily available resources. In addition, earth, being pliable, was one of the first building materials. Since there is no supply issue, it can be readily moulded and is easier to use than wood and stone; it has been a common construction material throughout history. The properties of the earth's components, the sizes and proportions of its grains and solids, and the quality and strength of its internal connections identify it (Laborel-Préneron et al., 2016). If adequate in the body, the dominating grain-type assembly indicates the soil. Ten to twenty percent clay is enough to provide soil cohesion and flexibility, making them cohesive or clayey. Earth has gases, liquids, and solids. Because these three components come from different sources, the body's solids, liquids, and gases may change depending on mass-volume relationships, soil texture, and structure. These elements may be summarised as follows: Air from outside settles in soil grain cracks and adds to soil gases. Air contains relative humidity, nitrogen, oxygen, carbon dioxide, hydrogen, and methane. Organic matter degradation

and soil life generate gases. Liquid components include rainwater, animal and human excrement in the soil, bedrock, and organic element dissolution. Solid matter makes up most of the soil and defines its characteristics. It contains water-insoluble organic and mineral components. Finally, soil cohesion is how well particles stick together. Plasticity is linked to this feature. Texture and Structure have not been invented, which can define and identify the qualities of all piles of earth of all origins and sorts employed for varied purposes in our environment. The literature for each field defines these concepts. Earth mechanics and civil engineering specialists divided soils into "cohesive" and "non-cohesive" and published just their structure (Roy & Bhalla, 2017).

The architectural applications of unbaked earth as a construction material are as follows:

- Construction of the load bearing and partition walls
- Roof and floor slabs
- Used as a filling material in walls
- Predetermined reinforcement production
- Manufacturing of ready-to-use materials for ornamental purposes

The architectural heritage of soil as a building material is unclear since it was not considered modern at the local, national, and international levels (Mara & Tasnádi, 2015). Earthen structures for traditional building construction were inappropriate in a timber-dominated environment. However, these wood-based constructions were plastered from the ground, insulated with beaten earth, and insulated with a thick layer of mixed soil on the floors and roofs. It revived when deforestation, timber shortages, and large-scale logging restrictions forced it to reconsider in the 18th century. The timber structure is dirt-based but usually hidden by plaster in whitewashed dwellings. The Auroville Earth Institute (2023) creates a classification system for the primary earth approaches based on the amount of water present in the combination (Figure 2.3)

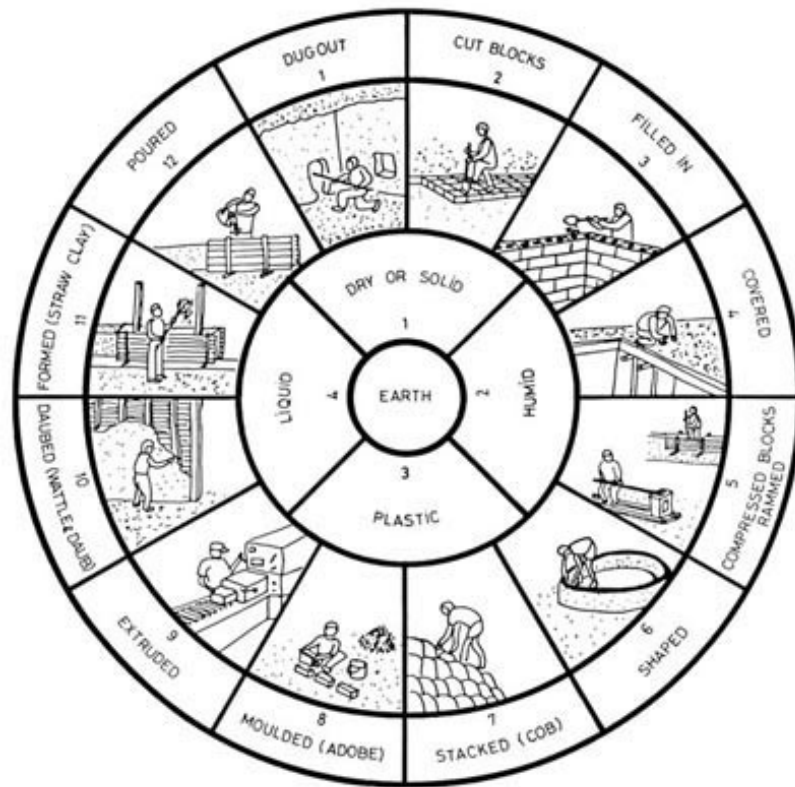


Figure 2.3 Twelve major strategies are connected to the earth's four phases (Auroville Earth Institute, 2023).

Earth-based construction refers to various approaches depending on the material combinations and building process parameters (Keefe, 2005). Numerous studies classify earthen construction systems (Kouakou & Morel, 2009). Hamard et al. (2016) assert that the differentiation between wet and dry compaction techniques for the formation of mixtures and geometries represents the most effective categorization (Figure 2.4). The wet approach utilizes plastic soil mixtures characterized by a comparatively high moisture content. Gomaa et al. (2022) argued that the structure's mechanical strength is achieved via hardening and densification during the drying and shrinking process until the desired moisture content is reached. Techniques like adobe and cob are included in the wet approach, although they are not the only ones. Techniques such as load-bearing compacted earth are used in the dry method. Water and subsoil are the two main ingredients of the soil combination (Keefe, 2005). Rammed earth is a dirt and water combination that may contain lime and/or tiny amounts of cement to stabilize it (Ávila et al., 2022). In contrast, subsoil, water, and fibers such as straw are used to make cob and adobe bricks. Certain adobe mixes use additional natural fiber elements to increase tensile strength and stop shrinking.

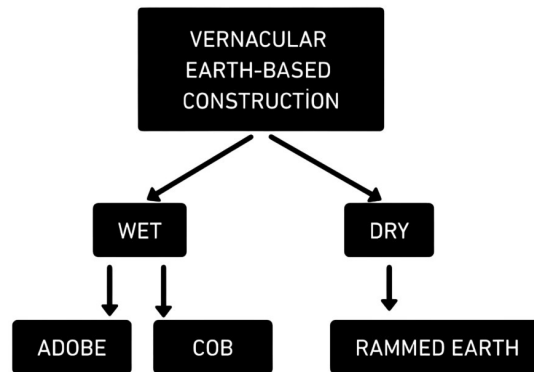


Figure 2.4 Earth-Based Materials Classification (adapted from Hamard et al. (2016) and Keefe (2005))

2.1 Adobe

The Neolithic age was a significant revolution in which people learned to domesticate animals, raise them, and build housing (Tunali, 2015). Adobe is one of the most well-known and adaptable methods of using earth in architecture. The range of adobe constructions worldwide is extensive, encompassing basic low-rise dwellings and more significant structures such as fortresses, palaces, monuments, and temples, some of which are of paramount aesthetic and historical significance (Xekalakis et al., 2023). Illampas et al. (2009) argued that in various of the world, the term refers to fresh material, the dried wall block, and the entire building. Furthermore, adobe obtains interest as an economical and ecological construction technique with natural resources. Houben and Guillaud (1994) claim that a significant benefit of adobe constructions is their capacity to be constructed using local materials and their energy efficiency. Adobe has been used as a construction material since the beginning of time, and today, it is widely used in various places, including Central Asia, Asia Minor, Africa, and South America. Single- and multi-story adobe houses are regularly encountered in many nations, including Anatolia. Adobe is widely used and produced according to strict technical criteria. As a result, the soil becomes structured. To produce an adobe, the soil used in its construction must have specific properties, such as stickiness in its chemical composition. Adobe brick is a mixture of fine-grained sand, rocky mineral aggregate, and clay. If the soil does not have the necessary properties, sand and clay must be added to make the soil suitable for adobe construction. Adobe is a relatively straightforward method of earth building that avoids

the shrinking that comes with constructing enormous constructions. Bricks are made from a range of soils and are available in two varieties: earthy adobe and lime adobe. According to Costa (2018), land-building has traditionally taken several forms in Europe; adobe and compacted earth buildings may be seen in southern Europe, while earth is used in connection with timber, twigs, plaster, and half-timbered methods in northern Europe. In addition, the mud is poured into wooden moulds and cured in the sun to obtain an adobe suitable for construction. Nevertheless, the lack of building norms and regulations for adobe construction makes adapting the material to modern structures problematic for architects and engineers (Illampas et al., 2009).

Various types of adobe buildings exist depending on the characteristics of geographical regions, climatic conditions, technology, and time. Figure 2.5 shows the production methods of Adobe (Made In Earth Collective, 2017).

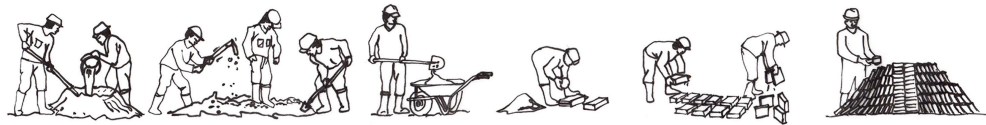


Figure 2.5 Production Methods of Adobe (Made In Earth Collective, 2017)

Adobe, an earth-based building material, is important in traditional construction methods. Various variations exist based on the climatic conditions of distinct geographical places, technical advancements, and evolving building processes (Illampas et al., 2009). The adobe production method is essential for the material's physical durability and performance. This procedure typically comprises four primary stages: mortar making, fermenting, forming, and drying. This section will provide a detailed discussion of Adobe manufacturing methods.

Mud ratios of clay to granules determine whether it is suitable for adobe production. If the proportions are insufficient, adding sand or clay to improve the situation is possible. The dough, or mortar substance that is used to construct the adobe mould is composed of two-thirds clay and one-third sand, along with one-third straw and water. The proportion of sand to clay in the mixture is thirty percent. Putting it another way, dirt will constitute

two-thirds of the entire amount of mortar. When adding water to mortar, do so at the correct rate and consistency. If an excessive amount of water is applied, the adobe will have a difficult time drying, the crack issue will get more severe, and its strength will decrease. Similar to the previous point, adding less water decreases quality (Elborgy & Berkin, 2018). Each soil produces a different grade of adobe material. On the other hand, the qualities of straw that determine its ability to attach might differ from one place to another. After the mortar making has been made and the binder and soil have been well combined, the mortar is then left for a while so that the fermentation process may take place. The process of carefully combining the earth with straw and then allowing it to rest for some time for fermentation is a crucial phase in producing adobe because it ensures that the finished product will be long-lasting. As a result of this fermentation process, specific chemical interactions occur between the straw's components and the elements present in the soil. After thoroughly mixing the raw adobe ingredients until they form a dough-like consistency, the fermentation process is left to happen for twelve to forty hours (Fathy et al., 1986). After a period has passed, the soil mixture is repeatedly mixed to expose the lactic acid in the mortar better. Carrying out the mixing procedure after sunset ensures superior outcomes. Once the fermenting procedure is complete, it is poured into moulds to produce the necessary adobe bricks in specific dimensions. To fill the moulds made of wood, the soil mixture is first squeezed and then filled. The construction of the mould often involves the use of pitch pine and extensive sanding of its interior. Depending on their location, the moulds consist of varying numbers of pieces. During pouring, sand or wet straw is spread on the ground below the mould to prevent mortar adhesion (Made In Earth Collective, 2017). To allow the mixture to cure, it is put in the moulds and then placed in an open location. The top layer of the adobe is inverted to allow it to dry after a specific time. It is expected that the bottom layer will dry and become more rigid as a result of this process. The adobe is ready for knitting once the drying process is complete (Made In Earth Collective, 2017).

2.2 Cob

Hamard et al. (2016) explain that cob was rarely discussed in the literature on earth construction; much of it focused on adobe or rammed earth methods. However, cob serves as an alternative to rammed earth and adobe in various regions, contributing to the

diversity of vernacular earth construction methods that utilise local resources (Hamard et al., 2016). A comprehensive understanding of this vernacular construction technique is essential for the preservation of cob heritage. According to evidence dating back ten thousand years, corn was one of the first materials that people used to build "permanent" structures. Sand, clay, straw, and water made the cob walls. Cob is a system distinguished using hydrated and rested mud with a viscosity similar to that used to manufacture adobe or plaster (Baca, 2020). Cob construction varies from other earthen construction techniques in that the walls are erected as a single solid structure rather than using forms in rammed earth or prepared bricks as in adobe. The first cob buildings were erected in England in the thirteenth century. By the fifteenth century, it had become the typical construction style in some locations, mainly where sandy-clay soils were abundant and other building materials, such as wood, were unavailable (Pullen & Scholz, 2011). Manufactured maintenance, including traditional cement-rich plaster that covers raw clay walls, are prevalent. Because these plasters are too rigid to support natural wall motions, they break quickly, and their limited porosity allows rainfall to penetrate and become trapped inside the wall. Plasters based on soil or lime might be more suited. It is also important to check the mechanical properties of earthen constructions to ensure they are safe. This is especially important for native earth building styles like cob that have not gotten as much attention as adobe (Quagliarini et al., 2010).

2.3 Rammed Earth

All continents have used rammed earth, a natural building technique, for thousands of years (Mihic et al., 2024). Rammed earth structures offer several advantages. It is a low-tech construction approach that is inexpensive to build. They are low-maintenance and excellent for cold and hot areas. The ancient rammed earth construction method employs only earth to make sturdy, durable, load-bearing, heat-storing, and recyclable walls. In order to create a masonry earthen wall, the rammed earth technique compresses the earth between vertical formwork planks, which are then removed. People usually use this method when the soil composition is unsuitable for making sun-dried clay bricks. Excavations in China have discovered compacted earth structures from the 7th century BC. About 5,000 years ago, builders used stone and rammed dirt to construct it as part of the Great Wall of China (Dabaieh, 2014). In the arid regions of North Africa and the

Middle East, where the earth was the only practical construction material, the rammed earth technique was employed to shield buildings from the heat and dust of the desert. Enormous, high walls with small gaps characterized these places. In the past, rammed earth was considered a quick and straightforward method of building fortifications, a cost-effective means to create homes, and, more recently, a sustainable construction method that uses just what is on hand. Excavating the earth from the ground, placing it in a mould, and compacting it in layers, typically 100 mm deep, is the process of constructing a rammed earth wall. Next, they remove the mould, revealing a solid wall. People performed this compression by hand in the past, but modern compacted earth buildings now use pneumatic rammers to achieve the same result. Rammed earth's low carbon content and inherent recyclability have led to its revival as a modern building technology. Modelling approaches for both historic and recently developed compacted earth buildings are required (Joaquin, 2008). Currently, only a few recommendations are available for analyzing vernacular rammed earth constructions. Due to their construction in soil, vernacular rammed earth structures are more susceptible to degradation from natural elements like rain, wind, and water runoff.

This section analyses adobe, cob, and rammed earth techniques, which provide sustainable construction options that align with traditional construction techniques and contemporary digital fabrication. Digital design and robotic manufacturing processes enhance clay constructions, resulting in greater efficiency, durability, and aesthetic sophistication. Gomaa et al. (2023) highlighted that digital manufacturing technologies are expected to enhance earth-based construction usage in the future.

Chapter 3

Digital and Robotic Fabrication in Construction

Since the 1990s, architectural design and manufacturing techniques have been developing (Meyer, 2016). Architectural design methods frequently entail the use of computers. Öztürk (2018) outlined the use of computers in the architectural design process, including digital fabrication, computerized design, visualization, and representation, from conception to construction. According to Öztürk (2018), these technologies move the focus of architecture from the finished outcome to the concept and manufacturing. To understand how the computer interacts with architecture, one must look back at how it was first employed in architectural design. Reichardt (1978) claimed that code-cracking devices introduced digital computing to the world in World War II, but analogue computers have existed for millennia. Mathematicians and scientists automated using early computers. According to Rosen (1969), ENIAC (Electronic Numerical Integrator and Computer), which does pattern recognition and calculation of mathematical problems for physical simulations, is an example of an early modern computer. The primary purpose of ENIAC was to enhance the reliability, precision, and speed of these computations.

Computers originally appeared in architecture with the creation of the first graphic systems in the 1960s (Fallon, 1998). Automation typology by Yershov (1965) was a director-agent interaction paradigm in 1963. Data is input and output through a closed black box and information gateway in this innovation. Caetano et al. (2020) say that people today use computer-aided design (CAD) tools like Yershov's manager-agent paradigm because the computer uses the command line, the mouse, and the script editor as input devices to get things done. Otherwise, the communication model will be upset if the "desired results" are not specified. Conversely, Gannon (2013) clarified that the human intellect limits the machine's usefulness. In contrast to Yershov's human-machine

interface, SketchPad, developed in the same year at the Massachusetts Institute of Technology (MIT) by Ivan Sutherland, enabled interaction between humans and computers via drawings. In addition, Sutherland (1963) built an interactive and visual interface for Sketchpad, which intends to empower artists, architects, and designers with a computing function. Sketchpad also distinguished between "computer programming" and "using a computer." The invention consists of two components. A lightweight pen with a button slot that allows the creator to start creating 2D and 3D images on the computer screen instantly. In conclusion, Pask (2023) suggests that architecture is defined by the complex interactions between material components and social participation to shape, comprehend, and create form, space, and structure. Menges and Ahlquist (2011) define Sketchpad as a process synthesis that builds on the cybernetic perspective of the human-machine interaction and reflects the changing system. Chrisman (2006) recommends a Sketchpad interface to preserve rule-based geometric linkages. Geometric limitations on the drawing model's points and lines limit design variable values. Mitchell (1977) used Negroponte's 1970 drawing program, Sutherland's Sketchpad, and COPLANNER to examine the industrialization of the design process. In the 1980s, architecture firms introduced CAD technologies like CATIA and AutoCAD.

Prior to the advent of CAD, architects sketched ideas on scrap paper, and builders built the designs as accurately as possible. According to Wiertelarz (2016), design processes began to evolve with the emergence of CAD programs in the 1960s, and CAD technologies were employed as technical assistance in the design's planning and construction stages (Arabacioglu et al., 2020). CAD is made up of several programs that produce varied outcomes. Some people can only draw in two dimensions, while others can make three-dimensional renderings and animations. Another advantage of utilizing CAD tools is the ability to move documents between software systems and formats. It is possible to turn a computational model into a tangible object using CAD (computer-assisted design) and CAM (computer-aided manufacturing) techniques for computational design (Alaloul, 2022). These tools drive computer numerically controlled (CNC) equipment using output data from the designer's computer. Additionally, Jacobs (2013) contends that the direct creation of computationally generated products is made possible by digital manufacturing technologies and methodologies.

Architects are advancing digital fabrication and construction processes by incorporating computational tools and robotic manufacturing technologies into the design and production workflow. Kolarevic (2004) argues that the employment of CAD and CAM technology has "radically altered the connection between conception and production, providing a direct link between what can be designed and what can be made" over the last two decades. Mobile manufacturing platforms that can execute and redesign operations replace CNC mills, waterjet machines, plasma, and laser cutters. Although AutoCAD software offers capabilities such as 3D modelling, parametric design, and BIM, it was mainly utilized in those years to move technical drawings created by architects to the computer environment. AutoCAD output in the 1980s was a line, a circle, or a mix of geometric information, and no semantic information could be placed into it (Pérez-Sánchez et al., 2017). As a result, the exported data in AutoCAD lacks the richness of representation; in other words, it cannot be loaded with meaning and remains merely a design. Digital manufacturing will not be viable if it is impossible to add meaning and information to the designs. There were tools like Solidworks that accomplished this in the 1980s, but they were not employed in the discipline of architecture. In brief, the usage of 3D printers in architectural practice has been delayed for around 20 years due to the technological inadequacies of the computer-assisted design software that dominates the architectural profession. Human-robot collaborations or autonomous articulated-arm robots with sensing skills can improve repetitive, accuracy-focused tasks like placing bricks or tiles. Additionally, it adapts to work cell conditions and material properties. Large-scale semi-autonomous or fully autonomous systems that enable fabrication-in-place robots also replace fixed toolkits and construction sites. The constraints of standardized materials, shapes, and sizes that drive digital manufacturing are being questioned and reformed. As well as developing, manufacturing, and integrating novel material systems such as carbon fiber-reinforced plastics, the inherent flexibility, adaptability, and autonomy of robotic systems today enable designers to reconsider classic construction materials such as wood, masonry, or stone. Steel, composites, foam, and compacted grains like gravel are being 3D-printed. Robotic production has changed the daily materials and equipment designers, architects, and builders use, allowing architects to question modern geometry, structure, interior space, and building systems. Sacks et al. (2011) assert that the fast rise of CAAD software over the past few decades has enabled parametric control of architectural forms, leading to design changes or general construction control. Ramani et al. (2004) underline that the execution of

parametric designs needs flexible techniques, known as mass customisation, that can create large volumes at low prices. Architects want to be able to manage the building and production of their designs, including the machining. A challenge in implementing freeform concepts is the lack of adequate tools for architects to manage the entire design process effectively. Current CAAD developers have not yet established effective methods for directly integrating various types of machines with CAD systems. Fabrication consulting in architecture is increasingly recognized as a specialized core sector, driven by mathematicians and computer scientists, as noted by Eigensatz et al. (2010). Brell-Cokcan and Braumann (2014) show how to evaluate the design of a parametric item and its manufacturing-related aspects using real-time feedback and manufacturing-intrinsic design. The product is user-customized CAAD software that instantly creates robot control data files for mass customization and incorporates machine limits as additional design parameters.

Two places along technological and temporal continuities overlap and take different routes: digital and robotic fabrication. Both of them do not replace each other. Digital fabrication technology is the foundation of robotic production, which provides degrees of freedom that allow for the emergence of new creative forms. Figure 3.1 illustrates a diagram encapsulating the evolution of industrial development and fabrication methods throughout history. It delineates the growth of machine tools and manufacturing techniques from the Industrial Revolution to the present, traversing four distinct industrial phases and associated technical advancements. It illustrates the fabrication timeline within a historical framework and their progression to contemporary digital production processes.

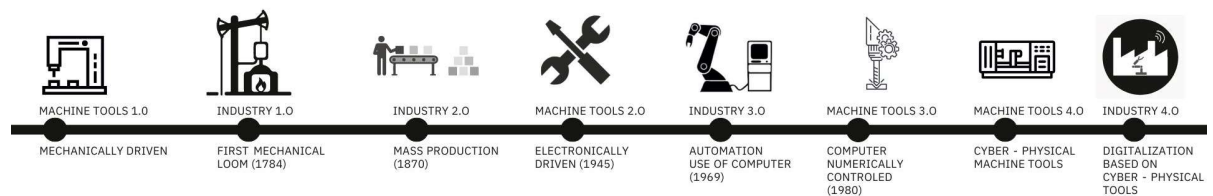


Figure 3.1 Timeline of Fabrication (Produced by The Author)

3.1 Digital Fabrication

According to Gorse et al. (2012), digital fabrication is the process of manufacturing or producing anything through a sequential sequence of actions or procedures. Mitchell (2003) proposed that digital fabrication tools function as machines that convert digital design elements into physical objects automatically. In addition, the term "digital fabrication" refers to all the tools and procedures required to create the digital design physically. Digital fabrication aims to create the "bit" of computer science equivalent to the "atom" of physical science. As a result, it may be claimed that digital manufacturing crosses the digital and physical worlds and establishes a portal from one dimension to another. Traditional production is centered on human work and typically employs specialized equipment. These instruments necessitate technically specialized and experienced labour (Gramazio, Kohler, & Oesterle, 2010). On the other hand, unlike traditional systems, digital fabrication tools do not require experienced human operators or years of expertise. The "digital world," as defined by Kolarevic (2004), has created a direct link between what can be produced and what is thought, changing the relationship between thinking and production. According to Kolarevic (2004), the question now is not whether a specific shape can be built but rather what new application tools are required to capitalize on the prospects given by digital fabrication in architecture. Our cultural context and education impact how we think and develop, as well as the tools we employ to do it; he contends that, depending on the degree of knowledge we have learned, tools will increase our bounds. In this manner, digital manufacturing techniques may broaden architects' thinking and design possibilities. The notion of "personal fabrication," which emerged in the early 2000s, represents a usage of digital fabrication that extends beyond the realm of specialists in advanced private laboratories and into the daily lives of individuals. The goal of personal fabrication is to provide people with the option of producing their goods rather than purchasing them. The emphasis is that regular users may now readily convert digital design, which can be worldwide across the internet, to physical form. Personal fabrication is an invention that allows individuals to create and make the tangible items they require wherever and whenever they require them. Digital fabrication is more than only creating three-dimensional mass structures; it also aspires to create a product in a single step using mechanical and electrical systems. Instead of generating the pieces of the uncrewed aerial vehicle, this circumstance is achieved by

acquiring the drone with its electrical and mechanical parts in a state that can fly as soon as it comes out of the printer. "Personal fabrication tools are similar to home printers in that they print 'objects' on paper rather than images." Although the history of current digital fabrication tools and processes stretches back to the 1960s, digital fabrication has just recently been used in architecture. The actual reality of the possibilities provided by digital design is brought to the forefront by digital manufacturing, especially in the field of construction.

Digital manufacturing shows practical options for representing, evolving, and redesigning complicated shapes. Sass and Oxman (2006) assert that incorporating digital processes in architectural design improves creativity and promotes continuity across design stages. Digital manufacturing should not be overlooked, despite appearing to be a subsequent step in the design process. Dunn (2012) states that manufacturing processes necessitate an early evaluation of production aspects by the designer during the ideation phase. Baquero and Giannopoulou (2015) maintain that understanding the appropriate manufacturing technology influences the design process. In this regard, the restrictions and approach most suited to the aim of the design should be addressed early in the design process. This section aims to provide a classification matrix that emphasizes the connection between design constraints and digital fabrication techniques since manufacturing technology selection might impact the design process. Because digital fabrication is a new subject, terminology amongst fabrication processes is constantly changing, shifting, and overlapping.

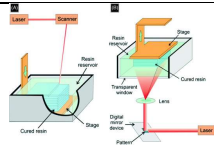
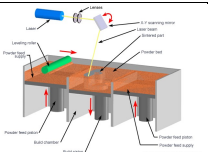
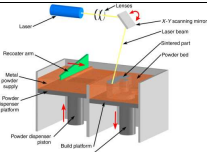
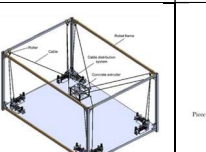
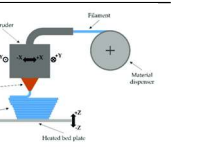
A categorization of digital fabrication tools has been established by examining current technical advances. Since it was developed lately and is more complete, a current classification suggestion has been made based on Hauschild and Karzel (2011). Robots are believed to be categorized separately under the proposed categorization. While all digital manufacturing instruments allow the physical generation of digital data, scanners that turn an existing physical item into digital data have been included as a fifth group in this categorization. The process of architectural design is made easier by scanners because they speed up the translation between digital and physical forms, which in turn improves the workflow for architects (Cruz, 2019).

3.1.1 Additive

Additive fabrication methods make it easier to use digital tools to make complex shapes, use environmentally friendly materials, and improve construction efficiency. Various sizes of elements can be manufactured using techniques such as Stereolithography (STL), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), 3D Printing (3DP), and Fused Filament Fabrication (FFF) (Munawar et al., 2022). These processes enable the design of architectural components like walls, facade panels, interior furnishings, and modular building parts. Additive manufacturing offers design flexibility, allowing the creation of unattainable shapes using conventional techniques while promoting environmental sustainability by minimizing waste and reducing the carbon footprint. However, critics argue that material properties' high initial costs and limitations may hinder widespread adoption in traditional construction practices, potentially leading to reliance on established methods prioritizing durability and cost-effectiveness over innovative design material waste. The advancement of ecological construction methods, particularly utilizing earth-based materials, demonstrates considerable innovative potential in design.

To make a component, an additive process deposits, selectively sinters, or mixes material layer by layer. Layers are typically horizontal. This can lead to more consistent and enhanced additive integrity, which is a key hurdle to adoption. There are various distinctions between additive and classic or subtractive approaches (Ngo et al., 2018). These are as follows: a new material is developed; the capacity to create geometric complexity is improved; the limitation of the reduction process is decreased; and waste is minimized. According to Munawar et al. (2022), some additive manufacturing processes provide supports, which are frequently made of a separate material. When the item is finished, the supports must be removed, but the backing material is frequently totally reusable. Digital fabrication technologies that use additive techniques enable manufacturing components in the required shape by physically and chemically mixing amorphous tiny raw ingredients (Table 3.1).

Table 3.1 Additive Fabrication Tools*

Stereolithography (STL)	Selective laser sintering (SLS)	Selective laser melting (SLM)	3D printing (3DP)	Fused filament fabrication (FFF)
				

*Images were taken from web-based sources.

These titles refer to the basic techniques used in additive manufacturing, which are used for various purposes in various sectors, such as construction. Munawar et al. (2022), highlighted that the techniques used in this context are defined as Stereolithography (STL), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), 3D Printing (3DP), and Fused Filament Fabrication (FFF).

Stereolithography (STL) operates on the laser-induced liquid resin solidification principle. It offers exceptional accuracy and surface finish and is often favored in the fabrication of intricate prototypes (Hull, 1986). Selective Laser Sintering (SLS) is the laser sintering of powdered materials to create a layered structure. It is compatible with polymer, ceramic, and metal materials. It is utilized in architectural modelling and resilient structural components (Deckard, 1988). Selective Laser Melting (SLM) operates on the premise of fully melting metal particles using a laser to create layers. It is appropriate for manufacturing structural components that need great strength (Kruth et al., 2007). 3D Printing (3DP) involves the sequential layering of powdered material with binding agents. It is utilised for cost-effective and rapid manufacture, making it suitable for ornamental architectural components (Sachs et al., 1998). Fused Filament Fabrication (FFF) is a widely utilized technique that operates by depositing molten filament in successive layers. It operates with polymer materials and is mostly utilised in prototype manufacturing (Crump, 1992).

Three-dimensional (3D) printers allow a computer design to be generated into a 3D physical object fast, in one step, and without the need for traditional methods such as CAD data. Rapid prototyping is the broad term used to manufacture 3D printers, including layered manufacturing, rapid prototyping and procedures, and solid freeform fabrication. According to Hauschild and Karzel (2011), Dunn (2012), and Kolarevic (2004), all fast-

prototyping approaches begin with the creation of horizontal design sections in a digital environment in layers. Each digital layer is then finished with amorphous raw material, with the fabricator's head growing in layers sequentially utilizing laser light, heat, or chemical processes, printing or processing the 3D physical output. Ryder et al. (2002) point out that digital data for 3D printers, like other digital fabrication equipment, should be available before entering the manufacturing phase. The user cannot meddle with printing after the digital design data is delivered to the 3D printer. 3D printers range in size from small desktop devices to big industrial-sized machines. A large variety of materials may be used with 3D printers. These materials are primarily plastic derivatives and metals. In addition, materials such as stainless steel, aluminium, Inconel, titanium, fiberglass, high-temperature fiberglass, onyx (micro carbon reinforced nylon), carbon fiber, nylon, and kevlar may be manufactured in 3D printers (Hauschild & Karzel, 2011). It became printable on clay materials from 3D printers in 2017. "Responsibility" is the process of assessing if an individual is accountable for his acts. Hauschild and Karzel (2011) further point out that the material may be coloured and cut and can sustain itself without the need for a structure.

3.1.2 Subtractive

The required form can be created using digital fabrication tools that use subtraction methods by cutting or etching the extra material from a specified volume of solid material (Flynn et al., 2015). Hauschild, Karzel, and Kolarevic (2004) indicate that mechanical, chemical, or electrical procedures can be utilized in this extraction process. Economic reasons are significant when selecting subtractive procedures because of material loss. Kolarevic (2001) indicates that the initial efforts to develop architectural models with a CNC milling machine occurred in the United Kingdom during the early 1970s. Subsequently, leading architectural firms like Skidmore, Owings, and Merrill in the United States utilized CNC milling machines and CNC laser cutters extensively for the production of architectural models. During the late 1980s and early 1990s, companies began utilizing CNC milling machines externally to produce specific building components. CNC (computer numerical control) manufacturing has increased in prevalence over the past twenty years. When paired with modern computational design tools, these technologies, frequently referred to as digital fabrication in architecture, have opened up new avenues for architects to create and realize their visions. This level of

industrial growth has supplied design and construction with new tools that are appropriate for this new century. Laser cutters, CNC mills, 3D printers, and other manufacturing equipment are increasingly used in design schools, professional practice sectors, and the home. It now extends beyond traditional architectural production forms. Robots are increasingly becoming crucial tools and colleagues, moving from faraway production floors. Robots invading manufacturing factories, design companies, studios, and labs and moving to the streets, according to Daas and Wit (2018), are altering the world and how the new world is envisaged, manufactured, assembled, developed, and sustained. Various CNC cutting instruments, such as laser beams and water jets, include biaxial cutting on sheet material. According to (Gökkılıç, 2023), these tools are classified according to whether the cutting head, the product bed, or both are moveable. CNC cutting tools are classified into three types: CNC laser cutting, which uses a laser beam to cut; CNC jet cutting; and CNC hot wire cutting, which uses water to cut (Table 3.2). The CNC milling machine operates according to the idea of getting the required form by cutting the material from the block with a quickly revolving hard and sharp tip. CNC milling machines are classified into two types: milling and routing. Routing is more suited to wood and plastic materials, whereas milling is better suited to metal materials.

Table 3.2 Subtractive Fabrication Tools*

CNC Laser cutting machine	CNC Jet cutting	CNC Hot wire cutting machine	CNC Milling machine
			

*Images were taken from web-based sources.

These titles refer to the different types of CNC machines used in digital fabrication processes. Each is optimized for specific materials and application areas. The techniques used in this context are defined as CNC Laser Cutting Machine, CNC Jet Cutting, CNC Hot Wire Cutting Machine, and CNC Milling Machine (Lalic et al., 2020).

CNC Laser Cutting Machine executes material cutting or engraving using a high-intensity laser beam. It delivers accurate cutting on materials including metal, wood, and plexiglass (Steen & Mazumder, 2010). CNC Jet Cutting is performed cutting process using a high-pressure stream of water or a water-abrasive combination. It enables

deformation-free processing of rigid materials, including metal, stone, and glass (Ramulu et al., 2016). CNC Hot Wire Cutting Machine uses hot wire to cut lightweight materials, like foam and plastic. It is often favoured in architectural model fabrication and facade systems (Boparai et al., 2017). CNC Milling Machine equipment removes material from workpieces by linear advancement using a multi-cutting blade. It processes flat and angled surfaces, creates channels, and produces flat and circular divisions (Webmaster, 2024).

3.1.3 Formative

The mechanical forces imposed on the material in the formative manufacturing process achieve the required form without causing a mass change. Heat or steam is commonly utilized in this procedure to help the material form more efficiently by increasing flexibility. According to Dunn (2012), the cooled material becomes rigid again when the shaping process is completed. CNC-enabled forming tools are used to build complicated surfaces precisely. Kolarevic (2004) asserts that these instruments fabricate materials like metal, plastic, and glass. The CNC bending tool numerically shapes raw or semi-finished materials, such as plates, wires, pipes, etc. According to Hauschild & Karzel (2011), CNC punching and engraving tools put high pressure on the material, with digitally controlled drilling heads moving on the vertical axis, allowing the shape to alter.

Table 3.3 Formative Fabrication Tools*

CNC Bending tools	CNC Punching tools	Welding tools
		

*Images were taken from web-based sources.

These heads are CNC-operated tools and welding apparatus utilized in metalworking and industrial operations. Each unit has distinct functions, guaranteeing accurate and efficient operations on the manufacturing line and these are defined as CNC Bending Tools, CNC Punching Tools, and Welding Tools.

CNC Bending Tools, such as CNC-controlled presses and bending machines, facilitate the bending of materials, including sheet metal and pipes, to specified angles and configurations. It provides exceptional accuracy and consistency (Kalpakjian & Schmid, 1990). CNC Punching Tools are Employed for perforating holes, severing, and fabricating diverse shapes in sheet materials. Offers rapidity and diversity with several drilling tips. It is mainly used to manufacture lightweight building components (Helduser, 2002). Welding Tools, CNC welding machines, provide precise joining of metal parts with automatic or robotically controlled systems (Zhang, 1999).

3.2 Robotic Fabrication

Robotic fabrication has assumed a significant role in digital fabrication processes, enhancing the design and construction sector as a flexible and adaptable manufacturing technique. The multi-axis mobility of industrial robotic arms, their adaptability with various end effectors, and their capacity to execute repeated tasks with high precision render this technology more versatile than conventional CNC machines (Gramazio & Kohler, 2008). The capability to execute several manufacturing processes, including handling, welding, milling, hot wire cutting, and 3D printing on a unified platform, allows robotic production to provide innovative solutions that surpass geometric architectural intricacy (Dunn, 2012). Furthermore, its integration with parametric design and digital modelling software facilitates the creation of unique shapes and promotes new assembly techniques in both prefabrication and building site applications (Mcgee & De Leon, 2014). In this setting, robotic manufacturing emerges as a significant technology that provides novel options in architectural applications by transcending the conventional barriers between design and production.

The robot arm may be conceived as a variable function instrument of digital manufacture. The "end effector" of the robot arm can hold tools with varied functionalities and be programmed to conduct sophisticated tasks. The robot arm can now execute a wide range of activities, including handling, putting, machining, welding, and scanning, thanks to these recommendations. Dunn (2012) investigates how a robot arm may be beneficial in the manufacture of shapes with complicated geometry due to its multi-joint construction and capacity to position itself using the material to be treated as a reference.

A 6-axis robot arm's working area significantly increases when installed on a horizontal movement mechanism. Robot arms are suitable for repetitive or recurring jobs because of their exceptional precision.

Another key characteristic of the robot arms is that they may be programmed in detail. According to Hauschild and Karzel (2011), there are three basic types of this programming: "procedure" programming, in which the designer calculates the working procedure ahead of time; "teaching" programming, in which the designer controls the work manually, and "self-determination" programming, in which the robot arm automatically decides which steps to take using the sensors placed on it. It may be used in additive processes by replacing the robot arms' ends with 3D printer heads. Furthermore, by moving the architectural components beyond the human hand's sensibility, it opens to new design options. Figure 3.2 highlights several categories of robots and their operational domains. Depending on their axis motions and construction, robot arms come in various forms, each offering unique benefits for specific manufacturing procedures (Ramb, 2023).

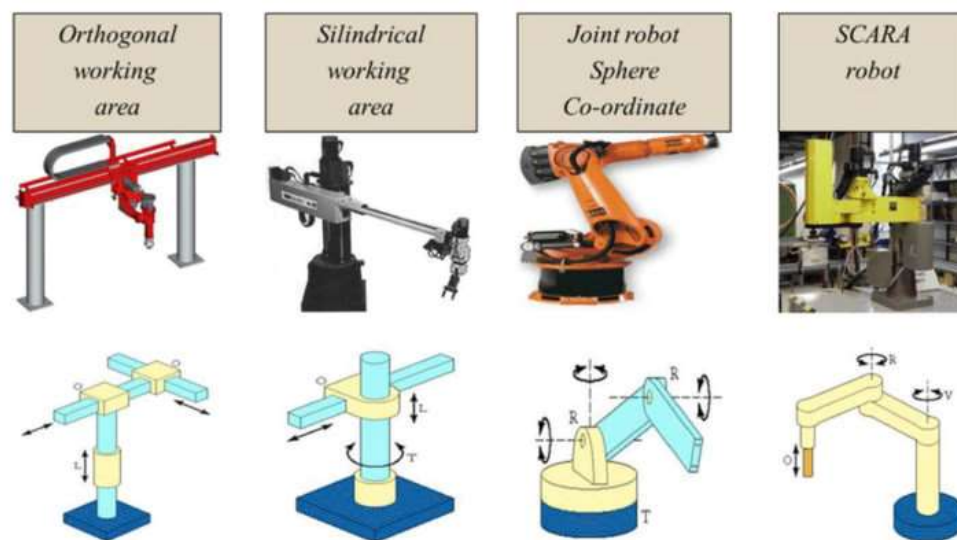


Figure 3.2 Basic types of industrial robots (Ramb, 2023)

These titles refer to the different types of Robots used in robotic fabrication processes. Each is optimized for specific materials, dimensions, and application areas. The techniques used in this context are defined as Orthogonal Working Area, Cylindrical Working Area, Joint Robot Sphere Coordinate, and SCARA Robot.

The Orthogonal Working Area category includes portal robots. Ramp (2023) states that these machines are commonly utilized in transportation and precision cutting tasks due to their vast workspace and great accuracy. Cylindrical Working Area robots typically operate in three dimensions, utilising both rotational and linear motions. Assembly and welding are two areas where these robots shine due to their ability to navigate tight spaces (Dunn, 2012). Joint Robot Sphere Coordinate robots can move in many directions simultaneously, like a human arm. Particularly in the context of free-form production and the processing of surfaces with intricate geometries, they are extensively employed (Kolarevic, 2004). SCARA Robot is recognized as a Selective Compliance Assembly Robot Arm (SCRA). Assembling tasks requiring rapid and accurate horizontal movement takes advantage of them (Bechthold, 2010).

Another beneficial application of robotic fabrication is its incorporation into production processes using digital fabrication techniques. Attaching a drilling head to the end of a robot arm can act as a precision milling tool for subtractive manufacturing processes. Additionally, integrating a hot wire into an auxiliary mechanism allows the robot to cut materials such as foam or lightweight composites with high precision. These techniques are fundamental in additive manufacturing workflows, where hybrid processes (combining additive, subtractive, and formative methods) are increasingly familiar to create complex architectural components. Robot arms are used in milling, such as inserting a drilling head on the ends and cutting with a hot wire inserted in an auxiliary mechanism, notably in additive techniques. (Figure 3.3).

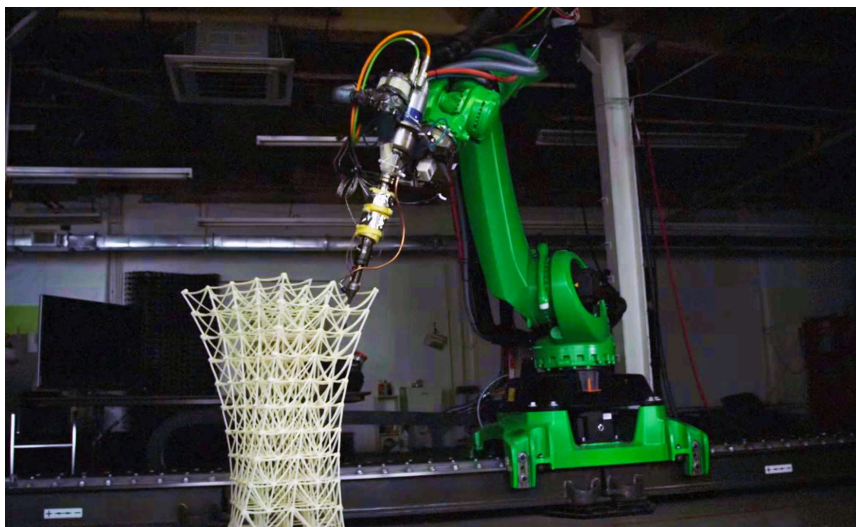


Figure 3.3 3D printing robot (Romeo, n.d.)

Both in prefabrication and on-site, robots can aid with assembly procedures, such as putting bricks or lifting and moving facade parts. The distances that can be reached by static or fixed-arm robots on the road are restricted by their arm length and fixed placements (Tehrani et al., 2022). On the other hand, Goessens et al. (2018) highlighted that the use of drones as an on-site assembly tool is currently being researched. Despite existing limits in placement precision and payload capabilities, robotic assembly with partially learned control has enormous potential for enabling complicated form assembly that results in superior performance architectural or structural solutions.

Integration between CAD and CAM technologies facilitates digital manufacturing processes, and robot programming is an important part of this process. Similar to the programming method for traditional CNC machines, offline programming of robots is done by transferring data from CAD to CAM software. Programming robots offline resembles the traditional approach used with CNC (Computer Numerical Control) machines, involving the transfer of data from CAD to CAM software, followed by NC processing (Da Silva Rosa, 2022). It is done on a computer outside the robotic cell. A CNC milling machine then receives the G-Code code. Additionally, a KUKA SimPro/CAMRob kinematic finisher/simulator is required for robot milling. Consequently, a digital process with at least three software products from various providers is created. Lee et al. (2022) show how parametric design tools for robot milling can be used to simplify the digital CAD-CAM-Robot workflow. The CAD software will demonstrate how to build the KUKA|prc (parametric robot control) component in Grasshopper, a Rhinoceros parametric design plug-in, to enhance offline programming. Understanding the robot's data processing allows custom scripting or offline programming to generate KRL code, enabling architectural bulk customization. Cartesian coordinate programming is needed for exact instrument placement in most architectural applications (Van Der Heijden, 2023). The robot's kinematics are decoded in real-time based on the end effector's location and orientation during KRL code execution in the control unit, eliminating the need for parametric modelling (Çapunaman & Gürsoy, 2024). In contrast, by addressing accessibility issues and possible collisions, the designer may maximize the available workspace by modelling the robot's kinematics within a design environment.

In reality, CAD technologies enable architects to embrace geometric complexity and diversity in design, whereas CAM technologies respond to the implementation of such distinct creative ideas. In recent years, the use of computer numerically controlled (CNC) manufacturing machines to make building components with customized shapes, textures, or forms has become a common practice in architecture and building construction. The industrial robot, which was initially built for other disciplines based on the logic of mass production, presents several significant potentials for a profession such as architecture that deals with non-standards. The robot may be configured to do a wide range of additive, subtractive, and formant manufacturing procedures that are often performed by different CNC machines by installing the right-end effector. Its 6-axis or more mobility in space already adds a more significant degree of freedom to the production process. With this advancement, research into other more particular processes, such as material handling, may broaden the effect of CAM in architecture beyond the fabrication of building components and into the construction of building elements.

In conclusion, after the crafts and mass production paradigms, architects are now confronted with a new digital technology scenario that allows for non-standard forms of design and construction. Sousa and Duarte (1970) state that the current global proliferation of digital technology has fuelled increased interest in investigating the distinctive forms and constructive solutions that may previously be developed and implemented in modern architecture. Due to automation concerns and budgetary constraints, Van Der Heijden (2023) claims that industrial robots have been used in full-scale construction in Japan since the 1980s to replace manual labour, with differing degrees of success. As Bechthold (2010) noted, using robots in "custom build" requires the development of automated programming techniques. Its objective is to make it possible for a broad range of architects to use robots that are as easy to use as typical CNC machines facilitating an intuitive approach to mass customization. Robotic fabrication technologies are revolutionising design processes within the architecture and construction sectors. They enable the creation of complex geometries, enhance precision, and facilitate customized production, all while minimising material waste and promoting sustainable, innovative building solutions (Fowdur et al., 2025).

Chapter 4

Industry 4.0 and Construction 4.0

Industry 4.0 is revolutionizing organizations globally with cutting-edge technologies like IoT, robotics, big data, and AI (González-Sarmiento et al., 2021). This paradigm shift emphasizes digital linkages, automation, and cyber-physical systems for intelligent and successful production (Schwab, 2017). Lekan et al. (2021) highlighted that Industry 4.0 is revolutionizing construction as well as product manufacturing. Building 4.0, an industry-specific adaption of Industry 4.0, aims to revolutionize buildings by using cutting-edge technologies. According to Oesterreich and Teuteberg (2016), it uses technologies like digital twins, 3D printing, smart sensors, and BIM to improve the built environment's resilience, sustainability, and productivity. Long-standing issues in the construction sector, such as labour-intensive procedures, excessive material waste, and inefficiencies, are being addressed by the implementation of Construction 4.0 technology, which also opens the door for more flexible and data-driven solutions (Sawhney et al., 2020).

The combination of modern technology and construction methods signals the beginning of a new age in which automation, digitization, and real-time decision-making improve traditional methods. In this regard, Construction 4.0 aims to satisfy the increasing need for more innovative, greener, and more robust infrastructure systems in addition to being in line with global trends toward sustainability and resource efficiency (Dallasega et al., 2018). With an emphasis on digital manufacturing techniques and their application to novel materials and processes, the link between the construction sector and Industry 4.0 is examined in this chapter.

4.1 Industry 4.0

Industry 4.0 underpins digital advances that are transforming product and service delivery and industrial business paradigms (Statsenko et al., 2022). Interconnected, real-time, self-optimizing production systems underpin Industry 4.0. German Industry 4.0 initially focused on digital production, digitization, and integrating value chains and organizations. Industry 4.0 integrates production and operations with ICT to enable digitalised operations and supply chains, human-technology interaction, process and technology, and semi-autonomous smart factories that prioritise decision-making. using near-real-time data gathering and transmission (Dalenogare et al., 2018). Many technologies and data management systems, particularly the expanding usage of ICT in industry and the falling cost of sensors have enabled revolutionary industrial change. Through interconnection and near-real-time data gathering and processing, Hecklau et al. (2016) claimed that artificial intelligence (AI) helps operations and supply chains swiftly adjust to external environmental changes. Industry 4.0 technologies provide innovation, flexibility, customisation, and operational efficiency, according to Lee et al. (2014). Figure 4.1 shows four stages of industry transformation.

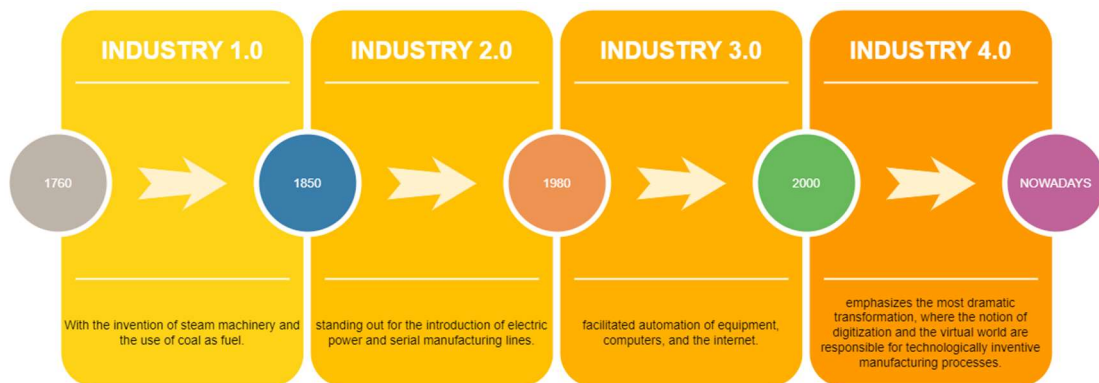


Figure 4.1 The Transition from Industry 1.0 to 4.0. Adapted from (Da Xu et. al., 2018 & Yin et.al., 2017)

Firstly, the Industry 1.0 mechanical stage implemented mechanical procedures and reinforced its economic structure by incorporating water-powered mechanical equipment into agriculture. The second occurred in the 1850s, when Industry 2.0, also known as the electrification phase, brought electricity. Electrical energy facilitated the creation of a technique for mass manufacturing that relied on human skill to boost success. Digital computers and telecommunications brought about industry 3.0 in the 1980s (Enders,

2023). In order to accomplish more ingenious production processes, Industry 4.0 encompasses future industrial development trends, including the operation of smart factories and the utilisation of Cyber-Physical Systems (CPS), the Internet of Things (IoT), and Cyber-Physical Production Systems (CPPS), and its applications (Zhou et al., 2015). Pradhananga et al. (2021) argued that the construction industry can potentially benefit from the use of novel ideas associated with Industry 4.0. Virtual reality can assist the construction machinery manufacturing sector in producing high-quality, cost-effective, and timely construction machinery (Wu et al., 2013).

In summary, the integration of design, construction, and maintenance of infrastructure with practical component integration for industrial and technical progress positions Industry 4.0 to facilitate the emergence of Construction 4.0.

4.2 Construction 4.0

Ronald Berger was the first to utilize "Construction 4.0." in its 2016 research "Digitalisation in Construction: Building Europe's Path to "Construction 4.0". Craveiro et al. (2019) called the rising digitization of the construction sector due to automated production "Construction 4.0". Digital technologies, automation, and data analytics can enhance construction productivity and efficiency (Sawhney et al., 2020). These technologies include prefabrication, off-site construction, robotics and automation, IoT, VR, AR, and BIM. Rastogi (2017) highlighted that the construction sector has evolved over the past century, transferring techniques, procedures, technologies, abilities, and values from one generation to the next. Rastogi (2017) claims that the progression may be broadly summed up as follows:

- Construction 1.0: Mostly labour-intensive, with few specialist skills that are now quite widespread.
- Construction 2.0: Building site work remained mostly labour-intensive even after the mid-1900s when specialized specializations and significant automation through construction equipment were introduced. Nevertheless, because of schedule and expense overruns, productivity remained comparatively low.

- Construction 3.0: Lean processes and procedures, technology-driven architecture and design such as BIM, more software, and increased automation of construction tasks were developed in the second part of the 20th century.
- Construction 4.0: Four significant innovations, such as technology, Gen Y and Gen Z, mass customization, and sustainability, have occurred in the twenty-first century, especially in the last eight to ten years, and they are growing rapidly.

Despite being a relatively new phenomenon, Construction 4.0 has roots in the 1960s and 1970s, when the construction industry started utilizing digital technologies. However, significant advancements were not made until the 1990s, when BIM was created. In the 2000s, it was widely used in industry (Llatasa et al., 2020). Consequently, stakeholders would be able to collaborate more effectively and reduce the possibility of making mistakes. Figure 4.2 depicts the evolution of the construction industry (Rastogi, 2017). Previously, economic growth was driven by agriculture, and from the early twentieth century until the mid-seventies, the economy was driven by the production of various items to improve people's lives. Later, growth was driven by the service economy, which included logistics and information technology. It is now being driven by internationally disruptive digital technologies (IoT, 3D printing, and a variety of other specialized developing technologies).

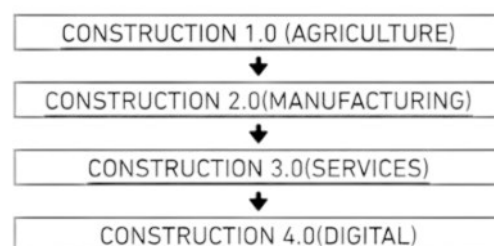


Figure 4.2 The evaluation of Construction 4.0 (Produced by The Author)

The Internet of Things (IoT)/Sensors, 3D printing, virtual and augmented reality, artificial intelligence, and other technologies have become more affordable and widely available, contributing significantly to this revolution. The emphasis on the building is shifting quickly toward mass customization, particularly in urban areas, while rural areas are rapidly transitioning to mass manufacturing (both for housing and other infrastructure). Sustainability and green building, which were formerly low priority due

to changing global climatic circumstances, are now given significant focus due to the developments provided by Construction 4.0. evolution. The construction sector generally lags behind in innovation and is hesitant to adopt new technologies (Clough, 2024). This may be largely attributed to the structure of the sector, which is comprised of a huge number of companies, extensive supply networks, and big-scale projects that involve a significant level of risk. Even though it is still in its infancy, the concept of building 4.0 has the potential to bring about a significant transformation in the planning, building, and maintenance procedures for infrastructure and the built environment (Kor et al., 2022). Therefore, most people consider C4.0 to be a technical breakthrough that promises significant improvements in building projects' time, costs, and performance (Van Der Heijden, 2023). Accelerated change in organizations worldwide and current global megatrends present significant difficulties to the construction sector. The increase in the global population necessitates the supply of cheap housing, social services, transportation, and infrastructure. The construction sector must consider the demands of society, assuring cheap costs, sustainable construction, and economic progress. The industry will need to prepare for technological and cultural changes in digital structure in order to quickly transition to a new dimension of the fourth industrial revolution. The design, development, operation, and maintenance of real estate, infrastructure, and other tangible assets are all changing slowly. According to Mhlanga (2023), from building material suppliers to construction equipment suppliers, contractors, engineers, architects, planning firms, and project owners. Furthermore, Mhlanga (2023) claims that the construction industry is going through a technological revolution that will drastically change the entire construction value chain from design to demolition.

Construction 4.0 refers to a notion that conveys the digital transformation of the building industry. In addition, it conveys the move from conventional construction techniques to procedures that are more efficient, environmentally friendly, and inventive (Hamalainen & Salmi, 2022). This paradigm change revolutionizes the value chain by thoroughly impacting design, manufacturing, construction, and maintenance processes. The pursuit of fundamental objectives such as efficiency, cost containment, and time management within the industry is expediting the integration of sophisticated technology. This is the context in which Construction 4.0 technologies are applicable (Van Der Heijden, 2023). The realm of digital construction holds considerable promise for all stakeholders engaged in the industry. In addition, the introduction of digital technologies

will improve the industry's efficiency, resulting in improved profitability and a safer workplace for everybody. Offering more appealing employment options to ambitious people can also help to close the present skills gap. To succeed in construction, players must adhere to key ideals that provide clear criteria for decision-making. Technologies, including BIM, 3D printing, robotic automation, IoT, AI, and augmented and virtual reality, are facilitating the transition of the construction industry from a conventional paradigm to one centered on digitalization. These technologies enable more effective management of processes, more sustainable material use, reduced error rates, and safer working environments.

This transformation process seeks to establish a more safe, sustainable, and productive workplace and integrate digital technology into the industry. Within this framework, the notion of Construction 4.0 symbolises the transformation of the construction industry from a conventional perspective to a digital-focused methodology. The implementation of several C4.0 technologies has facilitated this advancement.

4.3 Construction 4.0 Technologies

Technologies that could potentially alter the construction sector were defined, including BIM, IoT, sensors, robots, and augmented reality (Van Der Heijden, 2023). In addition, Industry 4.0 compatible technologies, such as building information modelling (BIM), virtual reality (VR), augmented reality (AR), and mixed reality (MR), are being quickly adopted by the construction sector. These technologies have different levels of maturity. BIM, cloud computing, mobile computing, and modularisation technologies have achieved relative maturity due to their extensive industrial adoption, while AR, VR, and MR remain in early developmental stages (Y. Chen et al., 2022). All of these technologies aim to increase output, reduce expenses, and facilitate better cooperation and communication between those involved in the building business. Also, with these technological advancements, Construction 4.0 is no longer a “conventional building” (Kozlovska et al., 2021). Kunic and Naboni (2023) claim that a significant change in planning, designing, constructing, utilising, and reusing cities, infrastructure, and buildings is expected due to the convergence of new technologies, digitalisation, cyber-physical systems, and human-robot collaborations.

Construction 4.0 incorporates advanced technologies, transforming traditional construction practices into more efficient, innovative, and sustainable processes (Y. Chen et al., 2022). BIM digitally represents physical and functional characteristics, facilitating better planning and collaboration. Baki (2025) argues that AR enhances the real-world environment with digital overlays, while VR creates immersive design, training, and visualization simulations. Robotics automates tasks such as bricklaying and welding, enhancing precision and decreasing labour costs. 3D printing facilitates the layer-by-layer fabrication of construction components, frequently utilising sustainable materials. AI contributes to predictive analytics and automation, optimizing project management and decision-making. Drones assist in site surveys, inspections, and progress monitoring, offering a bird's-eye view of construction sites. Finally, the IoT connects devices to collect and share real-time data, enabling more thoughtful and more responsive construction practices. These technologies enhance efficiency, sustainability, and innovation through advanced tools and methods such as automation, connectivity, and data-driven decision-making. Construction 4.0 is anticipated to encourage stakeholder engagement and information exchange. Collaborative technologies, cloud computing, and digital platforms enable smooth communication and information sharing across borders. Van Der Heijden (2023) argued that this encourages collaboration between clients, contractors, engineers, and architects, leading to more inclusive decision-making procedures and better project results. In fact, actual research has shown that Construction 4.0 technology fosters more social cohesion among all stakeholders and improves collaborative decision-making. Furthermore, facilitating stakeholder engagement in sharing expertise and insights throughout the project may enhance transparency and accessibility of project data, thereby fostering a collaborative culture (Bolhassan et al., 2022).

- **Building Information Modelling (BIM)**

BIM enables stakeholders to engage in collaborative efforts regarding project design, construction, and operation throughout the project's lifespan. It has 3D models containing data and information on many project elements, unlike 2D drawings. In addition, BIM allows 4D modelling, which adds a temporal dimension to a 3D building or infrastructure model (Schranz, 2021). The 4D model enables complete planning, construction, and information on a building or infrastructure project's life cycle. 4D modelling can assess what repairs are needed and when or how they may be made to

guarantee resources can be readily preserved when a building is demolished. While BIM has shown its potential to improve efficiency, stakeholder participation, and other advantages, the broader literature notes several constraints. BIM requires a significant investment in the construction business and training the current workforce. This is especially hard for small enterprises and those in emerging areas. Also, BIM implementation may be hindered by poor regulation. In addition to taking a long time, construction operations entailed complicated procedures involving management, process control, and quality control to completion, which led to various challenges (Arayici et al., 2012). Also, changing ground conditions can lead to building delays and expense overruns. Still, it unites all the projects and individuals engaged in the building process. BIM, for example, has data on geometry, materials, structure, energy performance, thermal efficiency, installations, and manufacturing costs. Masons could be directed step-by-step through the building process by augmented reality instructions that digitally overlay the workstation.

- **Augmented Reality (AR)**

Augmented Reality (AR) is not a new technology; it is commonly used in games. These technologies in the building business still have several phases to investigate. One great example is the merging of BIM with AR. AR-BIM enables users to bring immersive views to life, enhance existing difficulties and on-site integration, and present information in the as-built environment as intended (Chai et al., 2019). Both a data publishing tool and an information aggregator, AR lets the user actively interact with the published material, passively study the information shown, and instantly team with others from far-off places (S. M. Ahmed et al., 2020). With growing momentum in the building sector, AR is being investigated and tested throughout the project life in several use cases, like motivating AR-enabled production planning and enabling a remote expert system. Statsenko et al. (2022) claim that the Internet of Things technology, referred to as AR, enables the real-time integration of digital data with the user's environment. AR enhances the operator's perception of reality by superimposing digital information onto objects in the immediate environment.

- **Virtual Reality (VR)**

Virtual Reality (VR) may profoundly influence stakeholders' perceptions and the effective execution of building projects. Thabet et al. (2002) assert that VR technology

can improve efficiency and effectiveness across all project phases, encompassing initial conceptual design, detailed design, planning, preparation, and final construction completion. Using caps with 360-degree views, VR gives consumers a realistic and immersive experience that lets them explore a different environment. Li et al. (2018) claim that construction VR can be used for two purposes: safety education and training, where workers will receive training in a secure setting rather than on-site, which can be pricy and unsafe, and hazard identification, which enables crews to identify, evaluate, and eliminate possible hazards.

- **Robotics**

Robotics is the use of technologies to perform or replicate human activities (Van Der Heijden, 2023). Various sectors, such as manufacturing and aviation, extensively utilise robotics; the construction industry is similarly affected. Sawhney et al. (2020) argued that this technique is prevalent in the construction industry, especially in the context of high-rise building construction. Automation, robotics, and collaborative robots (cobots) will drastically change the construction industry (Burden et al., 2022). Automation, cobots, and robots are very useful in developing processes that range from labour-intensive, repetitive tasks to complex operations requiring accuracy and precision. Van Der Heijden (2023) explained that robots can effectively complete repetitive tasks that would take time and be physically demanding for human labour. According to Petersen et al. (2019), when taken to its most literal sense, the term "robotics" refers to the use of robots and sophisticated sensors throughout the whole building process. In addition, this helps to limit the number of errors that are caused by humans and generates outcomes of higher quality by ensuring that activities are carried out in a precise and consistent manner.

- **3D Printing**

Three-dimensional (3D) printing technologies are transforming traditional construction methods by enabling the accurate and cost-effective fabrication of complex architectural structures and components. Tabassum and Mir (2023) claim that 3D printing in the construction industry offers benefits such as design flexibility, customisation, cost savings, sustainability, and time savings. Li et al. (2022) assert that design flexibility is a crucial element of additive manufacturing and 3D printing. These technologies enable the

construction of intricate structures and complex geometries that are difficult or unachievable with traditional building methods. Engineers and architects can explore innovative concepts by overcoming the constraints of traditional production methods (Van Der Heijden, 2023). A further advantage of 3D printing in Construction 4.0 is the reduction of costs. These techniques minimise material waste and reduce costs by utilising exact quantities of construction materials. Moreover, automating certain building processes, optimising resource allocation, and decreasing project timelines through 3D printing can lead to significant labour cost savings. One notable benefit of 3D printing in construction is the reduction in time required for project completion. The duration of construction is notably reduced when components are manufactured swiftly and accurately on-site. Van Der Heijden (2023) argued that the initial expenses related to the acquisition and upkeep of 3D printing equipment, along with the necessary training for construction professionals, present considerable obstacles, particularly for enterprises in developing nations.

- **Artificial Intelligence (AI)**

Another technology that is anticipated to revolutionize conventional building procedures is artificial intelligence (AI), which enables resource optimization, improved project management, data-driven decision-making, and enhanced productivity. AI is a crucial component of Construction 4.0 as it enhances project planning. Massive amounts of data, such as environmental factors, design specifications, past project data, and resource availability, may be gathered and analysed with the help of these technologies (Pan & Zhang, 2021). Based on the information obtained from sensors and Internet of Things devices that are put in infrastructure and construction equipment, Van Der Heijden (2023) asserts that these systems can anticipate the breakdown of equipment, determine the need for repair, and plan preventative maintenance actions. The integration of these technologies into existing construction workflows and procedures necessitates organisational and cultural modifications. Similar to other technologies, small and medium-sized enterprises, as well as those in emerging economies, may encounter significant difficulties in effectively utilising AI, Big Data and Analytics tools, so construction companies should prioritise investment in workforce training and upskilling (Shad et al., 2022). Consequently, construction projects exhibit increased efficiency, reduced delays, and decreased costs.

- **Drones**

Emerging digital technologies seem to enhance productivity while decreasing construction projects' overall time and expense. Motavwa and Kardakou (2018) indicate that drones have recently been incorporated into the construction industry, following their widespread use in various other sectors, including mining, public safety, military operations, scientific research, security surveillance, and agriculture. Uncrewed aerial vehicles (UAV), or Autonomous Aerial aircraft, are tiny, remotely piloted aerial aircraft. In early 2006, UAVs were primarily utilized for military purposes. Their use in the building industry and other fields has expanded recently. Nisser and Westin (2006) explained that UAVs are predominantly utilised in the construction sector for monitoring and inspection tasks associated with facility management, construction, and surveying. The construction industry uses aerial vehicles for a variety of purposes, including surveying and mapping, construction supervision, wetland/environmental drainage and erosion assessment, traffic surveillance, emergency services, high mast lighting, wind turbines, cell towers, highways, bridges, roads, cell towers and building façades and roofs. Operators can share images with remote subcontractors, internal company personnel, and on-site employees (Bourque, 2017). UAVs provide critical support and cost efficiency through comprehensive surveillance of remote and hard-to-access locations. From this viewpoint, UAVs provide optimal access, while 360° panoramas depict real-time scenarios.

- **Internet of Things (IoT)**

The Internet of Things (IoT) significantly enhances Construction 4.0 by facilitating the integration and connection of physical items, sensors, and systems (Metinal & Ayalp, 2025). Chung et al. (2023) highlighted that IoT technology improves construction operations, productivity, and safety by collecting and sending real-time data to enhance construction sites. Van Der Heijden (2023) claims that more control over building materials may be obtained using IoT-enabled monitoring and inventory management systems, which can cut down on waste and delays. In addition, IoT technology also enables construction companies to optimize their usage of resources. Tool and equipment tracking provided by IoT encourages effective distribution, eliminates loss and theft, and boosts responsibility (Katiyar & Kumar, 2021). IoT may be crucial in bolstering safety procedures as well. By identifying fatigue and exposure to potentially harmful goods or

environments, wearable sensors, and other IoT devices can monitor the health and well-being of employees. These sensors' real-time data reduce the chance of accidents and improve worker safety by facilitating early intervention and preventive measures. In the event of a crisis or disaster, prompt identification and assistance are made possible via IoT-enabled location tracking and emergency response systems. Organizations can adopt industry-wide improvements and obtain valuable insights by collecting data from various construction sectors. IoT-generated data may be analysed using data analytics to identify patterns, streamline processes, and enhance decision-making (Dardouri, 2022).

4.4 Core Values of Construction 4.0

Sustainability, efficiency, safety, and innovation are transforming the construction industry (Oesterreich & Teuteberg, 2016). In this revolution, Industry 4.0 ideas are applied to building, and creating building 4.0 (Shafei et al., 2022). Construction 4.0 is based on Industry 4.0, although it focuses on construction. Construction 4.0 includes all technical advances related to embracing new processes, materials, and market work methods (Al-Sinan et al., 2023). Osunsanmi et al. (2020) define "C4.0" as a paradigm change that prioritizes cyber-physical systems (CPS) and built environment digitalisation. Furthermore, using cutting-edge technology in construction activities to increase sustainability, safety, and productivity is known as C4.0 (Shafei et al., 2022). This transition involves using innovative technologies to enhance building processes' sustainability, flexibility, and connectivity (Dallasega et al., 2018). Construction 4.0 is underpinned by a series of core corporate principles that shape the development of the industry. In addition to serving as the guiding principles for Construction 4.0, core values serve as the cornerstones of the industry's digital and automation-based transition (Hjelseth et al., 2023). In order to attain high performance, Construction 4.0 encourages the application of digitalization in the built environment through a CPS (Osunsanmi et al., 2020). Using automation, data-driven applications, and cutting-edge digital technology, Construction 4.0 will transform conventional construction techniques and signify a paradigm change in the construction sector. This change is consistent with the fundamental principles guiding these contemporary methods' application and development. Kumar et al. (2024) describe that the goal of Construction 4.0 is to develop

a more robust, flexible, and sustainable sector by embracing the concepts of innovation, sustainability, efficiency, and connection. At the core of Construction 4.0 is innovation, which drives the use of advanced technologies such as robotics, the Internet of Things (IoT), artificial intelligence (AI), and building information modelling (BIM) (Hjelseth et al., 2023). These developments are creating new opportunities in construction, material optimization, project management, and more innovative, more effective construction methods. In Table 4.1, by using new technologies such as robots, AI, BIM, DTT, AM, and BDA, among others, certain sub-criteria for each core value try to make the construction industry a safer, more efficient, and longer-lasting place to work.

Table 4.1 Core Values of Construction 4.0

Core Value	Description	Sub-Criteria
Sustainability	Focus on reducing environmental impact through energy-efficient practices, waste minimization, and the use of low-carbon materials. Emphasis on ethical sourcing, use of sustainable materials, and aligning with circular economy principles.	• Environmental Impact Reduction (EIR) • Energy Efficiency (EE) • Ethical Sourcing and Low-Impact Materials (ELM) • Circular Economy Principles (CEP)
Efficiency	Use of robotics, AI, and digital tools to optimize construction processes, reduce human error, and save time and costs.	• Process Optimization (PO) • Cost and Time Savings (CTS)
Flexibility	Integrating technologies like 3D printing and parametric design for mass customization and adaptive design solutions.	• Mass Customization (MC) • Adaptive Design and Fabrication (ADF)
Connectivity	Facilitating real-time collaboration among stakeholders using BIM and digital twin technologies to improve project outcomes.	• Building Information Modelling (BIM) • Digital Twin Technology (DTT)
Safety	Enhancing worker safety through automation, predictive analytics, and real-time monitoring to reduce on-site risks.	• Improved Worker Safety (IWS) • Predictive Analytics (PA)
Innovation	Adoption of cutting-edge technologies such as AI, robotics, and 3D printing to advance construction capabilities.	• Robotics and AI Integration (RAI) • Additive Manufacturing (AM)
Data-Driven Decision Making	Leveraging big data, IoT, and real-time monitoring to optimize construction processes and enable predictive analytics.	• Big Data and Analytics (BDA) • Real-Time Monitoring and Feedback (RMF)

Sustainability, efficiency, saving money and time, flexibility, connectivity, safety, innovation, and data-driven decision-making are some of the core values that have been developed. These values not only guide Construction 4.0 but also show the future direction of an industry ready to face modern challenges with modern solutions. The construction 4.0 core values include sustainability, efficiency, flexibility, connectivity, safety, innovation, and data-driven decision-making by supporting them with contemporary technology and digital solutions. Objectives aimed at minimising environmental effects, expediting processes, enhancing cooperation, improving worker safety, and facilitating informed decision-making through data analysis influence these principles.

4.4.1 Sustainability

The construction industry imposes significant strain because of natural resource usage and environmental repercussions, underscoring the necessity for sustainability (Ametepey & Ansah, 2015). Sustainability necessitates energy efficiency with a comprehensive knowledge encompassing ecological, economic, and social elements (Buyle et al., 2013). In this context, environmental impact reduction (EIR), energy efficiency (EE), ethical resource use and low-impact materials (ELM), and circular economy principles (CEP) are garnering attention. Digital manufacturing and building 4.0 methodologies substantially enhance sustainable building practices through the optimization of material usage, energy conservation, and the utilization of recyclable resources (Bilal et al., 2023).

Environmental Impact Reduction: Sustainability in Construction 4.0 aims to minimize the environmental impact of construction operations. In addition, this is accomplished using computerized tools that maximize material consumption, decrease waste, and promote energy-efficient designs, all of which lead to more ecologically friendly building practices. Construction consumes a considerable quantity of natural resources and has various environmental effects. These environmental issues are a key motivator for the sustainable design movement. Construction operations have an influence on the environment at all stages of progress. These impacts start with initial work on the property and continue through construction, use, and demolition at the end of a building's life. Ametepey and Ansah (2015) assert that, despite its brevity concerning

other phases of a building's lifecycle, construction exerts several notable environmental impacts. The construction sector has placed more emphasis on sustainable technologies and construction methods as environmental issues gain public consciousness. Building sustainability is influenced not just by energy use but also by ecological, economic, and social aspects. There are now several ways to evaluate sustainability from different perspectives and for different audiences as consumers grow more conscious of these issues. These consist of Material Flow Analysis (MFA), Environmental Audit, Economic and Environmental Accounting System (EEAS), and Environmental Impact Assessment (EIA). Additionally, Buyle et al. (2013) explained that specific systems, like BREEAM and LEED, which provide measurement scores for green buildings, were developed specifically for the construction sector.

In essence, Construction 4.0 prioritizes mitigating environmental problems as a primary objective. In this context, it seeks to mitigate the environmental harm inflicted by construction operations. This value strives to safeguard natural resources, reduce carbon emissions, and promote sustainable construction practices by minimizing waste creation. Strategies employed to attain the aim include optimising material and energy usage using digital simulations and AI-assisted analyses, utilizing eco-friendly building materials, and minimizing carbon footprint by digitizing logistical activities.

Energy Efficiency: Implementing sustainable construction practices will make Construction 4.0 initiative activities more energy efficient. According to Zekić-Sušac et al. (2021), numerous countries have implemented action plans to minimize energy usage in their construction sector. The attractiveness of energy efficiency is well recognized, not just for its ability to save money on power bills but also for its ability to reduce emissions. With the emergence of Construction 4.0, cutting-edge technology is helping to reduce energy usage in the construction industry (Bilal et al., 2023). Energy-efficient building design and construction are made possible by digital technologies, which improve long-term environmental performance while lowering energy consumption and operating expenses (Badar et al., 2024). Guaranteeing that buildings have a lower carbon footprint throughout their lifetime aligns with the global drive toward sustainable development goals (Hafez et al., 2022).

In conclusion, reducing energy consumption is crucial for the creation of more sustainable and economically viable buildings. Reducing energy consumption and

operational costs throughout the life cycle of buildings is a key objective of this value (Wu et al., 2011). To attain this objective, instances such as the incorporation of intelligent energy management systems, the modelling of energy-efficient edifices using digital design tools, and the optimization of energy use using IoT devices are utilized.

Ethical Sourcing and Low-Impact Materials: There is increasing demand in the construction industry to use sustainable practices to manage resource constraints and minimize their environmental impact. Sustainable building materials help to achieve these aims by lowering carbon emissions, decreasing waste, and encouraging circular economy concepts (Patil et al., 2024). The construction must meet the demand for sustainable raw material sources. The construction sector is a cornerstone of contemporary civilization, shaping the physical infrastructure that underpins everyday life. However, its substantial environmental impact has prompted a critical re-evaluation of previous methods. The extraction of raw materials, energy-intensive manufacturing processes, and high emissions connected with construction and operations all indicate the need for a paradigm change in industrial building practices. Innovative sustainable materials, long considered niche alternatives, are now emerging as viable, cost-effective alternatives to established solutions (Mfon & Bassey, 2023). As part of the construction 4.0 paradigm, sustainability extends to the supply chain. Iuorio and Kitayama (2024) highlighted that in order to promote ethical sourcing and lessen the total environmental effect of the building, digital technologies make it possible to use sustainable, low-impact materials like recycled or earth-based materials.

In essence, ethical sourcing entails regulating resource usage in alignment with sustainability ideals. The conservation of natural resources, the transition to sustainable raw materials, and the selection of environmentally benign materials are key objectives of this value. Implementing recyclable materials, prioritizing local and renewable resources, and maintaining resource traceability through supply chain digitalization are examples of methods being used to attain the objective.

Circular Economy Principles: With its 'take-make-dispose' methodology, the traditional linear economic model is a major departure from the circular economy. Furthermore, Barbhuiya et al. (2024) suggest a regenerative and restorative approach to economic activity. Getting as many uses out of a thing as feasible is the aim. Reusing materials in accordance with the reuse idea is a significant component of this process

(Donnelly, 2023). The construction sector contributes considerably to global waste production and resource depletion. Conventional building procedures generate a tremendous quantity of waste, posing a serious environmental risk. Sustainable solutions must be developed to address these significant challenges, notably through the use of circular economy concepts (Saroosh & Khan, 2024). On a global scale, the building sector accounts for about 40% of resource utilization, waste generation, and over 33% of greenhouse gas emissions. According to Gowsiga et al. (2023), one of the options for resolving these unsustainable challenges is the adoption of the circular economy and its principles. The "circular economy" concept is increasingly acknowledged as a significant concern for the building sector and a major topic on the legislative agenda. This economic approach aims to increase resource use and minimize waste (Afshari & Górecki, 2019). A circular system lowers emissions, waste, and resource input by postponing, closing, and reducing energy and material loops. According to Geissdoerfer et al. (2017), design, maintenance, repair, reuse, remanufacturing, refurbishing, recycling, and repurposing may all contribute to this goal. Charter (2018) claims that the circular economy emphasises design thinking, systems thinking, product life extension, and recycling to develop models that are economically and environmentally sustainable. Construction and demolition waste can contain hazardous substances that need to be identified and eliminated from building materials prior to recycling. This process is essential to prevent the inclusion of hazardous substances in the recycling loop, thereby mitigating health and environmental risks in subsequent product cycles (Keena & Friedman, 2024).

In essence, the circular economy is essentially a business concept that aims to reduce resource waste by prolonging the life of products. The objectives of this value include minimising resource use, enhancing recycling rates, and optimising waste management. Instances such as the reusability of components through modular construction designs, reassessment of construction and demolition debris, and on-site manufacturing and waste management utilising digital fabrication techniques are implemented to attain the objective. In addition, digital manufacturing processes enable the employment of local, renewable resources, lowering carbon impact and supporting more sustainable construction practices.

4.4.2 Efficiency

Cost and time savings (CTS) and process optimization (PO) are among the most important elements that directly influence the success of construction projects. According to Shanmuganathan and Baskar (2016), having an efficient approach to project management is of utmost importance in avoiding time and money overruns and ensuring that projects are finished on time. Analyses that are backed by artificial intelligence, robotic construction technologies, and digital project management tools have the ability to optimise resource allocation, which would result in faster project completion at cheaper costs (Van Der Heijden, 2023). The concepts of process optimisation, cost, and time savings are examined in this part, and solutions to boost construction efficiency within the framework of Construction 4.0 are explained.

Process Optimization: Simulation and process optimization are essential components of the construction business to increase construction quality and efficiency. Automation of construction workflows using AI, robots, and IoT technology ensures a more fluid, accurate, and error-free process. Automating repetitive and complex operations decreases human intervention while increasing efficiency. By simulating several aspects of the building process, including material selection, component assembly, staff scheduling, and so on, construction process simulation may help identify possible issues early on and avoid mistakes and conflicts. On the other hand, by appropriately allocating resources and processes, construction process optimization may improve construction efficiency, reduce expenses, and minimize waste (Zhao, 2024). In several areas relating to construction, optimization can turn out valuable. The uniqueness of managing building projects lies in their unpredictable and dynamic environment, despite the frequent repeating procedures, one of which is optimization. At this stage, the proper flow of information is critical for optimizing building processes. Thus, evaluating which of the available solution strategies is best suited for a particular situation is crucial. As a result, a greater understanding of modern process optimization methodologies can benefit all construction industry decision-makers, particularly project managers and production preparation specialists (Venkrbec et al., 2018).

In summary, Construction 4.0 regards process optimisation as a crucial element for enhancing efficiency and minimizing errors in construction operations. Its objectives include improving resource utilisation, augmenting production, decreasing expenses, and

minimising waste. The objectives also include data-driven process management utilising AI and IoT technologies, material selection through simulation tools, workforce planning and pre-testing of assembly processes, and the automation of repetitive and complex jobs using robotic systems.

Cost and Time Savings: Despite recent improvements, the construction industry is still falling compared to other sectors regarding productivity, quality, and efficiency. This situation calls for modifications in management practices, alongside enhancements in production and product development processes (Santos & Famá, 2023). However, in any construction sector, the primary aim is to complete the project successfully. In order to accomplish this goal, the construction industry has to effectively manage time, cost, and performance. If time is not effectively managed, cost overruns arise in building projects. A solid project management approach is to control costs effectively (Shanmuganathan & Baskar, 2016). Project cost control defines collaboration in the construction sector, governance, owner organization and personnel, project execution techniques, reporting, and communication (Basak, 2006). Implementing digital technologies such as robotic construction and AI-powered analytics allows for more effective resource allocation, resulting in cost savings and speedier project completion timeframes. The technical advances of Construction 4.0 have directly resulted in increased planning and resource allocation efficiency (Van Der Heijden, 2023).

In conclusion, the two most significant factors in the construction industry that directly impact project performance are time and cost savings. One objective is guaranteeing that projects are executed more swiftly and at reduced expenses. The objectives include expediting work processes through robotic construction systems and automation, enhancing resource management via artificial intelligence-assisted analysis, and refining communication, reporting, and cooperation using digital project management tools.

4.4.3 Flexibility

Flexibility in construction refers to the ability to adapt to changing conditions, user needs, and design specifications. This idea is essential to modern building practices, which are changing how structures are planned, built, and altered via digital technology and cutting-edge manufacturing processes. In addition to helping to streamline the building process, flexibility fosters the creation of more environmentally friendly and

user-friendly construction solutions (Senatore et al., 2018). The concepts of mass customisation (MC) and adaptable design and fabrication (ADF) are currently receiving attention in this area.

Mass Customization: Mass customisation is a business approach that combines two opposed production theories: mass manufacturing and customisation. Mass customisation may lead to a problematic production environment with high volume and a great product variety, where consumers demand customised goods to cost the same as mass-manufactured items (Radder & Louw, 1999). Barman and Canizares (2015) stated that mass customization starts economies of manufacturing by producing units at a low cost and enabling flexibility and individual product modification. The contemporary architectural and construction sectors commonly view customization as a method for producing incredibly unique 3D-shaped elements or constructions. Compared to standardised mass production, customisation is a strategic approach that allows customers to purchase personalised or even bespoke items at the same or lower cost (Bock & Linner, n.d.). One of the primary advantages of Construction 4.0 is its capacity to deliver mass customisation, allowing for the construction of individualised, unique architectural ideas. The manufacturing business has effectively used mass customization to meet clients' unique demands at a cost-effective price. Construction companies must concentrate on novel improvement strategies and mass customisation concepts to effectively raise the manufacturing industry's competitiveness and efficiency (Jensen et al., 2020). Keshtkar et al. (2023) argued that digital fabrication techniques and parametrically driven design procedures enable the building of complex structures suited to individual demands or preferences previously unavailable using traditional construction methods.

In summary, mass customisation is a unique production methodology that enables the customisation of individual items at little expense. Construction 4.0 introduces this concept to the construction industry. Furthermore, Mantha et al. (2020) claim that enabling the production of tailored building components that meet the precise requirements of consumers. One of its objectives is to create customised and distinctive building designs while preserving economic scalability. Its objectives include facilitating adaptable design methodologies using parametric design and digital modelling tools, creating intricate architectural components via digital fabrication methods like 3D printing, and incorporating quick prototypes and manufacturing processes in response to user requirements.

Adaptive Design and Fabrication: A mechanical structure, construction, or building component that may alter its geometry, position, configuration, or physical characteristics in reaction to environmental changes is called an adaptable system (Akgün, 2021). Technology has played an ever-more-important role in enabling architectural innovation and flexibility, especially in the last decades of the 20th century. Adaptive systems are becoming increasingly helpful in structural engineering and architecture thanks to automation, computers, and materials science developments. These advancements have led to the integration of sensors, control intelligence, and actuators into all adaptive systems from that era (Senatore, Duffour, & Winslow, 2018). Because of their advantages over traditional structures, this interaction has raised interest in these systems, and academics, engineers, and architects have created and implemented a variety of adaptable systems to meet user demands (Schumacher et al., 2019). Whether it is a design solution, a shift in the climate, or basic sustainability considerations, constantly shifting site conditions require various approaches and solutions. According to Mésároš et al. (2021), the optimal level of construction quality may be achieved while adapting to changing conditions. Digital construction technologies provide more adaptable designs that accommodate site-specific circumstances and client needs. Adaptive manufacturing procedures allow modifications to be easily integrated throughout production, eliminating delays and guaranteeing that the end product is compatible with the original concept (Thirumal et al., 2024).

In conclusion, adaptive design and fabrication indicate the capacity of architectural components to react to climatic fluctuations, human needs, or design specifications. One objective is to attain optimal construction quality and develop sustainable solutions by adjusting to always-evolving site circumstances. Other objectives include the creation of smart building components that incorporate sensor and control systems, the facilitation of design modifications through digital manufacturing processes, and the mitigation of project delays by ensuring flexibility in the production process.

4.4.4 Connectivity

Building Information Modelling (BIM) and Digital Twin Technologies (DTT) are essential developments in this revolution. BIM enhances collaboration and transparency by overseeing design and construction processes in a virtual setting, whereas Kumar et al. (2024) claim that DTT facilitates real-time monitoring, modelling, and predictive

analysis by generating a virtual replica of physical assets. This section will cover the applications of BIM and DTT in construction projects, their benefits, and how these technologies foster a more interconnected work environment within the construction sector.

BIM (Building Information Modelling): BIM is a technique that enhances design, construction, and management processes via digital models in construction projects (Oesterreich & Teuteberg, 2016). Reducing waste and inefficiencies can be achieved using industrial buildings that BIM permits. At the physical layer, having real-time access to enormous amounts of data would increase decision-making and give project teams financial incentives to work together and develop (Sawhney et al., 2020). Oesterreich and Teuteberg (2016) explained that BIM is a crucial technology for advancing the construction industry and supporting Industry 4.0. A key element of BIM is the bidirectional synchronization of virtual and actual spaces. In addition to improving construction control and gathering valuable data for future maintenance and design, this coordination produces a digital duplicate of the building (Begić & Galić, 2021). Additionally, BIM allows contractors, engineers, and architects to collaborate in real-time on a project. By integrating digital models, a shared, current picture of the building's construction and design is produced, facilitating better communication, reducing disagreements, and boosting project efficiency overall (Elalwani & Çalışkan, 2024).

In conclusion, through digital modelling and data exchange, BIM is a crucial technology that makes building project processes more effective, transparent, and cooperative. Its objective is to minimise waste by promoting data-driven decision-making, enhancing communication, and ensuring efficiency in project management. The objective is to grant stakeholders real-time access to project data, facilitate the concurrent synchronisation of virtual and physical environments with digital twin models, gather essential data for maintenance and design during the building lifecycle, and enhance project efficiency through improved communication.

Digital Twin Technology: The digital twin, a sophisticated digital technology, enables the construction industry to progress toward intelligent construction and digital transformation. Its ultimate objective is to attain precise digital simulation for the thorough optimisation of all building project stages (Yang et al., 2024). Digital twinning uses intelligent enabling technologies to digitally represent a physical object by gathering

real-time updates and ensuring the virtual model accurately or nearly replicates the original object (Madubuike et al., 2022). Additionally, digital twins can significantly improve project management regarding cost and schedule. Hu et al. (2022) assert that time-based analysis is an established manufacturing technology within Industry 4.0, utilising digital twin-enabled technologies to enhance project timelines, reduce disruptions, and mitigate the risk of delays. To improve product service, these technologies create realistic digital duplicates of tangible resources and allow for two-way, real-time communication for modelling and decision-making. Mateev (2020) highlighted that as a ground-breaking technical advancement with the potential to revolutionize tomorrow's industrial scene, the Digital Twin has received a lot of traction. This technology promotes a connected construction environment where real-time data and results inform decisions and are optimized by enabling continuous monitoring, modelling, and predictive analysis.

In summary, Wang and Guo (2022) explained that a digital twin is a real-time digital representation of a physical structure within a virtual environment. Using this technology, a construction site may be linked to ongoing modelling, monitoring, and predictive analysis. It aims to minimise expenses and time inefficiencies, avert disruptions, and enhance project management precision. The objective is to enhance project timelines by acquiring real-time data, facilitating proactive decision-making via continuous monitoring and predictive analysis, accurately replicating physical assets, and establishing a bidirectional data link with smart sensors and IoT devices.

4.4.5 Safety

Using sensors, IoT devices, and machine learning algorithms, data-driven predictive analytics techniques can identify possible safety issues beforehand and reduce risks (Shafei et al., 2024). Predictive modelling seeks to avert workplace accidents and enhance operational efficiency by facilitating proactive management decisions (Adamtsevich, 2023). This section will examine the enhancement of safety measures using digital technology and the creative methods employed to augment occupational safety in the construction industry. The benefits of technologies like robotic systems, IoT sensors, and augmented reality regarding safety are outlined in the Improved Worker Safety (IWS) section. In contrast, the Predictive Analytics (PA) section will explore the influence of data analytics and machine learning algorithms on construction safety.

Improved Worker Safety: Safety on construction sites has become a primary focus for the global construction sector. Construction labour is frequently viewed as risky and placing workers at risk of significant injuries and diseases (Musarat et al., 2022). The successful completion of any construction project depends on the coordinated efforts of many individuals from all walks of life and professional fields, all of whom must adhere to strict safety protocols (Ogundipe et al., 2018). Various strategies for health and safety have evolved over time to enhance working conditions. According to Abina et al. (2023), technologies associated with Industry4.0, including augmented reality, robotics, automation, sensor-based technologies, drones, big data, uncrewed aerial vehicles, the internet of things, photogrammetry, wearable technology, virtual reality, radio frequency identification, building information modelling, 3D printing, four-dimensional (4D) computer-aided design, and laser scanning, have been identified as potential safety applications in building project delivery. Robots and automation can replace hazardous tasks, reducing the possibility of accidents or injuries at work. Additionally, digital technology such as wearables and sensors offer real-time worker health and safety monitoring, allowing for proactive interventions and a safer work environment (Trivedi & Alqahtani, 2024).

In conclusion, in order to ensure worker safety, digital technology, and automation systems must be used to create safer work environments with less hazardous jobs. Among the objectives are reducing the possibility of worker accidents and injuries and ensuring safe working conditions. The objectives include using robots and automation technologies to perform risky tasks without human intervention, wearable technology and sensors to monitor employee health in real-time, drones and augmented reality applications to monitor dangerous areas remotely, and proactive interventions to identify and eliminate hazards before they become serious.

Predictive Analytics: Construction 4.0 technology, such as predictive analytics, is crucial for increasing built-environment resilience. One kind of data analysis technique, predictive analysis, forecasts how a system or its parts will behave so that management decisions may be made in advance and crises can be avoided. Furthermore, since there are moderate to strong connections between technologies that increase the resilience of the built environment, Construction 4.0 technologies must be adopted collectively (Shafei et al., 2024). Additionally, predictive analysis is extensively utilized across multiple industries, such as information technology, banking and financial services, insurance, the

public sector, pharmaceuticals, and communications. Instances of predictive analysis in the construction sector are present, though they tend to be more innovative and focus on the operation of advanced machinery (Adamtsevich, 2023). To identify and reduce potential issues before they arise, predictive analytics makes use of data from sensors, Internet of Things devices, and machine learning algorithms. Site safety and project dependability are increased due to better planning, risk assessment, and well-informed decision-making.

In summary, one technological advancement that makes it possible to identify and stop possible security issues before they arise is data-driven predictive analytics. It seeks to enhance project planning, risk assessment, and decision-making procedures in order to improve field safety and project continuity. It seeks to analyse data using sensors, IoT devices, and machine learning algorithms; forecast possible risks ahead of time and take the appropriate precautions; make management decisions early to avoid crises; and develop predictive models for safer operation procedures and better machine performance.

4.4.6 Innovation

Integrating Robotics and Artificial Intelligence (RAI) diminishes mistake rates and enhances productivity by optimising automation, data analysis, and predictive maintenance in building projects (Bryson et al., 2017). Additive Manufacturing (AM) technologies facilitate the creation of intricate structural components by minimising material waste and enhancing design flexibility (Ozturk, 2018). This section will explain the application of robots and artificial intelligence in the construction sector and their contributions to project management and construction processes. Furthermore, a discussion of the benefits of additive manufacturing techniques over conventional manufacturing methods will be conducted, along with an analysis of their impact on design flexibility, material optimisation, and sustainable production processes in the construction industry.

Robotics and AI Integration: AI and robotics are key elements of Construction 4.0 developments. These technologies improve building speed, accuracy, and flexibility by providing capabilities beyond typical human approaches. The combination of AI and robots has greatly enhanced predictive maintenance procedures. The construction industry regularly uses robotics technology, especially when building big projects (Taher,

2021). A machine that mimics human thought processes is called artificial intelligence (Rao, 2020). Additionally, a variety of construction jobs, including painting, bricklaying, and earthworks, may be performed by robots. C4.0 refers to a specific version or classification within a defined system or framework, often indicating a particular stage or level of development. It is essential to understand its context for accurate application and analysis. AI can be utilised in adaptive vision systems within the construction industry to recognise different site elements and to analyse sounds and patterns for detailed monitoring of construction workers' progress (Bryson et al., 2017). Baum et al. (2017) identify three categories of artificial intelligence: artificial narrow intelligence, artificial general intelligence, and artificial superintelligence. AI algorithms use data from sensors implanted in robotic systems to forecast maintenance requirements, decrease downtime, and enhance overall asset management (Mia & Shuford, 2024). Robots can self-assemble complicated structures, while AI improves predictive modelling and decision-making. AI-powered construction robots offer proactive measures by anticipating future concerns and forecasting construction hurdles, ensuring that possible issues are handled before they become more serious (Liu et al., 2024).

In conclusion, robotics and AI are two cutting-edge technologies that improve building operations' speed, accuracy, and flexibility. Their objectives include improving project management, decreasing mistake rates, and raising productivity in building operations. Their objectives include using AI-supported algorithms to analyse sensor data and forecast maintenance needs beforehand, allowing robots to self-assemble intricate structures, using voice and image recognition systems to monitor construction sites, and enhancing project performance with sophisticated decision support systems.

Additive Manufacturing: One Additive Manufacturing (AM) type is 3D printing. AM technology produces parts with intricate geometry, giving designers more "design freedom" (Bikas et al., 2016). This means that designing, which includes data on materials, processes, and 3D models, is one of the three most important parts of using and analysing additive manufacturing (Olsson et al., 2021). As additive manufacturing technology has advanced over the past three decades, 3D printing has also advanced. According to Craveiro et al. (2019), AM entails the construction of objects through the assembly of materials based on 3D model data, typically employing a layer-by-layer approach, in contrast to subtractive manufacturing methods like conventional machining. Furthermore, AM refers to a manufacturing system's ability to adjust and enhance

operations in response to real-time data, feedback, and changing situations (Rana & Jani, 2023). Technology for 3D printing provides benefits over conventional production methods and allows for design optimization. 3D printing technology has consequently drawn much attention as a fresh strategic concern in the building sector. The construction sector views 3D printing as a new building technology idea (Ozturk, 2018). In the construction industry, 3D printing reduces material waste while enabling the creation of distinctive building components. Gonidakis et al. (2024) stated that AM techniques broaden the scope and creativity of construction projects by enabling the production of intricate shapes that would be difficult or impossible to produce using traditional methods.

In summary, building components that are impossible to produce using conventional techniques may now be produced thanks to additive manufacturing technologies, which provide design freedom. Its objectives include encouraging design improvements and decreasing material waste, enabling more ecologically friendly production methods. Creation of building pieces with complicated geometry, the use of 3D printers to reduce material waste, the customisation of building components using parametric designs, and the realisation of concepts that are not achievable with conventional techniques.

4.4.7 Data-Driven Decision Making

While real-time monitoring and feedback (RMF) systems enable project managers to monitor performance in real-time and respond promptly, big data and analytical (BDA) approaches enable the optimisation of critical aspects of construction projects, including labor efficiency, energy use, and material consumption (Liu et al., 2024). This section will examine the application of BDA in construction projects and the influence of data analytics on decision-making processes. The examination will focus on the impact of RMF technology on enhancing project performance, boosting efficiency, and improving environmental quality.

Big Data and Analytics: Due to significant developments in digital technology for data management, big data has emerged as a crucial component of many research fields. In contrast, Munawar et al. (2022) argued that even construction is a data-intensive business where most data are generated but not thoroughly evaluated because of a lack of technology adoption. Despite producing many data, the construction industry is not as adopting Big Data as other industries. There is increasing interest in leveraging Big Data

technologies to increase construction process efficiency as the technology required to store, compute, process, analyse, and display Big Data becomes more reasonably priced (Bilal et al., 2016). Utilizing big data, C4.0 evaluates and enhances several aspects of construction projects, such as labour productivity, energy usage, and material use. Data analytics guarantees optimal project outcomes and appropriate resource deployment by facilitating informed decision-making. Construction operations are expected to become more efficient due to the development of technology for the storage, computation, processing, analysis, and presentation of big data (Garyaev & Garyaeva, 2019).

In conclusion, big data and analytics are important technologies that support process optimisation by enabling more informed decisions at every stage of construction projects. One goal is to improve project outcomes by allocating resources correctly. Big data can be used to evaluate labour, material, and energy consumption data, improve decision-making processes by analysing data generated throughout the structure's life cycle, and provide accurate information.

Real-Time Monitoring and Feedback: Utilising C4.0 technologies, including more common dashboards, may ease construction monitoring by providing efficiency, cheap development and operation costs, and insight into construction performance (Yousif et al., 2022). Continuous real-time data collecting on building operations is made possible by the integration of IoT devices and sensors. This data enables project managers to monitor construction progress, track performance, and make timely modifications, therefore enhancing the quality and efficiency of work completed (Ibrahim et al., 2024). In order to improve the quality of life inside buildings, it is essential to monitor building performance.

In summary, real-time monitoring and feedback tools make effective project management possible, which provide tracking performance and advancement in the field. The objectives include minimising any delays, improving efficiency, and raising project quality. Among the objectives of giving project managers prompt, precise input and enabling immediate modifications are continuous data collecting via IoT devices and sensors, performance monitoring, and assessment of environmental quality indicators.

Chapter 5

A Review of Digitally Manufactured Earthen Structures

In this section, following the concepts of traditional earth-based materials, industry 4.0, and construction 4.0, the selected case studies were examined, and the examined case studies were classified in terms of material, technique, and labour and evaluated according to the core values of construction 4.0. Finally, according to the evaluation results, the relationship between the case studies and the core values of construction 4.0 was revealed. The thesis's goal in conducting this comparative study is not only to identify each project's strengths and weaknesses but also to provide strategic recommendations to close gaps and maximize compliance with Construction 4.0 principles, as well as to lay the groundwork for future construction industry innovations.

5.1 Proposed Approach

Gray and Hughes (2001) define technology as ‘the sum of scientific knowledge, technical methods, skills, tools, equipment, empirical applications and objective products of man.’ When explanations regarding technology are examined, it is seen that an abstract or concrete product and the knowledge, method (process, action, technique, etc.), and tools (material, equipment, labour, etc.) used to realize the product are emphasized. These can also be considered as components of technology. Technology's essential function or purpose is to expand the boundaries of human possibilities (Edis, 2006).

The purpose of this thesis is to assess and analyse the characteristics of numerous earthen constructions such as Gaia, Mud Frontiers, Printed Stairs, Clay Rotunda, Digital Soil, and Terramia included in the C.4.0 framework, with a focus on their alignment with developing technologies, sustainability goals, and efficiency techniques. This study attempts to determine how each project embraces the Construction 4.0 principles by applying a systematic criterion that looks at sustainability, efficiency, flexibility, connectivity, security, innovation, and data-driven decision-making. Innovation and

technology integration were taken into consideration when selecting cases. The extent to which the projects adopted digital and robotic production techniques was evaluated. Sustainability elements such as reducing environmental impacts due to the use of earth-based materials and the use of local materials were taken into consideration. The projects' applicability in different geographical and climatic conditions and their suitability for production on a large scale were examined.

The following criteria were used in the evaluation criteria and analysis of the selected projects:

- Sustainability Criteria: Reduction in carbon footprint, Increase in the use of Ethical Sourcing and Low Impact Materials (ELM), Improvement in the material life cycle sustainability index.
- Efficiency Criteria: Reduction in project delivery time, Cost savings achieved through Process Optimization (PO) and Cost and Time Savings (CTS), and Increase in resource use efficiency.
- Flexibility Criteria: Rate of adoption rate of Mass Customization (MC) and modular construction solutions, Ability to accommodate design changes throughout the construction process without delay or cost overruns, Variety of materials, techniques, and workflows applicable across different project types, Number of project-specific adjustments successfully implemented using Adaptive Design and Manufacturing (ADF).
- Safety Criteria: Reduction in site accidents, Increased deployment of Improved Worker Safety (IWS) technologies, Rates of worker satisfaction, and productivity improvements.
- Innovation Criteria: Success of advanced technologies such as Additive Manufacturing (AM), Robotics and Artificial Intelligence Integration (RAI), Gains in precision, speed, and resource savings through innovative techniques, Patents, or new methods developed as part of projects.

- **Connectivity Criteria:** Rate of integration of Building Information Modelling (BIM) and Digital Twin Technology (DTT) across project phases; Improvements in real-time communication and collaboration between stakeholders; Success of digitalized and monitored workflows through connected tools.
- **Data-Driven Decision-Making Criteria:** Insights generated through Big Data Analytics (BDA) and their contribution to decision-making; Increase in efficiency and performance optimization achieved using Real-Time Monitoring and Feedback (RMF); Volume of data collected and analysed for predictive modelling and risk management.

In the following sections, firstly, the selected case studies will be examined in terms of material, technique, and labour characteristics based on technology components. Then, these characteristics will be interpreted within the framework of primary evaluation criteria such as sustainability, efficiency, flexibility, connectivity, security, innovation, and data-driven decision-making. By applying these comprehensive criteria, this thesis aims to provide a nuanced evaluation of each project, identifying strengths and areas for improvement. The ultimate goal is to offer strategic recommendations that enhance alignment with Construction 4.0 principles, thereby contributing to the evolution of sustainable and efficient practices in the construction industry.

5.2 Digital and Robotic Fabrication Cases Produced with Earth-Based Materials

Due to increased resource usage and environmental restrictions, the construction industry is at a crossroads, and established methods are under pressure to change. Adobe, cob, and rammed earth are traditional building materials with high thermal efficiency and low environmental impact that provide viable paths to sustainable construction (Hamard et al., 2016). However, their traditional application methods frequently hinder scalability, structural accuracy, and adaptability across climates. Recent advances in digital and robotic manufacturing have created new possibilities for adobe and cob construction by integrating computational design, robotic 3D printing, and sustainable materials. These

technologies provide precise regulation of material composition, structural integrity, and energy efficiency, providing durable, climate-resilient edifices with a negligible carbon impact (Firoozi et al., 2024). Notable initiatives demonstrate the potential for these strategies to alter construction by using local resources, minimizing waste, and increasing building performance. In order to show how digital innovation may rejuvenate conventional materials to suit contemporary environmental issues, this section presents projects that are examples of robotic and digital fabrication with earthen materials.

- **Gaia**

Gaia highlights the promise of 3D printing technology for sustainable design and ecologically friendly construction solutions (Figure 5.1). The project demonstrates the feasibility of low-cost building with local resources and serves as an essential model for energy-efficient and low-environmental-impact constructions. WASP Corporation created the eco-friendly house prototype Gaia, which was constructed with 3D printing technology. Named using raw earth as the main binder of the component combination, The project demonstrates how locally and naturally obtained materials can be used to create affordable building solutions. To reduce the structure's environmental effect and increase energy efficiency, raw soil, rice hulls, and hydraulic lime were utilized during construction (Jordahn, 2020).

The building was built using raw earth that was sourced from the area. This material was combined with leftover rice hulls from rice cultivation to improve its durability and insulating qualities. In order to increase the material's mechanical strength, hydraulic lime was also used as a binder. In order to bring Gaia to life, RiceHouse Corporation created a composite consisting of 40% shredded rice straw, 25% site soil, 30% clay, 40% silt, and 30% sand (Rice House, 2022). Additionally, this blend of recyclable and natural materials has a minimal carbon imprint. For the technique, a large-scale 3D printer known as Crane WASP was used to build Gaia. Using additive manufacturing, this technology applies the material directly to the ground to construct the building. The walls' energy performance has improved due to the strong thermal insulation qualities that the additive construction has given them. Compared to conventional building techniques, material waste has been dramatically decreased by 3D printing technology. Additionally, the delivery and preparation of materials marked the start of Gaia's building phase. A homogenous

combination of hydraulic lime, rice hulls, and locally sourced raw soil was created in the initial phase. The Crane WASP 3D printer was fed this combination, and the additive manufacturing process was used to construct the structure's walls. The printing process was meticulously regulated to guarantee that the construction materials had the proper viscosity and drying time. Only the processes of material preparation, printer calibration, and final inspection included human participation. The 3D printer's modular design allowed for process deployment in the field and provided flexibility to accommodate various structure types (Chiusoli, 2024).



Figure 5.1 Gaia Project (Chiusoli, 2024)

- **Mud Frontiers**

Mud Frontiers is an innovative project by architects Ronald Rael and Virginia San Fratello (Figure 5.2). It combines traditional Adobe architecture with modern 3D printing technology to explore sustainable and accessible construction methods. The project was carried out in the San Luis Valley of Colorado, on the former borderlands of the Rio Grande River. Using materials such as local soil, water, and wheat straw, four different structures were constructed using a portable 3D printer: Hearth, Beacon, Lookout, and Kiln. The hearth emphasizes the cultural differences between the exterior and interior of the structure by extending beyond the walls and remaining flush on the inside. It also examines how the thin adobe wall structure can be strengthened by using rot-resistant, locally available juniper wood to hold the two walls together (Fratello & Rael, 2020). Beacon, which illuminated at night, revealing the differences between the concave and convex curves that make up the mud walls, is investigating how the texture and undulations of a 3D-printed mud coil might produce the smallest practical confinement structural solution. The coils are illuminated at night to highlight the distinction between

the concave and convex curves of the mud walls. Furthermore, Fratello and Rael (2020) stated that Lookout is a building study featuring a 3D-printed staircase constructed entirely by Adobe. In addition, this demonstrates how airy and big walls may be used to construct insulating interior enclosures, particularly in the San Luis Valley's severe winter environment, when temperatures can drop as low as -20° F (Gibson, 2020). Many of the presented strategies are explored in the furnace, such as wavy or interlocking mud deposition to construct insulating and structural walls. In order to suck in oxygen and hold onto heat, a section of locally obtained clay is additionally burnt in a kiln using juniper wood that is burning hot. The Mud Frontiers project combines modern 3D printing technology with the use of micaceous clay inspired by the traditions of Taos and Picuris Pueblo (Picuris Pueblo | Native American Pottery, n.d.). In this project, a micaceous coating is applied to the surface of each 3D-printed ceramic vessel. During the firing process, when the carbon is completely burned off, a shimmering gold color appears on the surface, while areas, where the carbon has not burned off, reveal deep black tones reminiscent of Taos Pueblo traditions. Micaceous clay is traditionally used by the Taos and Picuris Pueblos of Northern New Mexico, and when fired, it imparts a distinctive metallic sheen. As a result, the Mud Frontiers project aims to preserve cultural heritage through innovative methods and provide sustainable architectural solutions by combining the traditional use of micaceous clay with modern 3D printing technology.



Figure 5.2 Mud Frontiers Project (Mud Frontiers Rael San Fratello, n.d.)

- **Printed Stairs**

The Printed Stairs project shows the integration of conventional materials with cutting-edge 3D printing technology to produce multipurpose architectural systems (Figure 5.3). WASP offers the chance to participate in existing architectural research

topics and access firm laboratories and technology through worldwide networks with architectural design colleges (Carlota, 2019). 3D printing technology is increasingly being recognized as a feasible building choice due to improvements in design approaches brought about by educational programs. The IAAC's Open Thesis Manufacturing program trains academics and professionals in robotic manufacturing, materials engineering, and computational design to promote innovative design alternatives in bioclimatic architecture. The project used a mixture of locally available clay and rice fibers to create 40 cm thick walls, which feature interlocking wooden elements for improved structural integrity. This technique guarantees structural stability while providing aesthetic variety, demonstrating the capabilities of 3D printing in contemporary buildings. It has the potential to stimulate the creation of novel building scenarios (Chiusoli, 2019). This work is a crucial first step toward developing load-bearing clay buildings. According to Chiusoli (2019), the wall was built with a combination of clay and rice fibres given by RiceHouse specifically for this purpose. A total of 2 cubic meters of material were utilized during the 40-hour printing process, which included interior modelling of various surfaces that might add both durability and visual appeal. Given Gaia and the outcomes of this project, Crane WASP is proving to be a more and more helpful tool for transferring design logic to actual construction models, making it simple to test novel architectural systems. Furthermore, it promotes 3D printing development in the construction sector.



Figure 5.3 Printed Stairs Project (Say, 2024)

- **Clay Rotunda**

A self-contained, earth-based cylindrical structure, the Clay Rotunda is the outside, soundproof shell of SE MusicLab, a top-notch music theatre located in Bern's recently renovated Gurten Brewery (Figure 5.4). The cylindrical structure uses computational

design approaches and clay, a building material (Vasey et al., 2024). With just 15 cm of unreinforced clay, the structure is around 11 meters in circumference and 5 meters high. Over 30,000 soft clay bricks were produced on-site over 50 days using a mobile robotic machine. The wavy design increases the footprint and stabilizes the structure to avoid buckling, making Clay Rotunda very slim (Gramazio Kohler Research, n.d.). The Clay Rotunda combines sustainable, zero-waste building materials with advanced computational design techniques. The structure measures approximately 11 meters in diameter and stands 5 meters tall, constructed from 15 centimetres of unreinforced clay. Over a 50-day period, a mobile robotic system produced more than 30,000 soft clay bricks on-site, each measuring 9 cm in diameter and 15 cm in height (Gramazio Kohler Research, n.d.). The undulating design of the Rotunda enhances its structural stability by increasing the footprint and reducing buckling effects. Extensive material testing was conducted to optimize the clay mixture, balancing workability, compressive strength, and minimal shrinkage. This project exemplifies the fusion of traditional building materials with modern technology to create sustainable architectural solutions.



Figure 5.4 Clay Rotunda Project (Gramazio Kohler Research, n.d.)

- **Digital Soil**

The notion of "Digital Soil" defines an innovative methodology in sustainable design and construction, emphasizing the utilization of biodegradable materials and sophisticated production processes (Figure 5.5). Granular materials made of organic components present a competitive substitute for non-biodegradable composites, which are extensively used in digital manufacturing and building construction. Current materials research in architecture mainly supports tactics that encourage consistent, long-lasting, and uniform solutions, even though there is a need to develop alternatives to fuel-based solutions (Mitterberger & Derme, 2020). Materials such as soil present new opportunities

and difficulties due to their physical properties and changeability, which will change how we design, build, and integrate material systems and environmental factors (Barbacci, 2020). For the technique, Mitterberger and Derme (2020) highlighted an innovative earthen construction framework using high-resolution, 3D-printed biodegradable materials and cutting-edge robotic additive manufacturing. Furthermore, the research influences ideas like conformance and tolerance in digital manufacturing, particularly biomaterials and robotic production. There is a long history of using earth for construction. Recent advancements in clay architecture demonstrate how earthen constructions may provide innovative, flexible, and long-lasting buildings. However, today's large-scale earth-building techniques are limited to creating elementary forms with coarse geometric joints. Based on tolerance management techniques, Digital Soil predicts a shift in digital manufacturing and design practices. In this case, architectural resolution is influenced by geometric and material attributes, including natural evaporation rate, hydraulic conductivity, and material porosity, leading to a matter-driven design process (Bryson et al., 2022). Digital Soil shows the possibility for a recyclable, biodegradable production method for load-bearing architectural parts, opening up new sustainable material systems that might improve architectural buildings' ecological potential.

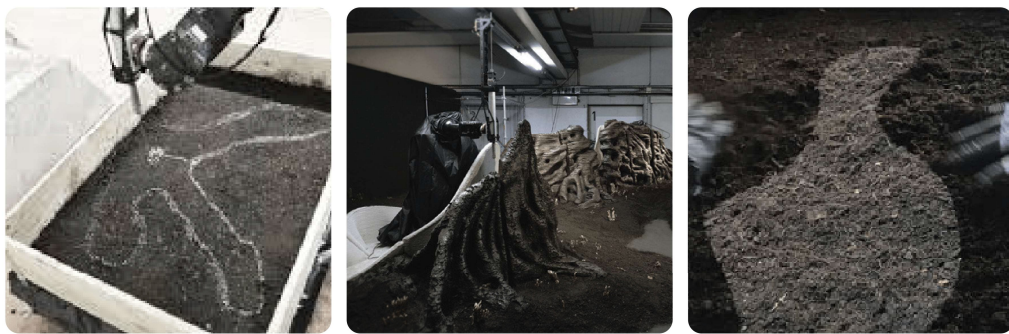


Figure 5.5 Digital Soil Project (Mitterberger & Derme, 2020)

- **Terramia**

The Terramia experiment demonstrates how using a drone to spray extremely thin mortar layers quickly can help meet construction deadlines and have the potential to save material if used in the shotcrete industry as a whole (Figure 5.6). The project, which was implemented in Palazzo Regione Lombardia in just 5 days, was made using local raw materials such as mud and bamboo. The skeleton, made of bamboo supplied from a forest

20 kilometers away from Milan, was covered with a specially made fabric (Reed, 2019). Drones were used to reduce the cost of construction, including the lifting and covering process of this fabric. Drone technology has also been used to blow wet mixes and dry fibers for insulation and durability. Focusing on combining innovative systems with raw and local materials to deliver faster and cheaper structures in various contexts, MuDD creates a new aesthetic and architectural form where human responsibility is at the forefront (Chaltiel et al., 2019). Contrary to the mega, sterile, and expensive future projections brought by technology in architecture, it draws a more humane and primitive futuristic scenario with the same technologies. Terramia, which shows the combination of digital tools such as drones with local material formulations, is a work that reminds us of our resources and what we need as humans, even though it is far from our current understanding of aesthetics. On the other hand, it also shows how technologies such as drones will take part in architecture.

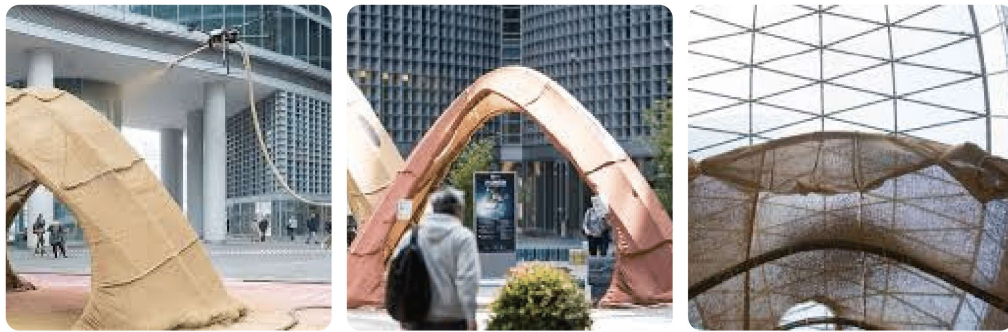


Figure 5.6 Terramia Project (Reed, 2019)

Table 5.1 summarizes the construction technologies based on materials, equipment, and techniques observed in the case projects. GAIA is produced using a 3D printer and digital factory method for housing units using natural materials and rice hydraulic lime; Mud Frontiers presents structures constructed using digital methods by combining clay and agricultural waste. The term "Clay Rotunda" describes a structure produced using natural materials and robotic techniques, whereas "Printed Stairs" refers to phases that are made from clay and rice fibers. Using robotic manufacturing techniques, Digital Soil creates a combination enhanced with polysaccharide-based hydrogels; Terramia is a structure that envisions the use of drones to apply bamboo arches coated in jute cloth and bio cement. This chart offers a crucial viewpoint regarding the utilization of sustainable materials and creative building methods.

Table 5.1 Classification of Cases According to Materials, Equipment, and Techniques

	CONSTRUCTION TECHNOLOGY			
	MATERIALS		EQUIPMENT	TECHNIQUE
	BASIC	ADDITIVES		
GAIA	soil, clay, silt, and sand from straw-chopped rice, rice husk, and hydraulic lime	rice hydraulic lime	3D Printer	Digital Fabrication
MUD FRONTIERS	clay	agricultural waste	3D Printer	Digital Fabrication
PRINTED STAIRS	a mixture of clay	rice fibres	3D Printer	Digital Fabrication
CLAY ROTUNDA	clay, sand, small stones, and water	-	Robot	Robotic Fabrication
DIGITAL SOIL	a mixture of clay and sand	polysaccharides based hydrogels	Robot	Robotic Fabrication
TERRAMIA	mud	stressed bamboo arches clad with jute fabric and bio mortars	Drone	The Drone Spraying

5.3 Findings and Discussion

In recent years, sustainable construction technologies and materials developments have gained significant attention as industries seek to address environmental challenges, increase efficiency, and improve overall performance. The integration of innovative techniques such as 3D printing, robotic fabrication, and drone spraying has facilitated the creation of structures with reduced environmental impact, increased flexibility, and optimized resource utilization. Furthermore, an emphasis on data-driven approaches, adaptable manufacturing techniques, and the use of locally available or waste-derived materials has further contributed to sustainable and cost-effective construction solutions.

This section comprehensively discusses the alignment between construction technologies and C4.0 core values by examining the digitally fabricated earthen structures. By reviewing these examples' materials, manufacturing techniques, and labour characteristics, this study highlights the role of modern technologies in advancing a sustainable, efficient, and adaptable construction sector. This section examines six digital

and robotic fabrication projects with earthen materials within the scope of Construction 4.0 core values and discusses the information obtained about each project.

Table 5.2 shows the contribution of construction technology dimensions, materials, technique, and labour, within the scope of the construction 4.0 core values for the Gaia Project.

The Gaia Project integrates advanced technology components to uphold core values across construction and design. Emphasizing sustainability, it utilizes local soil and organic materials to minimize carbon emissions, employs passive design strategies to reduce energy consumption, sources entirely local and recyclable materials, and achieves zero post-production waste with all materials being reusable. To enhance efficiency, the project accelerates construction through 3D printing technology and maximizes output with minimal labour via robotic production. Flexibility is addressed by designing structures adaptable to various local conditions and needs, optimizing geometry and material properties based on local soil characteristics. Connectivity is improved through digital models that enhance production efficiency and continuous monitoring of digital processes during production. Safety measures include employing robotic systems to eliminate human involvement in hazardous tasks and optimizing production processes based on material behaviour analysis. Innovation is demonstrated by providing fully integrated design and production processes through robotic systems and implementing layered structure production using 3D printers. Finally, data-driven decision-making is facilitated by managing processes through material data analysis and continuously monitoring soil properties during production. This comprehensive approach ensures the Gaia Project effectively integrates advanced technologies to uphold its core values across all aspects of construction and design. In summary, The Gaia Project emphasizes sustainability, efficiency, flexibility, connectivity, safety, innovation, and data-driven decision-making through advanced digital fabrication technologies. In addition, reducing environmental consequences has been made possible in large part by the use of local materials and the pursuit of a low carbon footprint. High accuracy and low energy consumption in the building process have been made possible by the combination of robotic systems with 3D printing technology. A successful example of contemporary digital building technology, Gaia stands out for its design that adheres to the circular economy and natural material usage while fusing creativity and adaptability with robotic operations.

Table 5.2 Gaia Project

			Technology Component		
Core Values		Description	Materials	Technique	Labor
Sustainability	EIR	The use of local soil and organic materials minimized carbon emissions during the project.	▪	◻	◻
	EE	Passive design strategies have reduced energy consumption.	▪	▪	◻
	ELM	The materials are entirely local and recyclable.	▪	◻	◻
	CEP	Post-production waste is zero, and all materials can be reused.	▪	◊	◻
Efficiency	PO	The construction process has been accelerated with 3D printing technology.	◻	▪	◻
	CTS	Robotic production has provided maximum production with minimum labor.	◻	▪	▪
Flexibility	MC	The design has been developed to be adaptable to different local conditions and needs.	◊	◊	◻
	ADF	The geometry and material properties of the project have been optimized according to local soil properties.	▪	◊	◻
Connectivity	BIM	Digital models have increased efficiency in production.	◻	◊	◻
	DTT	Digital processes were constantly followed during production.	◻	▪	◻
Safety	IWS	Robotic systems have prevented humans from being involved in dangerous processes.	◻	▪	▪
	PA	Production processes are optimized according to material behaviour.	▪	◊	◊
Innovation	RAI	Robotic systems provide fully integrated design and production processes.	◻	▪	◊
	AM	Layered structure production was carried out with 3D printers.	◊	▪	◊
Data-Driven Decision Making	BDA	Analysing material data managed the process.	▪	◻	◻
	RMF	Soil properties were continuously monitored during production.	▪	▪	◻

▪were present ◻not present ◊potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.3 shows the contribution of construction technology dimensions, materials, technique, and labour, within the scope of the construction 4.0 core values for the Mud Frontiers Project.

The Mud Frontiers Project illustrates the integration of cutting-edge technology with conventional building methods to maintain fundamental principles in construction and design. The project emphasizes sustainability by minimizing its carbon footprint through the use of local clay and organic materials, realizing energy savings relative to traditional methods, and using a circular economy approach in waste management. Robotic solutions enhance construction efficiency, facilitating project completion with less human labour and time. The design is flexible to local geographical circumstances, accommodating diverse geometries and configurations, thereby improving flexibility. Connectivity is enhanced by digital modelling techniques that augment production precision and facilitate real-time oversight throughout the building. Safety protocols encompass robotic manufacturing to safeguard workers and the application of predictive analytics grounded on material characteristics to oversee a secure operation. Innovation is exemplified by the modernization of conventional building techniques through robotic systems and the assurance of design uniqueness via layered manufacturing processes. Data-driven decision-making is enhanced by examining the soil's physical qualities to optimize operations and use real-time feedback to guide production decisions. In conclusion, this holistic approach guarantees that the Mud Frontiers Project successfully amalgamates new technology with conventional methods, maintaining its fundamental principles throughout all facets of construction and design.

Table 5.3 Mud Frontiers Project

			Technology Component		
Core Values		Description	Materials	Technique	Labor
Sustainability	EIR	Carbon footprint is reduced by using local clay and organic materials.	▪	◻	◻
	EE	Energy savings have been achieved compared to traditional methods.	▪	◻	◻
	ELM	Completely natural and environmentally friendly materials were preferred.	▪	◻	◻
	CEP	An effective circular economy strategy has been implemented in waste management.	▪	◊	◻
Efficiency	PO	Robotic systems have optimized the construction process.	◻	▪	◻
	CTS	The project was completed with less human-power and less time.	◻	▪	▪
Flexibility	MC	The design was developed to be adaptable to local geographical conditions.	◊	◊	◻
	ADF	The project was flexible enough to support different geometries and designs.	◊	◊	◻
Connectivity	BIM	Digital modelling processes have increased manufacturing accuracy.	◻	◊	◻
	DTT	Digital processes provided real-time control during the construction phase.	◻	▪	◻
Safety	IWS	Robotic production has ensured worker safety.	◻	▪	▪
	PA	A safe process was managed with predictive analytics based on material properties.	▪	◊	◊
Innovation	RAI	Robotic systems have modernized traditional construction methods.	◻	▪	◊
	AM	The originality of the design is ensured through layered production processes.	◊	▪	◊
Data-Driven Decision Making	BDA	The process has been improved with analyses based on the physical properties of the soil.	▪	◻	◻
	RMF	Real-time feedback has been instrumental in decision-making during production.	◊	▪	◻

▪were present ◻not present ◊potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.4 shows the contribution of construction technology dimensions, materials, technique, and labour, within the scope of the construction 4.0 core values for the Printed Stairs Project.

The Printed Stairs Project shows how innovation may respect building and design ideals. With its creative structure and energy-efficient construction, Printed Stairs attract attention. The project, which was constructed using 3D printing technology, has demonstrated remarkable results in terms of cost reductions and process improvement. Utilizing locally sourced materials has helped to lessen environmental effects while enabling the construction of a structure that adheres to the circular economy's tenets. Robotic technologies have made it possible to customize the geometry of the building and have been effectively used in intricate form-making procedures. Risks associated with human labour during production have been reduced by digital methods. Throughout the project, data-based analysis and feedback systems have improved production processes and strengthened the structure's endurance. In summary, this comprehensive approach ensures the Printed Stairs Project effectively incorporates advanced technologies to uphold its core values across all aspects of construction and design.

Table 5.5 shows the contribution of construction technology dimensions, materials, technique, and labour, within the scope of the construction 4.0 core values for the Clay Rotunda Project.

The eco-friendly Clay Rotunda, which uses local clay and soil, is an ideal instance of sustainable construction. In addition to being a trailblazer in minimizing environmental effects and utilizing ethical materials, the project is notable for its cost and energy savings. The project's robotic manufacturing methods improved the design's flexibility and customizability while also speeding up the building phase. Digital twin technology decreased material waste and improved design accuracy throughout production. The construction was unique in both appearance and functionality thanks to cutting-edge additive manufacturing technology. With a design approach backed by data-driven decision-making, Clay Rotunda has demonstrated that contemporary technology can coexist peacefully with the environment. As a conclusion, The Clay Rotunda Project integrates traditional, locally sourced materials with cutting-edge technologies to promote sustainable, efficient, and safe construction.

Table 5.4 Printed Stairs Project

			Technology Component		
Core Values		Description	Materials	Technique	Labor
Sustainability	EIR	Environmental impacts have been reduced by using natural materials.	▪	◻	◻
	EE	Production was carried out with minimum energy consumption.	▪	◊	◻
	ELM	Natural soil was used for low environmental impact.	▪	◻	◻
	CEP	The structure is built entirely with recyclable materials.	▪	◻	◻
Efficiency	PO	Production has been accelerated with 3D printing processes.	◻	▪	◻
	CTS	Intricate designs produced at low cost.	◊	▪	▪
Flexibility	MC	Different geometries were supported during the production process.	◊	◊	◻
	ADF	The design has been developed to be adaptable to different topographic needs.	▪	◊	◻
Connectivity	BIM	Digital modelling and manufacturing are integrated.	◻	◊	◻
	DTT	Digital twin technology has increased the accuracy of processes.	◻	▪	◻
Safety	IWS	Robotic manufacturing has reduced human error. Robotic production has ensured worker safety.	◻	▪	▪
	PA	Safe decisions were made by monitoring material behaviour.	▪	◊	◊
Innovation	RAI	Robotic processes are integrated into the design.	◻	▪	◊
	AM	3D printing technology has offered an innovative production method.	◊	▪	◊
Data-Driven Decision Making	BDA	Data analytics has been used for process optimization.	◻	◊	◻
	RMF	Soil material was monitored during production.	◊	▪	◻

▪were present ◻not present ◊potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.5 Clay Rotunda Project

			Technology Component		
Core Values		Description	Materials	Technique	Labor
Sustainability	EIR	The project's natural soil and clay reduce the building materials' carbon footprint and environmental impact.	▪	◻	◻
	EE	Robotic manufacturing optimisation cuts energy utilisation.	▪	◊	◻
	ELM	Local, non-toxic, and renewable resources such as clay and soil were used.	▪	◻	◻
	CEP	No trash was produced during construction, and materials were meant to be reused.	▪	◊	◻
Efficiency	PO	3D printing technology has sped the construction process and increased efficiency in the process.	◻	▪	◻
	CTS	Using local resources cut logistics and construction expenses.	▪	◊	◻
Flexibility	MC	The flexibility to employ clay in varied geometries allows the design.	▪	◊	◻
	ADF	The Clay Rotunda's shapes are optimised for various geographic and climatic circumstances.	▪	◊	◻
Connectivity	BIM	Digital modelling enabled continuously monitoring the production process and minimizing errors.	◻	◊	◻
	DTT	Digital twin technology has increased accuracy by using real-time data from the production phase.	◻	▪	◻
Safety	IWS	Robotic manufacturing has prevented workers from being involved in dangerous processes.	◻	▪	▪
	PA	A safe structure was built by analysing the soil's durability and drying processes.	▪	◊	◊
Innovation	RAI	Robotic processes have been used successfully in the creation of organic forms.	◻	▪	◊
	AM	3D printing technology has increased the aesthetic and functional originality.	◊	▪	◊
Data-Driven Decision Making	BDA	During the project, analytical data was used to optimize the physical properties of the materials.	◊	◊	◻
	RMF	Real-time input throughout production led to instant design and implementation adjustments.	◊	▪	◻

▪were present ◻not present ◊potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.6 shows the contribution of construction technology dimensions, materials, technique, and labour, within the scope of the construction 4.0 core values for the Digital Soil Project.

Using in situ materials, the Digital Soil initiative contributes to innovation and sustainability. This project represents a significant advancement in energy efficiency and environmental impact reduction as it directly employs dirt as a construction material. Layered design technologies and digital manufacturing procedures have sped up production and expanded the structure's customizability. Digital twin technology and building information modelling have made it possible to implement real-time production monitoring and feedback systems. In terms of safety, material durability studies have aided in the design of safe buildings, while the usage of robotic systems has decreased worker dangers. Digital Soil is an illustration of how cutting-edge building technologies and eco-friendly methods may coexist.

Table 5.7 shows the contribution of construction technology dimensions, materials, technique, and labour, within the scope of the construction 4.0 core values for the Terramia Project.

The Terramia Project is a comprehensive example of sustainable and efficient construction. It is built entirely from local, natural materials that minimize environmental impact while harnessing natural lighting and ventilation to achieve energy savings. The project's sustainable approach is further underscored by its use of eco-friendly soil and a robust waste management strategy that recycles materials post-construction. Efficiency is driven by digital production processes that accelerate construction and reduce costs by leveraging local resources in this project. The design is flexible, customized to suit various climatic and geographical conditions, and adapted to the site's soil properties. Connectivity is enhanced through digital tools such as BIM and digital twin technology, which provide real-time monitoring and ensure production accuracy. Safety is prioritized by reducing human labour and risk via robotic production and predictive analytics that monitor material behaviour. Additionally, innovation is achieved through the integration of robotic systems and drone spraying techniques, while data-driven decision-making optimizes soil durability and overall production processes.

Table 5.6 Digital Soil Project

			Technology Component		
Core Values		Description	Materials	Technique	Labor
Sustainability	EIR	The project eliminated the environmental impacts resulting from material production by using the soil.	■	□	□
	EE	Energy use is kept to a minimum thanks to the on-site processing of soil.	■	□	□
	ELM	Natural materials such as soil and water taken directly from the site make the project environmentally friendly.	■	□	□
	CEP	The materials used in the project are either recyclable or biodegradable.	■	□	□
Efficiency	PO	On-site fabrication technology has significantly reduced construction time.	□	■	□
	CTS	Digital processes have provided efficiency in terms of cost and time.	◇	◇	□
Flexibility	MC	Digital processing of soil has provided customized solutions.	◇	■	□
	ADF	The structure has been made reproducible in accordance with changing environmental conditions.	◇	◇	□
Connectivity	BIM	Digital modelling was used throughout the project, increasing accuracy in the processes.	□	◇	□
	DTT	The digital twin model enabled performance monitoring during and after the production process.	□	■	□
Safety	IWS	Robotics and automated processes have prevented workers from working in hazardous areas.	□	■	■
	PA	A safe structure was created by analysing the mechanical behaviour of the soil.	■	◇	◇
Innovation	RAI	Artificial intelligence has been used to optimize the soil cultivation process.	◇	◇	◇
	AM	Robotic spraying was applied in the construction stages instead of additive manufacturing processes.	□	□	◇
Data-Driven Decision Making	BDA	Factors such as material durability and drying times are optimized with big data analytics.	■	□	□
	RMF	Real-time feedback systems were used during production.	◇	■	□

■were present □not present ◇potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.7 Terramia Project

			Technology Component		
Core Values		Description	Materials	Technique	Labor
Sustainability	EIR	The project was constructed entirely from local and natural materials.	▪	◻	◻
	EE	Energy savings were achieved with natural lighting and ventilation solutions.	▪	◊	◻
	ELM	The soil used in the project is an environmentally friendly and sustainable material.	▪	◻	◻
	CEP	Waste management strategies aim to recycle all materials after construction.	▪	◻	◻
Efficiency	PO	Fast and efficient construction was achieved with digital production processes.	◻	▪	◻
	CTS	Low cost was achieved through the use of local materials and digital production.	▪	◊	◻
Flexibility	MC	The design can be customized according to different climate and geographical conditions.	▪	◊	◻
	ADF	The project was shaped according to the physical properties of the soil on the site.	▪	◊	◻
Connectivity	BIM	Efficiency in the production process has been increased with digital models.	◻	◊	◻
	DTT	The production process was monitored in real-time with the digital twin.	◻	▪	◻
Safety	IWS	The need for human-labor and worker risk have been reduced with robotic production.	◻	▪	▪
	PA	During the project, safe production was ensured with predictions based on material properties.	▪	◊	◊
Innovation	RAI	Robotic systems have been instrumental in creating innovative designs.	◻	▪	◊
	AM	The structure was completed using drone spraying rather than a modern additive manufacturing process.	◻	◻	◊
Data-Driven Decision Making	BDA	During the project, soil durability and production processes were optimized with data analytics.	◊	◊	◻
	RMF	Real-time data was analysed during production.	◊	▪	◻

▪were present ◻not present ◊potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

5.4 Overall Assessment

The assessment of the Gaia, Mud Frontiers, Printed Stairs, Clay Rotunda, Digital Soil, and Terramia projects is conducted through the lens of C4.0 core values, including sustainability, efficiency, flexibility, connectivity, safety, innovation, and data-driven decision-making. Firstly, by comparing the projects for each construction technology component (material, technique, and labour), these are evaluated in line with the core values of construction 4.0. Then, the results that stand out in the case studies are classified in terms of the relationship between the technological components and the core values of construction 4.0. This evaluation considers the presence of these values across three primary components: materials, techniques, and labour. Table 5.8, Table 5.9, and Table 5.10 comprehensively assess the material performance of the Gaia, Mud Frontiers, Printed Stairs, Clay Rotunda, Digital Soil, and Terramia projects against the C4.0 core values. These core values include sustainability, efficiency, flexibility, connectivity, security, innovation, and data-driven decision-making. The evaluation uses symbols to indicate whether certain features are present (▪), not present (◻), or potentially present (◊) in the projects. Detailed explanations of the abbreviations used are provided below the table. Lastly, each component is categorized as having either a high (H) or low (L) presence of the core values, facilitating a comprehensive analysis of how digital fabrication processes align with contemporary construction priorities.

Table 5.8 evaluates six projects which are Gaia, Mud Frontiers, Printed Stairs, Clay Rotunda, Digital Soil, and Terramia, across core values according to the materials of the projects. In the sustainability category, all projects strongly align with EIR, EE, ELM, and CEP values. Regarding efficiency, features such as PO and CTS are missing in some projects but have a potential presence. Features such as MC and ADF are often potentially present in the flexibility category. Connectivity is weak in most projects; BIM and DTT were not implemented. All projects showed strong performance regarding safety, focusing on IWS and PA. In the innovation category, RAI and AM capabilities have a widespread potential presence. BDA and RMF capabilities have been implemented inconsistently in data-driven decision-making across projects.

Table 5.8 Materials Assessment of The Projects According to C4.0 Core Values

		Gaia	Mud Frontiers	Printed Stairs	Clay Rotunda	Digital Soil	Terramia
Sustainability	EIR	▪	▪	▪	▪	▪	▪
	EE	▪	▪	▪	▪	▪	▪
	ELM	▪	▪	▪	▪	▪	▪
	CEP	▪	▪	▪	▪	▪	▪
Efficiency	PO	◻	◻	◻	◻	◻	◻
	CTS	◻	◻	◊	▪	◊	▪
Flexibility	MC	◊	◊	◊	▪	◊	▪
	ADF	▪	◊	▪	▪	◊	▪
Connectivity	BIM	◻	◻	◻	◻	◻	◻
	DTT	◻	◻	◻	◻	◻	◻
Safety	IWS	◻	◻	◻	◻	◻	◻
	PA	▪	▪	▪	▪	▪	▪
Innovation	RAI	◻	◻	◻	◻	◊	◻
	AM	◊	◊	◊	◊	◻	◻
Data-Driven	BDA	▪	▪	◻	◊	▪	◊
Decision Making	RMF	▪	◊	◊	◊	◊	◊

▪were present ◻not present ◊potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.9 evaluates six projects across core values according to the technique of the projects. While PO, CTS, and IWS are consistently present across all projects, EIR and ELM are not present. EE and CEP are inconsistently applied, with only partial implementation in a few projects. Most projects show potential for MC and ADF but only partially integrate BIM. DTT and RMF are fully implemented across all projects. RAI is largely present, but AM is missing in the Digital Soil and Terramia projects. BDA and PA are only partially adopted across the table, indicating areas for further development in data-driven practices.

Table 5.9 Technique Assessment of The Projects According to C4.0 Core Values

		Gaia	Mud Frontiers	Printed Stairs	Clay Rotunda	Digital Soil	Terramia
Sustainability	EIR	□	□	□	□	□	□
	EE	▪	□	◇	◇	□	◇
	ELM	□	□	□	□	□	□
	CEP	◇	◇	□	◇	□	□
Efficiency	PO	▪	▪	▪	▪	▪	▪
	CTS	▪	▪	▪	◇	◇	◇
Flexibility	MC	◇	◇	◇	◇	▪	◇
	ADF	◇	◇	◇	◇	◇	◇
Connectivity	BIM	◇	◇	◇	◇	◇	◇
	DTT	▪	▪	▪	▪	▪	▪
Safety	IWS	▪	▪	▪	▪	▪	▪
	PA	◇	◇	◇	◇	◇	◇
Innovation	RAI	▪	▪	▪	▪	◇	▪
	AM	▪	▪	▪	▪	□	□
Data-Driven Decision Making	BDA	□	□	◇	◇	□	◇
	RMF	▪	▪	▪	▪	▪	▪

▪were present □not present ◇potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

Table 5.10 assesses the labour aspects of six projects according to C4.0 core values. The CTS and IWS criteria are consistently present across all projects, indicating a focus on reducing labour costs and ensuring safety. However, most other core values, including EIR), EE, ELM, CEP, and PO, are not present. There is potential for PA, RAI, and AM across all projects, but these technologies are not fully integrated. MC, ADF, BIM, DTT, BDA, and RMF are completely not present, reflecting a limited application of advanced digital and data-driven approaches in the labour processes.

Table 5.10 Labor Assessment of The Projects According to C4.0 Core Values

		Gaia	Mud Frontiers	Printed Stairs	Clay Rotunda	Digital Soil	Terramia
Sustainability	EIR	□	□	□	□	□	□
	EE	□	□	□	□	□	□
	ELM	□	□	□	□	□	□
	CEP	□	□	□	□	□	□
Efficiency	PO	□	□	□	□	□	□
	CTS	■	■	■	■	■	■
Flexibility	MC	□	□	□	□	□	□
	ADF	□	□	□	□	□	□
Connectivity	BIM	□	□	□	□	□	□
	DTT	□	□	□	□	□	□
Safety	IWS	■	■	■	■	■	■
	PA	◇	◇	◇	◇	◇	◇
Innovation	RAI	◇	◇	◇	◇	◇	◇
	AM	◇	◇	◇	◇	◇	◇
Data-Driven Decision Making	BDA	□	□	□	□	□	□
	RMF	□	□	□	□	□	□

■were present □not present ◇potentially present

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

While the previous interpretations provided a projects overview of materials, techniques, and labour components of construction technology for the case projects according to the C4.0 core values, Table 5.11 presents a detailed analysis of the same core values through three essential components: materials, techniques, and labour. According to the core values, the asset levels in these components are classified as 'high' (H) and 'low' (L). This approach allows a more detailed perspective to be assessed on the performance of projects in areas such as sustainability, efficiency, flexibility, connectivity, security, innovation, and data-driven decision-making. The table evaluates the material, technique, and labour of 6 different projects within the framework of C4.0 core values. Each C4.0 core value covers important concepts such as Sustainability,

Efficiency, Flexibility, Connectivity, Safety, Innovation, and Data-Driven Decision Making. The table examines each core value regarding materials, technique, and labour and shows which projects contribute more or less to these values.

Table 5.11 Overall Assessment of The Projects

Core Values		Materials	Technique	Labor
Sustainability	EIR	H	L	L
	EE	H	L	L
	ELM	H	L	L
	CEP	H	L	L
Efficiency	PO	L	H	L
	CTS	H	H	L
Flexibility	MC	H	H	L
	ADF	H	H	L
Connectivity	BIM	L	H	L
	DTT	L	H	L
Safety	IWS	L	H	H
	PA	H	H	H
Innovation	RAI	L	H	H
	AM	L	H	H
Data-Driven Decision Making	BDA	H	L	L
	RMF	H	H	L

H: High Presence **L:** Low Presence

Core Values Abbreviations:

EIR: Environmental Impact Reduction; **EE:** Energy Efficiency; **ELM:** Ethical Sourcing and Low-Impact Materials; **CEP:** Circular Economy Principle; **PO:** Process Optimization; **CTS:** Cost and Time Savings; **MC:** Mass Customization; **ADF:** Adaptive Design and Fabrication; **BIM:** Building Information Modelling; **DTT:** Digital Twin Technology; **IWS:** Improved Worker Safety; **PA:** Predictive Analytics; **RAI:** Robotics and AI Integration; **AM:** Additive Manufacturing; **BDA:** Big Data and Analytics; **RMF:** Real-Time Monitoring and Feedback

- The “Sustainability” criteria focus on the environmental sustainability of the materials. The case projects highly select materials according to the EE, EIR, ELM, and CEP criteria. According to the literature, it is necessary to reduce the environmental consequences of traditional construction materials (Pomponi & Moncaster, 2017). These materials are usually recyclable or obtained from local sources and offer energy efficiency with minimal natural resources usage

(Asdrubali, 2017). On the other hand, the projects generally show a low presence in technique and labour in terms of sustainability criteria.

- The “Efficiency” criteria include PO and CTS. Cost-time savings and the efficiency of techniques in the production process are critical in terms of efficiency criteria. In particular, techniques compatible with digital production technologies of materials used in the projects offer significant advantages in terms of time and cost compared to traditional production methods (Khoshnevis, 2004). The literature also emphasizes that digital production techniques increase efficiency in the construction sector (Meisel & Bock, 2014). New production methods, such as digital production techniques, optimize time and cost by offering design freedom and material flexibility in the projects. The use of local materials is highly prevalent due to material access and cost. On the other hand, the labour criterion of the projects has a low presence.

- The “Flexibility” criteria emphasize the degree to which a project or material can adapt to changing requirements and conditions. MC and ADF are the criteria to evaluate flexibility criteria. Gibson et al. (2010) showed that mass production can be used to achieve cost efficiency and customize materials to meet specific project requirements. Most of the projects’ materials and techniques are highly present in the flexibility criteria. The literature also noted that mass customization is a common trend in digital manufacturing processes. Literature suggests adaptive design as a method to produce more sustainable and efficient solutions in construction projects (Kolarevic, 2004). While the materials and techniques used in the projects generally show a high presence, labour shows a low presence.

- The “Connectivity” criteria represent the integration and compatibility levels of digital systems and technologies. This category includes requirements for BIM and DTT. BIM enables better project planning and coordination by digitally simulating the entire building lifecycle. Eastman et al. (2011) argued that BIM is considered a breakthrough in the digitalization of construction processes and more efficient management of projects. On the other hand, DTT creates digital copies of real-world structures to provide real-time monitoring and analysis. Research suggests that DTT is a way to improve decision-making, especially in large-scale

projects (Negri et al., 2017). It shows high responsibility due to the digital and robotic fabrication techniques used in projects but low responsibility in terms of the connectivity of materials and labour parts.

- IWS and PA are two key metrics that the “Safety” criteria evaluate construction materials in terms of how they support structural and worker safety. The term “Enhanced Worker Safety” refers to the implementation of technologies or materials designed to enhance worker safety during the construction process (Ahmed et al., 2024). Since construction work has always been considered a high-risk occupation (Hallowell & Gambatese, 2009), occupational safety is a primary concern in every project. Digital manufacturing processes can reduce the need for manual labour, thereby improving worker safety through the use of materials in projects. The potential reduction of occupational accidents is facilitated by these materials requiring less physical labour than traditional construction techniques (Sacks et al., 2015). Data-driven methods that enable predicting and managing safety hazards have been incorporated into PA. Sensors and big data analytics are among the tools that enable this technology to predict potential hazards and occupational accidents. PA can prevent potential accidents by continuously monitoring conditions on site and predicting safety hazards (Zhou et al., 2013). In addition to preventing workplace accidents, selecting materials with occupational safety in mind can also increase the overall effectiveness of the construction process (Oladiran & Dickins, 2024). Sacks et al. (2015) have shown that safer work environments can increase worker morale and productivity. The safety criteria for the case projects demonstrate the importance of data-based decision-making processes and digitalization in improving worker safety in global construction projects. Due to the planning and implementation of safety measures with the technique used, technique and labour have a high presence in the IWS criterion. Materials, techniques, and labour have also a high presence in the PA criterion.

- “Innovation” criteria are evaluated based on AM and RAI criteria. Innovation is a category that evaluates the compatibility of materials and processes with innovative technologies and the potential for innovation in future construction projects. The integration of robotics and artificial intelligence is an innovation that

has the potential to increase labour efficiency and reduce human errors in construction processes. Moreover, additive manufacturing technology is perceived as a technological advance in the context of digital manufacturing processes, especially concerning materials. Additive manufacturing is considered an important innovation due to its ability to produce building elements. The technique and labour of the case projects generally show a high presence, while the material aspect shows a low presence.

•“Data-Driven Decision Making” is a term that denotes the process of making more informed, and optimized decisions in construction projects by utilizing big data analytics, and real-time monitoring technologies. The approach contains two primary criteria under this title: RMF and BDA. According to Bilal et al. (2016), the literature also emphasizes the importance of big data and continuous monitoring systems in construction projects. The materials of the projects assessed in this category also show how digitization has been incorporated into decision-making processes in the construction industry. In the construction sector, BDA can be implemented in various applications, including energy consumption, field operations, material utilization, and occupational safety. RMF technologies enable the collection of immediate data in project processes and the rapid formulation of decisions based on this data. This criterion is associated with the presence of systems that provide immediate feedback and continuously monitor the performance of the materials used in the field. In construction endeavours, data-driven decision-making offers a significant advantage in areas such as materials and technique. In the literature, data-driven techniques are especially advised to find answers to the complexity of building projects and improving project sustainability (Dave et al., 2013).

This overall assessment shows how materials, techniques, and labour are used in different projects that align with the core values. Each Construction 4.0 core values are evaluated at high or low levels according to specific techniques and labour needs. Values such as sustainability, flexibility, connectivity, and innovation generally show high involvement, while values such as security and data-driven decision-making require detailed and continuous improvement of processes. In summary, the overall assessment reveals that while digital fabrication techniques show strong alignment with C4.0 core

values, significant gaps exist in the integration of these values into materials and labour. Prioritizing improvements in connectivity, safety, and data-driven decision-making for materials and labour will enhance the holistic implementation of C4.0 principles. This comprehensive analysis provides a foundation for advancing sustainable, efficient, and innovative practices in future digital fabrication projects.



Chapter 6

Conclusions and Future Prospects

6.1 Conclusions

By combining the cutting-edge technology of Construction 4.0 with the traditional advantages of earthen materials, such as affordability, sustainability, and thermal efficiency, digitally generated earthen constructions offer a revolutionary shift in the construction industry. This review has shown that earthen construction can reach new heights of sustainability, efficiency, flexibility, connectivity, safety, innovation, and data-driven decision-making by integrating technologies such as digital twin technology, additive manufacturing, big data and analytics, etc. Scaling these advances for broad use is still tricky, however. The issues that must be resolved are the lack of defined protocols, the high initial costs of digital technology, and the limited supply of digital talents in specific fields. Furthermore, it takes constant research and development to strike the correct balance between integrating energy-intensive digital manufacturing processes and maintaining the sustainability of earthen materials. To sum up, digitally manufactured earthen constructions are an outstanding instance of how conventional materials and contemporary technology may be used to satisfy the needs of a quickly changing industry. They provide scalable answers to global issues, including resource scarcity, urbanization, and climate change, by conforming to the tenets of Construction 4.0.

Future developments in material science, digital technologies, and legislative frameworks will be essential to guaranteeing the broader adoption of these creative strategies, and pave the way for a more technologically sophisticated and sustainable construction sector. This study focused on all these and sought answers to the following questions:

- **What are the material properties of the earth that make it suitable for construction?**

Because of its environmental benefits and structural qualities, earth has been favoured as a material for construction (Pelé-Peltier et al., 2022). In addition, due to its high thermal mass characteristic in soil mass structures, it balances temperature variations and saves energy (Minke, 2005). Furthermore, earth is a particularly sustainable building resource because it is readily available locally and can be reused (Houben & Guillaud, 1994). However, because the quantities of clay, silt, sand, and organic matter affect soil composition, problems like cracking or inadequate strength might arise if the correct mixing ratio is not given (Jaquin et al., 2009). Therefore, while producing soil-based building materials, using the right resources and manufacturing techniques is crucial.

- **What are the constraints and capacities of vernacular and digital manufacturing methods using earth-based materials?**

When it comes to using soil-based materials, vernacular and digital manufacturing techniques have various capabilities and constraints. Traditional techniques, which rely on local knowledge, enable the utilization of natural resources in an affordable and accessible manner. Nevertheless, these systems' manufacturing processes are frequently laborious and challenging in delivering consistent quality (Houben & Guillaud, 1994). For instance, the material's human preparation and compaction quality are critical to the homogeneity and longevity of methods like adobe and rammed earth walls (Walker et al., 2005). Soil-based materials can be processed more precisely and precisely thanks to digital fabrication techniques, particularly technologies like robots and 3D printing. These approaches may manufacture complicated shapes while decreasing material waste (Donnadieu et al., 2021). Conversely, digital fabrication techniques can demand specialized knowledge, substantial upfront expenses, and sophisticated technology. Furthermore, it is not easy to manage soil materials' fluidity and heterogeneous structure in digital manufacturing methods (Perrot et al., 2018). Therefore, digital manufacturing technologies provide more design freedom and material efficiency, while conventional techniques offer cost-effective and locally customized solutions.

By analyzing the limitations and possibilities of all these methods, this research aims to highlight the broader implications of integrating sustainable materials with

emerging construction technologies. The focus of this research was to explore all these issues and answer the following questions:

- **What digital manufacturing techniques are presently employed to produce earthen structures?**

In order to improve material efficiency, permit complicated geometries, and speed up production processes, digital fabrication techniques are now employed in the creation of earth-based structures. Robotic arm technology, 3D printers, and CNC-guided tools stand out among these methods. One of the most prevalent digital manufacturing approaches is to employ soil-based materials in conjunction with an additive manufacturing process (extrusion). 3D printers enable the exact creation of complicated geometric objects while minimizing material waste (Perrot et al., 2018). However, controlling the soil mixture's fluidity and bonding qualities is a significant design and production problem. Compressed soil panels or blocks are cut and shaped using CNC machines. High-accuracy, repeatable structural parts may be produced using this technology. Complex moulding systems may also be made using it (Garrido et al., 2020). Earth-based materials are processed and shaped with extreme accuracy using robotic arms. This approach works particularly well with parametric designs and organic shapes. Additionally, robotic systems can integrate several patterning and compression techniques (Donnadieu et al., 2021). In addition, some projects have merged traditional techniques with modern production processes. For instance, rammed earth methods and digitally created moulds have been used to create hybrid production processes. These techniques combine digital technology's design flexibility with local materials' low-cost benefits (Drot et al., 2020). By optimizing material and manufacturing conditions, these strategies seek to improve performance while facilitating the digital revolution of sustainable construction.

- **How do digital fabrication methods improve the efficiency and precision of earth-based construction?**

When constructing soil-based constructions, digital manufacturing techniques are a potent tool for improving accuracy and efficiency. These approaches speed up production processes, make complicated ideas more straightforward to realize and waste less material

than previous methods. Initially, while manufacturing soil-based constructions, digital manufacturing maximizes the utilization of materials. Robotic arm systems and 3D printers reduce waste by ensuring that the material is only applied where needed. Since soil-based components are typically sourced locally, and environmental preservation is the goal, this is particularly crucial in terms of sustainability (Perrot et al., 2018). Furthermore, by utilising digital fabrication techniques, geometric precision is enhanced, allowing for the production of complex structures that were previously impossible to achieve through conventional methods. This makes it easier to assemble structural components and ensures project repeatability (Donnadieu et al., 2021). Automation during manufacturing minimizes human error and lowers labor costs by lowering reliance on manual labour (Nerella et al., 2019). Last but not least, digital production techniques provide a chance to enhance structural durability and material performance. Through monitoring the soil mixture's characteristics, digital technologies offer ongoing quality control. This guarantees the durability of the buildings and helps standardize the material's mechanical and physical qualities during construction (Velasco et al., 2020).

- **In what ways do digitally fabricated earthen structures contribute to sustainability goals in alignment with Construction 4.0 principles?**

By adhering to the principles of Construction 4.0, digitally produced earth-based structures support sustainability objectives in several ways. In terms of social, economic, and environmental sustainability, these construction techniques provide several advantages. Digital manufacturing processes ensure that only proper amounts and places of the material are used. Earth decreases transportation-related carbon emissions since it is a locally accessible resource. Furthermore, Houben and Guillaud (1994) claim that earthen constructions may be readily recycled or reused without causing harm to the environment, and they have a limited environmental impact throughout the course of their life cycle. Compared to conventional building methods, digital production processes use less energy. By promoting the reuse of earthy resources, digital fabrication methods support the circular economy. Furthermore, constructions may be readily tailored to meet local circumstances and environmental needs thanks to automation technology and parametric design (Donnadieu et al., 2021). To improve the longevity of earthen constructions, Construction 4.0's data-driven analytical concepts enable ongoing monitoring of material characteristics and structural behaviours. Because digital

manufacturing methods lessen the severe burden in the construction industry, they create safer working environments. Additionally, via information exchange and learning new skills, digitization opens up economic potential for nearby communities (Garrido et al., 2020). Consequently, with their numerous advantages, including material savings, energy efficiency, circular economy, and social development, digitally created earth-based buildings effectively support sustainability goals. The building 4.0 concepts, which seek to make the building industry more inventive, efficient, and environmentally friendly, are immediately compatible with these structures.

By exploring these key questions, this research aims to contribute to the ongoing transformation of sustainable earthen construction practices by bridging traditional knowledge with digital and robotic technology within construction core values.

6.2 Societal Impact and Contribution to Global Sustainability

Integrating Adobe, Cob, and Rammed Earth materials into digital and robotic production has far-reaching consequences for both societal effects and global sustainability. These developments hold the potential for providing underprivileged communities with accessible and reasonably priced housing on a social level, especially in regions that are struggling financially and in terms of infrastructure. These construction techniques minimize the need for costly carbon-intensive materials such as concrete and steel by utilizing readily available, locally accessible resources such as clay, sand, and straw. In terms of global sustainability, these technologies greatly minimize the building industry's environmental imprint. On the other hand, earthen constructions are essentially low carbon since they use natural, lightly treated materials. By maximizing material consumption and reducing waste, robotic 3D printing further improves this and makes resource-saving sensitive applications possible. These applications emphasize recycling, waste reduction, and sustainable resource management, all in line with the tenets of the circular economy. Therefore, this study significantly contributes to SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

- **(9) Industry, Innovation, and Infrastructure:** SDG 9's emphasis on infrastructure innovation is shown in using robots and digital manufacturing in conventional construction methods. By combining technology with earth-based materials, the construction industry can create creative, long-lasting structures that fulfil current requirements while reducing environmental impact. This aim promotes infrastructure transformation via sustainable practices and technical developments that improve construction innovation, productivity, efficiency, and quality.
- **(11) Sustainable Cities and Communities:** SDG 11 focuses on developing affordable, environmentally friendly housing and infrastructure as part of sustainable construction techniques. Digital fabrication and robotic manufacture of adobe, cob, and rammed earth materials help to achieve this aim by enabling efficient, cost-effective construction methods that exploit local resources. In addition to saving energy, this builds climate-resistant communities and decreases city growth. Buildings that prioritize sustainable materials may lower their carbon footprint, enhance indoor air quality, and minimize their reliance on non-renewable resources.
- **(12) Responsible Consumption and Production:** This SDG's primary goals are better using natural resources and reducing waste. Traditional earthen constructions support SDG 12 by encouraging the use of local, renewable materials while minimizing reliance on products with significant environmental effects, such as cement and steel. Digital and robotic production techniques also help to optimize resource utilization, reduce building waste, and enable circular economy concepts. For instance, constructions may be removed, and materials repurposed or returned to the environment, promoting resource efficiency and waste reduction.
- **(13) Climate Action:** SDG 13 is significant for construction and contributes significantly to global greenhouse gas emissions. Earth-based materials, especially combined with digital fabrication, provide a low-carbon alternative that minimizes the energy required for building production and operation. The natural insulating qualities of earth-based materials help regulate indoor temperatures, lowering the demand for energy-intensive heating and cooling equipment. By using these sustainable practices, buildings may become more robust to climate change and contribute to global carbon reduction goals.

6.3 Future Prospects

The future of integrating earth-based materials with digital and robotic fabrication has the potential to radically transform sustainable design, low-impact urban planning, and global construction techniques. Here are some significant prospects that demonstrate how developments in this sector might evolve and meet future challenges:

- The potential of earth-based constructions to adapt to various climates should be further investigated in future studies. The need for structures that can naturally control temperature and endure harsh weather conditions will grow as climate change worsens. Research and development in adaptive material formulations, such as combining earth-based materials with bio composites or investigating site-specific material blends, may result in structures that operate well in high heat, cold, or humidity conditions. Improved methods for recycling earthen construction, which would enable its local reuse with less waste, might be one of the advancements in sustainable construction. Building lifecycles might also be enhanced by innovations in material recycling, such as biodegradable binders and non-sustainable additions.
- Digital fabrication of earth-based materials is globally scalable. As these sustainable techniques become more refined and affordable, there is potential for them to be adopted in both urban and rural areas worldwide. This will support affordable housing initiatives, especially in developing regions where current materials and construction methods are prohibitively expensive or environmentally unsustainable. Expanding this method could significantly impact the global housing shortage and provide environmentally friendly, low-cost construction alternatives.
- Digital and robotic fabrication may create increasingly intricate architectural designs and deal with a greater variety of natural materials as they get more accurate and adaptable. Additionally, by maximizing material utilization, structural integrity, and energy efficiency, AI-powered design tools may further lower costs and their environmental impact.
- As knowledge of environmental issues increases, governments and organizations worldwide can encourage or even regulate sustainable construction practices. This

approach may be approved by international green building certifications and regulatory frameworks if further research is done. In addition, it is shown that digital manufacturing using earth-based materials is reliable, affordable, and sustainable. With more governmental support, these methods will be used, perhaps becoming the standard for sustainable building worldwide.

- As environmental concerns increase, regulations may favour sustainable building. The dependability and cost-effectiveness of digital manufacturing using earth-based materials should boost their acceptability in worldwide green construction standards. Policy incentives for local resource usage, technology adoption, and labour training may make construction more egalitarian and sustainable. This congruence with fundamental principles may increase earth-based digital manufacturing as a solution for inexpensive and ecologically responsible homes globally. The public and corporate sectors might collaborate to build open-source knowledge platforms and standardization processes for wider deployment and accessibility.

As a result of these prospects, the transformational potential of merging earth-based materials with digital and robotic production is brought into focus. Through the alignment of technology breakthroughs with the fundamental principles of sustainable materials, creative processes, and equitable labour practices, the construction industry has the potential to take the lead in solving the housing requirements of the world as well as the issues posed by climate change. To advance material science, refine fabrication methods, and establish regulatory frameworks, future research and industrial applications need to collaborate to ensure that these discoveries contribute meaningfully to both local and global sustainability goals.

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SELECTED PUBLICATIONS AND PRESENTATIONS

C1) Sayın, İ., & Metin, B. (2022). Using digital fabrication techniques with Earth-Based building materials. In *9th International Conference Kerpik'22: Re-Thinking Earthen Architecture for Sustainable Development*.