

University of Southern Queensland

School of Engineering

**Project Management in 3D Printed Concrete
Structures/Buildings**

A dissertation submitted by

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in fulfillment of the requirements of

ENP4111 Professional Engineer Research Project

towards the degree of

Bachelor of Engineering Honours

2024

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University of Southern Queensland

School of Engineering

ENP4111 Dissertation Project

(This is a 2-unit research project in Bachelor of Engineering Honours Program)

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ABSTRACT

This dissertation investigates into the field of project management concerning 3D printed constructions and buildings by delving into the unique challenges and opportunities brought about by this innovative construction method. With the rapid progress of 3D printing technology in the construction sector, comes a demand for adjusting project management approaches to accommodate this building technique. By conducting an in-depth literature review analysis of academic studies and industry reports covering the period from 2015 to 2024, the study examines current project management methodologies while trying to identify key issues in implementing 3D concrete printing and by proposing new strategies to enhance efficiency and sustainability in construction projects. The research shows gaps in existing project management framework when it comes to tackling the scheduling and quality assurance challenges raised by 3D concrete printing technology. It also highlights the absence of standardisation in procedures and materials as a key barrier to widespread adoption. The study sheds light on how digital tools like Building Information Modeling (BIM) and artificial intelligence are integrated with conventional project management methodologies. The research findings indicate that although 3D concrete printing presents promising opportunities to enhance construction sustainability and efficiency it necessitates tailored project management strategies to optimize its advantages. This lays the groundwork for creating project management strategies designed for 3D printing in construction projects which could enhance project results and adds insights to the existing pool of information regarding the handling of innovative construction technologies while offering practical implications, for industry professionals and scholars involved in the field of 3D printed building projects.

ACKNOWLEDGEMENTS

I want to thank my supervisor Professor Saya Ramakrishnan for all his help and guidance during this research project, his support and knowledge have really made a difference in developing this dissertation.

I am thankful and express my gratitude to the professors and staff at University of Southern Queensland for providing the resources and whose support and the conducive academic setting enabled me to conduct this research.

Finally, my appreciation goes to my family and friends for their support and understanding throughout my course of this study and their words of encouragement have truly kept me going.

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NOMENCLATURE

While this dissertation on project management in 3D printed concrete structures does not heavily rely on mathematical formulations, the technical nature of the topic and the various abbreviations and specialized terms used throughout the text warrant a nomenclature section. This detailed table offers definitions for key abbreviations, technical terms, and symbols used in the discussion of 3D concrete printing and project management and it is intended to serve as a quick reference for readers, enhancing the clarity and accessibility of the content presented in the following chapters.

Table 2 Nomenclature

Abbreviation	Description
3DCP	3D Concrete Printing
AM	Additive Manufacturing
BIM	Building Information Modeling
CAD	Computer-Aided Design
CNF	Cellulose Nanofibrils
CO ₂	Carbon Dioxide
DfAM	Design for Additive Manufacturing
FDM	Fused Deposition Modeling
IoT	Internet of Things
JIT	Just-In-Time
LCA	Life Cycle Assessment
ML	Machine Learning
PM	Project Management
QA/QC	Quality Assurance/Quality Control
SDGs	Sustainable Development Goals
WBS	Work Breakdown Structure

GLOSSARY

<i>Term</i>	<i>Definition</i>
3D Concrete Printing (3DCP)	An innovative construction technique that employs computerised equipment to build complex structures by layering concrete without traditional formwork (Buswell et al. 2018).
Additive Manufacturing (AM)	A fabrication method that creates objects by depositing materials in layers, guided by digital 3D models (Paolini, Kollmannsberger & Rank 2019).
Agile Manufacturing	A production approach that prioritises customer needs while maintaining quality standards and managing production costs effectively (Paul et al. 2018).
Buildability	A measure of how well a building's design facilitates efficient construction, considering the overall requirements of the finished structure (Sanjayan et al. 2018).
Building Information Modeling (BIM)	A digital system that represents a facility's physical and functional attributes, serving as a shared information resource (AMC Bridge n.d.).
Computer-Aided Design (CAD)	The application of computer technology to assist in the creation, modification, analysis, or optimisation of designs (Wu, Wang & Wang 2016).
Contour Crafting	An advanced layered fabrication method developed for the automated construction of entire structures or their components (Xiao et al. 2021).
Design for Additive Manufacturing (DfAM)	The practice of creating product or component designs specifically tailored for additive manufacturing processes (Zhang et al. 2019).
Digital Twin	A virtual model representing a physical object or system throughout its lifecycle, utilising real-time data to enhance understanding and decision-making (Xiao et al. 2021).

Extrudability	The capacity of a material to be forced through a shaped opening under specific conditions (Panda et al. 2018).
Extrusion-Based 3D Printing	A 3D printing technique where material is precisely dispensed through a nozzle or opening (Buswell et al. 2018).
Fused Deposition Modeling (FDM)	An additive manufacturing process that utilises a continuous filament of thermoplastic material (Paolini, Kollmannsberger & Rank 2019).
Geopolymer	A type of cementitious material formed by the reaction between an aluminosilicate powder and an alkaline silicate solution under near-ambient conditions (Panda et al. 2019a).
Just-In-Time (JIT)	A production strategy that aligns supplier orders with production schedules to optimise efficiency (Rahul & Santhanam 2020).
Large-Scale Additive Manufacturing (LSAM)	Scaled-up additive manufacturing processes designed for producing large components or structures (Xiao et al. 2021).
Lean Construction	A method of production aimed at reducing waste, increasing productivity, and maximizing value in the construction industry (Paolini, Kollmannsberger & Rank 2019).
Life Cycle Assessment (LCA)	An analytical technique used to evaluate the environmental impacts associated with all stages of a product's life (Strohle et al. 2022).
Printability	The ability of a material to be successfully extruded and deposited in a controlled manner during the 3D printing process (Panda et al. 2018).
Rheology:	The study of material flow behaviour, particularly in liquids, but also in soft solids or solids under conditions where they exhibit plastic flow rather than elastic deformation (Ma & Wang 2018).
Slicing	The process of converting a 3D model into a series of thin layers for 3D printing purposes (Wu, Wang & Wang 2016).

Slump	A measurement used to assess the consistency and workability of fresh concrete (Rahul & Santhanam 2020).
Sustainable Development Goals (SDGs)	A set of 17 interconnected global objectives designed to create a more sustainable and equitable future for all (Alami et al. 2023).
Workability	The ease with which fresh concrete can be handled, placed, consolidated, and finished while maintaining homogeneity (Ma & Wang 2018).

CHAPTER 1 INTRODUCTION

The construction sector is, on the brink of a change due to the emergence of concrete printing technology. This new method of constructing buildings is set to transform how we conceptualize and carry out construction projects. With the advancement of this technology come challenges and chances that call for a reassessment of conventional project management approaches, in construction.

The use of 3D printing, as part of additive manufacturing presents several advantages such as more creative design options and lessened material wastage while also speeding up construction processes according to (Panda et al. 2018). However, achieving integration of this technology into construction projects faces obstacles like constraints in materials available lack of standardized practices and uncertainties, in regulations (Sanjayan et al. 2018).

The intersection of 3D printing and project management poses a challenging and difficult problems that merits further investigation. Given that the construction sectors struggle with incorporating this technology it is crucial to explore how current project management practices could be adjusted and identify any novel strategies needed to successfully oversee 3D concrete printing projects.

This thesis intends to conduct a comprehensive assessment of the existing status of project management methods in 3D concrete printing construction projects and pinpoint key challenges and potentials while examining innovative approaches for efficient project management, in this field of expertise. The study will focus on various critical factors:

- ❖ Examining how conventional project management approaches, like Lean Construction, Agile methodologies and in Time (JIT) are suitable, for 3D concrete printing initiatives.
- ❖ Investigating the obstacles presented by 3D concrete printing, in domains like ensuring quality control and managing risks and the supply chain management.
- ❖ Exploring how technologies such as Machine Learning (ML), Artificial Intelligence (AI) and Digital Twin are being incorporated into project management for the advancement of 3D concrete printing projects.
- ❖ Examining the environmental impacts and sustainability factors in 3D concrete printing projects.
- ❖ Analysing the existing regulatory landscape and initiatives aimed at establishing standards in the industry.

The research methodology used for this thesis includes an examination of literature, from a wide range of academic and industry sources to analyse current practices, emerging trends, and future directions in project management for 3D concrete printing.

By addressing these objectives, this research aims to add to the existing knowledge in construction project oversight and offer perspectives for professionals wanting to integrate 3D concrete printing technology into their projects. The outcomes of this examination could guide the design of improved project management strategies customized to the unique features of 3D concrete printing technology and thereby promote broader acceptance of this innovative technology within the construction sector.

The dissertation is structured as follows:

- ❖ Chapter 2 of the study will explore an analysis of existing literature on 3D concrete printing technology and its impact on construction project management.
- ❖ Chapter 3 of the study report you can find an explanation of the research methods used including how the literature was reviewed and the data analysed systematically.
- ❖ Chapter 4 of the report are the results and discussion that brings together the insights from the literature review and analysing how they impact project management in 3D concrete printing.
- ❖ Chapter 5 wraps up the dissertation, by highlighting the discoveries and addressing any study limitations while also proposing areas for research projects.

By bridging the gap between conventional construction management practices and the demands of this emerging technology, this study aims to direct project management in the field of 3D concrete printing in this evolving era of digital fabrication and automation in the construction sector. It also seeks to contribute to the successful implementation of 3D concrete printing within the built environment.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION TO 3D CONCRETE PRINTING IN CONSTRUCTION

2.1.1 Historical Development

The idea of 3D printing first appeared in the early 1990s with significant progress being made in the last ten years (Tay et al. 2017). Originally focused on small scale models, this technology has progressed to allow for the construction of full-scale buildings as well. Khoshnevis et al. (2012) in their work from 2012 on Contour Crafting technique pioneered a method to scale 3D concrete printing. Marking a significant shift from traditional building methods to automated manufacturing processes within the construction sector.

The development of 3D printing has seen notable progress over time with several key milestones. Bos et al. (2016) discussed the shift from small scale testing in labs to use on construction sites revealing the technology's viability for building projects. Gosselin et al. (2016) further contributed by introducing concrete with exceptionally high performance for large scale 3D printing purposes thereby broadening material choices and enhancing structural strengths of printed components.

In the recent years there has been a rapid advancement in research and real world applications in this field of study. Alami et al. (2023) pointed out that the number of 3D printed structures has significantly risen since 2014 which shows a rise in industry approval and development in this technology. However, challenges persist in expanding the use of this technology and incorporating it into common construction methods.

Researchers have approached 3D concrete printing from several aspects including practical testing, philosophical study and historical recollection. Panda et al. (2019) conducted real

world experiments to test materials and processes. Gosselin et al. (2016) in their work from 2016, delved into the social and ethical considerations in the integration of 3D printing in construction projects using philosophical methods. Meanwhile, Bos et al. (2016) explored the development of technology and its significant influence on the construction sector.

2.1.2 Current State of Technology

This thesis discusses "Project Management in Structures/Buildings constructed using 3D printing technology." The study digs into current project management approaches, problems encountered, and opportunities for improvement in the field of 3D printed concrete structures. The literature study covers a wide range of subjects connected to 3D concrete printing, including materials, processes, and project management strategies while the purpose is to provide a full understanding of ongoing research and identify potential avenues for additional investigation.

The field of 3D printing has seen notable advancements since its early days and initially, research focused mostly on improving materials and printing methods Bos et al. (2016). Pioneering studies have highlighted 3D printing's transformative potential in building, stressing cost savings and increased efficiency Tay et al. (2017). As technology has advanced it is now possible to create increasingly sophisticated and vast structures Kruger et al. (2023).

2.2 CURRENT RESEARCH AND DISCOVERIES IN 3D CONCRETE PRINTING PROJECT MANAGEMENT

Recent studies have also looked into combining project management strategies with 3D printing methods. Ghafur (2023) carried out a thorough analysis of 3D printing and stressed the importance of using tailored project management methods to tackle the distinct hurdles associated with this technology. The research underscored the significance of incorporating material properties evaluation, economic factors and environmental sustainability, into project management models.

Companies like Sika are leading the way in making 3D concrete printing industry-ready. They offer complete support from CAD and technical design to material supply, integrating automation with process control and extrusion systems. This indicates that 3D concrete printing is moving from experimental stages to practical implementation in the construction industry (Sika Australia, n.d.).

In the studies carried out there has been a growing emphasis on integrating project management strategies with 3D concrete printing advancements. Ghafur (2023) pointed out the necessity of customized project management techniques to tackle the unique challenges posed by this technology. The study underscored the significance of integrating assessments of material properties along with factors like economics and environmental sustainability, into project management frameworks. Ter Haar, Kruger and van Zijl (2023) explored the potential of off-site construction utilizing 3D printing and shed light on emerging project management hurdles concerning logistics, in transportation and assembly as well as ensuring quality control within regulated environments. Their research highlights the necessity for project managers to adjust methods to cater to the unique characteristics of 3D printed elements.

2.3 PROJECT MANAGEMENT CHALLENGES IN 3D CONCRETE PRINTING

2.3.1 Planning and Scheduling for 3D Printed Projects

The field of construction project management conventionally follows a step, by step process referred to as the 'waterfall' technique that comprises five stages. The process kicks off with project initiation. Then moves on to planning followed by implementation of the laid out plan while keeping a close eye on progress and making necessary adjustments before wrapping up the entire project Buswell et al. (2018). Progressing through each phase depends on the completion of the previous one, with milestones and deliverables signifying the progression from one phase to the next, in a systematic manner.

During the stage of a project's development process the team outlines the project's objectives. Determines its feasibility. At this point, project managers evaluate if the project is workable and in line with the company's goals. This typically includes conducting a study to assess feasibility or analysing a business case to weigh the risks and rewards of pursuing the project.

Once the project receives approval to proceed the implementation phase will commence. One of the steps in managing a project involves creating a plan that outlines all tasks to be done the resources needed to complete them on time and within budget limits while also considering the potential risks (Dey et al., 2022). Project managers use tools, like critical path analysis, Gantt charts and Work Breakdown Structures (WBS) to manage resources and arrange tasks effectively. (Dey et al., 2022).

The implementation stage is when the real construction takes place and project managers are, in charge of supervising activities to ensure they align with the plan and meet quality

requirements as mentioned by Ghafur (2023). This period typically involves coordinating teams and subcontractors while handling logistics and addressing any arising challenges.

As the execution phase of the project begins, the monitoring and controlling phase will run alongside the execution. Project managers closely monitor progress by comparing it to the plan and making adjustments to ensure things stay on course (Jayathilakage et al., 2022). This includes providing regular updates, performance checks and handling risks as they arise.

The final stage indicates the completion of the project where project managers perform checks and obtain required permissions before delivering the project to the client (Jipa & Dillenburg 2022). Additionally, they evaluate the project's performance to determine its effectiveness and collect lessons and insights for future projects.

2.3.2 Resource Management in 3D Concrete Printing

The field of construction project management is detailed and complex as it entails supervising all aspects of a construction project right from the initial idea until stage of structural completion. The ultimate objective is to ensure that projects are finalized within the timeline and stay within budget while maintaining the desired quality benchmarks Alami et al. (2023). This process involves a variety of responsibilities such as resource management, scheduling tasks efficiently monitoring expenses carefully ensuring standards of quality and facilitating communication among all stakeholders involved in the project.

Lately, in the construction sector there has been a growing acceptance of flexible and versatile project management techniques that draw inspiration from software development

and other domains emphasizing adaptability and quick response to changes Khoshnevis et al. (2012). Agile strategies in construction frequently feature planning and implementation processes that enable adjustments informed by feedback and evolving conditions.

Wu, Wang and Wang (2016) highlight the unique resource management challenges in 3D concrete printing projects, including the need for specialised personnel trained in both construction and 3D printing technologies. They also discuss the significance of managing novel equipment and materials, which may require different procurement and maintenance strategies compared to traditional construction projects.

2.3.3 Quality Control and Assurance Strategies

Quality control in 3D printing poses distinct challenges in contrast to traditional building techniques. Shakor et al. (2019) investigates the mechanical characteristics of 3D-printed cement-based materials and emphasize the significance of understanding the impact of printing parameters affect final product quality.

One major challenge is maintaining uniform material characteristics across the printed framework. Panda et al. (2019) discusses techniques to improve the qualities of geopolymers components that are 3D printed, by underlining the importance of precise management of mixture composition and printing parameters to attain the intended strength and endurance.

New techniques are being created to check the integrity of 3D printed buildings with Non-destructive printing methods. According to Sanjayan et al. (2018), traditional testing methods might not work well with 3D printed components and thus there is a need for fresh protocols to ensure their reliability.

In the mix design process, it's crucial to add materials to improve the print quality and structural strength of the mixture used for 3D printing. As discussed by Jayathilakage, Rajeev and Sanjayan (2022) in their recent study published in 2022, they emphasized the significance of grasping and managing the flow properties of printable concrete through rheometry analysis. Their research underlines the necessity for testing protocols to guarantee performance of materials in various 3D printing settings and surrounding environments.

The impact of process parameters on the quality of 3D printed structures is a crucial area of study. According to Wolfs, Bos and Salet (2019) conducted an in-depth investigation in 2019 on the solidified characteristics of concrete that was 3D printed with an emphasis on interlayer bonding strength. Their research paper highlights how variables like nozzle standoff, print speed and distance between layers greatly influence the adhesion between them. This study emphasizes the significance of carefully tuning printing parameters to guarantee the structural durability of 3D printed concrete components.

2.4 INTEGRATION OF DIGITAL TECHNOLOGIES IN 3D CONCRETE PRINTING PROJECT MANAGEMENT

2.4.1 Building Information Modeling (BIM) for 3D Printed Structures

A significant change in the field of construction project management involves the increasing use of technologies like Building Information Modeling (BIM). This technology has had an impact on how projects are planned and carried out (Li, Li & Zou 2023). BIM enhances cooperation among project stakeholders and enhances project visualization while offering precise estimations of costs and timelines. Furthermore, it aids in identifying and resolving

conflicts resulting in reduced expenses due to errors and rework during the construction process.

The merging of Building Information Modeling (BIM) with printing marks a notable progression in construction project management. Paolini, Kollmannsberger and Rank (2019) review the uses of BIM in manufacturing for construction emphasizing its ability to streamline the design-to-print workflow and boost project coordination.

BIM enables precise modeling of 3D printable structures, allowing for optimization of design for additive manufacturing (DfAM) principles. This integration facilitates better communication between architects, engineers, and construction teams, potentially reducing errors and improving project efficiency. It demonstrates advanced software capabilities including path generation for robotic arm printers, collision detection analysis, and visualization of the printing process. These tools enable project managers to anticipate and resolve issues before they occur on-site, potentially reducing delays and improving overall project efficiency (AMC Bridge n.d.).

However, challenges remain in fully integrating BIM with 3D concrete printing processes. Robayo-Salazar et al. (2023) note that while BIM can significantly enhance project planning and visualization, there is a need for specialized tools and workflows to address the unique requirements of 3D printed structures, such as toolpath generation and print parameter optimization.

AMC Bridge (n.d.) showcases software functions such as generating paths for robotic arm printers and analysing collision detection while also offering visual representations of the printing process to help project managers foresee and address potential problems in advance—potentially minimizing delays and enhancing project efficiency overall.

2.4.2 Artificial Intelligence and Machine Learning Applications in Project Management

The combination of Building Information Modeling (BIM) and 3D printing has paved the way for advancements in project management. One illustration of this is the merging of BIM with 3D printing methods which simplifies the conversion of designs into structures. This process enhances accuracy and minimizes errors significantly (Perkins & Skitmore 2015).

Artificial Intelligence (AI) and Machine Learning (ML) are now more commonly used to enhance 3D concrete printing procedures by providing potential solutions to challenges in mix design refinement, print parameter control, and quality assurance.

Ghafur (2023) discusses the potential of AI in predicting and enhancing the characteristics of concrete mixes that can be 3D printed, potentially reducing the need for extensive experimental testing. ML algorithms can analyze vast datasets of material properties and printing parameters to identify optimal combinations for specific project requirements.

In the realm of process control, AI-driven systems can potentially adjust printing parameters in real-time based on environmental conditions and material behavior, ensuring consistent print quality. However, the implementation of such systems in practical construction scenarios remains a challenge and requires further research.

2.5 RISK MANAGEMENT IN 3D CONCRETE PRINTING PROJECTS

2.5.1 Identifying and Assessing Risks

Perkins and Skitmore (2015) identify several risks specific to 3D printing in construction, including technological uncertainties, material performance variability, and regulatory compliance issues. They emphasise the need for project managers to develop new risk assessment frameworks that account for these unique challenges.

2.5.2 Risk Mitigation Strategies

Project managers also face unique challenges when it comes to safety issues. It is essential to prioritize the safety of both workers and the public by engaging in preparation processes along with training and vigilance (Lu et al. 2019). Adherence to regulations and comprehensive safety programs are essential in this regard.

Risk management in 3D concrete printing projects require consideration of both traditional construction risks and those unique to this technology. Perkins and Skitmore (2015) provide an early review of 3D printing in the construction industry, identifying potential risks related to material behavior, equipment reliability, and regulatory compliance.

More recent work by Wu, Wang and Wang (2016) critically investigates the use of 3D printing in the building industry, highlighting the need for specialized risk management strategies that address the technological uncertainties and potential failure modes specific to 3D printed structures.

A key aspect of risk management is the development of contingency plans for equipment failures or material inconsistencies during the printing process. The QOROX 3D printing technology case study on Construction Accord (n.d.) demonstrates the importance of robust quality control systems and backup procedures to mitigate risks in large-scale printing projects.

In summary although 3D concrete printing shows promise for revolutionizing the construction sector it also brings about hurdles concerning ensuring quality and managing risks. Research and hands on learning will play a role in devising comprehensive strategies to tackle these obstacles and unlock the complete benefits of this technology.

2.6 SUSTAINABILITY CONSIDERATIONS IN 3D CONCRETE PRINTING PROJECT MANAGEMENT

2.6.1 Environmental Impact Assessment

In construction project management today, sustainability has become a focus for project managers who must integrate strategies such as energy efficiency and waste reduction (Ma & Wang 2018). This frequently entails working with specialists and integrating eco-friendly design principles from the project's inception.

The ongoing debate surrounding 3D printing focuses on its environmental implications. De Schutter et al. (2018) present insights into the technical aspects as well as the economic and environmental benefits of utilizing concrete in 3D printing processes. These include reductions in waste and energy usage when contrasted with conventional construction methods.

Pessoa et al. (2021) carried out an analysis of the 3D printed building's thermal performance which proposed that better designs made possible by 3D printing could result in enhanced energy efficiency for buildings. However, they also note the influence of design decisions and printing settings in determining the environmental advantages of this technology.

Environmental impact assessment involves looking at the lifecycle of 3D printed buildings or objects to understand the environmental effects thoroughly. The process of printing itself might have aspects, however it's crucial to also take into account factors like creating custom concrete mixes and guaranteeing the printed structures longevity over time. Strohle et al. (2022) emphasize the importance of conducting thorough life cycle assessments to gain a view of how 3D concrete printing technology impacts the environment.

2.6.2 Sustainable Materials and Practices in Project Planning

Sustainable materials play a role in advancing 3D concrete printing technology and have the potential to make construction more environmentally friendly. Bhattacharjee et al. (2021) offer an in depth analysis of materials for 3D concrete printing by emphasizing the benefits of using alternative binders and recycled aggregates alongside industrial, by products.

Dey et al. (2022) highlights the utilization of industrial waste products in creating sustainable concrete through 3D printing technology to lessen waste generation and environmental impact during construction activities. They propose incorporating materials like fly ash and along with recycled aggregates into printable mixes for 3D printing, with some challenges needing to be overcome for maintaining performance consistency and durability over time.

The application of methods in the realm of 3D concrete printing goes beyond just choosing materials, it also involves refining process optimization and developing innovative design approaches to ensure efficiency and effectiveness, in construction projects. Witteveen+Bos (n.d.) emphasize the importance of optimizing structural designs to minimize material use while maintaining performance, a capability uniquely enabled by 3D printing technology.

Reinforcement integration in concrete buildings that are 3D printed, presents both challenges and opportunities for sustainable construction practices. Asprone et al. (2018) propose rethinking reinforcement strategies for concrete digital fabrication, exploring innovative approaches such as continuous fiber reinforcement and the incorporation of short fibers into printable mixes. Their work suggests that tailored reinforcement techniques for 3D printing could lead to more efficient use of materials and improved structural performance, potentially enhancing the sustainability of printed concrete structures.

In studies which have been conducted lately there has been a lot of attention given to improving the quality and effectiveness of mixes that can be used in 3D printing projects. Panda, Unluer and Tan (2018) investigated the use of using geopolymers mortars based on high-volume of fly ash to create concrete mixes for 3D printing purposes, their findings showed enhancements in the rheological properties as well as a decrease in its negative impact on the environment. Similarly, Li, Li and Zou (2023) explored the development of 3D printing concrete with a lower pH level using waste materials as ingredients, this not only addressed concerns related to sustainability but also aimed to improve the overall performance of such materials used in construction.

In their comprehensive analysis of the thermal performance of 3D printed buildings, Pessoa et al. (2021) conducted a study on the efficiency of 3D printed structures and highlighted

the importance of controlling material flow properties (rheological characteristics) and improving structural integrity in their research finding. A thorough analysis of the 3DCP's materials and process characterization, financial implications, and environmental sustainability was given by Ahmed et al. (2023), who also emphasized the necessity for more study on the mechanics of 3D printers and the standardization of printer nozzles.

The selection of materials for 3D concrete printing plays a crucial role in project management processes. Lu et al. (2019) provides a comprehensive review of cementitious substances that be 3D printed, emphasizing the need for project managers to balance printability, buildability, and mechanical properties in their planning and execution strategies.

2.7 REGULATORY AND STANDARDIZATION ISSUES IN 3D CONCRETE PRINTING PROJECTS

2.7.1 Current Regulations and Their Impact on Project Management

With the jurisdictions lacking specific guidelines for this new technology the regulatory landscape for 3D printed construction is still evolving. Siddika et al. (2020) highlight difficulties that arise from the lack of regulations which could result in uncertainties during project approval and quality control procedures.

Some nations and areas are starting to create rules for 3D building projects. For instance, the Dubai Municipality has put forth regulations for 3D printed buildings, setting a precedent for other jurisdictions (Parametric Architecture n.d.). However, these regulations are commonly based from modifications of existing building codes and may not fully address the distinctive features of 3D printed structures.

2.7.2 Efforts Towards Standardization and Project Implications

Standardization efforts in the field of 3D printing are currently in progress as different stakeholders collaborate to establish recommendations and optimal approaches for the process. The American Concrete Institute (ACI) has formed a committee that concentrates on 3D concrete printing, with the goal of creating standards related to material characteristics, pertinent design factors and construction methodologies (Sika Australia n.d.).

Jipa and Dillenburger (2022) discuss the advancements in 3D printed formwork technologies and emphasize the importance of standardized methods to guarantee reliable quality and effectiveness consistently achieved in the field of construction work with this cutting edge technology. They point out that despite advancements in material development and printing techniques that have taken place over time a major challenge hindering acceptance is the absence of universal standards, across the industry.

The development of 3D printing technology is advancing swiftly posing challenges for standardization initiatives given the varied approaches being explored in this field by different stakeholders such as regulatory bodies and industry organizations who must navigate between establishing norms while encouraging creativity and progress.

2.8 FUTURE DIRECTIONS FOR PROJECT MANAGEMENT IN 3D CONCRETE PRINTING

Even though there have been progressions, in this field there are still obstacles to overcome in creating mixes that're appropriate for large-scale printing purposes. Ma and Wang (2018) critically review the preparation design and concrete material workability measurement for

large-scale 3D printing by identifying gaps in current knowledge and proposing for future research initiatives.

In their extensive analysis of 3D concrete printing, Strohle et al. (2022) identified key challenges such as developing materials with desired characteristics and enhancing printer nozzle technology and automation in reinforcement processes. They also emphasized the importance of investigating the use of grained aggregates in large scale structural projects and understanding how 3D printers operate.

In the future of 3D printing project management, it is expected to progress in several key aspects:

- ❖ Integration of advanced digital technologies: Future project management systems include Artificial intelligence (AI) and machine learning (ML) to predict trends better and manage printing parameters and resources efficiently in real-time (Ghafur 2023).
- ❖ Sustainability-driven project planning: As environmental concerns become more pressing, project managers are expected to focus more on incorporating sustainable methods and eco-friendly materials into their planning processes (Alami et al. 2023).
- ❖ Standardisation and regulation: As standards for 3D concrete printing become more established, project management practices will need to adapt to ensure compliance and leverage these standards for improved efficiency and quality (Siddika et al. 2020).
- ❖ Skill development: Due to the advancements in 3D concrete printing technology, it will require ongoing training and skill development for project managers and team members as highlighted by Wu, Wang & Wang (2016).

- ❖ Off-site and modular construction: This could bring about project management methods by combining manufacturing principles with construction practices through the use of off-site 3D concrete printing (Ter Haar, Kruger & van Zijl 2023).

In the years ahead of us indicate that the field of project management in 3D concrete printing will persist as a lively and progressing area that requires flexibility and ongoing education from professionals.

CHAPTER 3 METHODOLOGY

3.1 GOALS AND OBJECTIVES

The primary aim of this research is to conduct an assessment of the existing literature regarding project management methods employed in the construction of 3D printed concrete structures and buildings. In doing so the research is expected to achieve the specific objectives:

- ❖ To identify the most effective project management techniques, obstacles, and trends for 3D concrete printing projects.
- ❖ To investigate how conventional project management techniques are affected by the development of 3D concrete printing technology.
- ❖ Investigate the sustainable practices of project management in 3D concrete printing.
- ❖ Investigate 3D printing's contribution in achieving pertinent sustainable development.
- ❖ To review existing construction project management technologies and develop strategies for their adaptation to concrete 3D printing.
- ❖ To pinpoint knowledge gaps and provide avenues for further study in this area.

3.2 RESEARCH METHODOLOGY

This research will use an approach to review the literature and analyze the existing studies on this research topic.

3.2.1 Search Strategy

The literature search will be conducted utilizing the databases listed below:

- ❖ Google Scholar
- ❖ ScienceDirect
- ❖ Scopus
- ❖ UniSQ Library (<https://www.unisq.edu.au/library>)

The literature search utilized a combination of comprehensive academic databases and specialized resources. Google Scholar provided broad coverage across disciplines, while ScienceDirect and Scopus offered high-quality, peer-reviewed research in relevant fields. The UniSQ Library database provided access to institution-specific resources. Additionally, industry-specific sources such as American Concrete Institute publications and reports from organizations like Witteveen+Bos and AMC Bridge were consulted. This diverse range of sources ensured comprehensive coverage of both academic research and industry developments in project management for 3D concrete printing.

Search terms will include:

- "3D printed concrete" AND ("project management" OR "construction management")
- "3D concrete printing" AND (planning OR scheduling OR quality OR risk OR sustainability)
- "Additive manufacturing" AND "concrete" AND "construction"
- "Construction automation" AND "3D printing"

- "Digital fabrication" AND ("construction" OR "building")
- "Robotic construction" AND "project management"
- "Lean construction" AND "3D printing"
- "Agile construction" AND ("additive manufacturing" OR "3D printing")
- "BIM integration" AND "3D concrete printing"
- ("Off-site construction" OR "Modular construction") AND "3D printing"
- "Regulatory challenges" AND "3D printed buildings"
- • "Material innovation" AND "3D concrete printing"
- "Supply chain management" AND ("additive manufacturing" OR "3D printing")
AND "construction"
- ("Cost-effectiveness" OR "Time efficiency" OR "Quality control") AND "3D
concrete printing"
- "Circular economy" AND "3D printed buildings"
- "Life cycle assessment" AND "3D concrete printing"
- "Embodied carbon" AND ("additive manufacturing" OR "3D printing") AND
"construction"
- ("AI" OR "Artificial Intelligence") AND "3D concrete printing"
- "Digital twin" AND "3D printed buildings"

- "IoT" AND ("additive manufacturing" OR "3D printing") AND "construction"

The search procedure will include additional terminology related to particular areas, such as materials science, structural design, architectural applications, and developing technologies, in addition to the main search phrases. This method guarantees thorough discussion of the multidisciplinary aspects of 3D concrete printing. The primary focus of the search will be articles published between 2015 and 2024 in order to catch recent developments in this quickly developing discipline. However, if they offer fundamental ideas or approaches that are still applicable to modern practices, ground-breaking publications published prior to 2015 might be included. Preprints and conference proceedings, where cutting-edge research is frequently initially presented, will also be included in the search to account for the rapid advancements in this field. Throughout the study period, the literature search will be updated often to take into account the most recent discoveries and developing trends in project management for 3D concrete printing.

3.2.2 Inclusion and Exclusion Criteria

Inclusion criteria:

- ❖ Peer-reviewed journal articles and conference papers.
- ❖ Publications from 2015 onwards, with exceptions for seminal works prior to 2015 that provide foundational concepts still relevant to current practices.
- ❖ English language publications.
- ❖ Articles that address at least one of the following project management aspects in relation to 3D printed concrete construction:

- Planning and Scheduling
- Resource allocation and management
- Quality control and assurance
- Risk management and mitigation strategies
- Sustainability considerations in project planning
- Integration of digital technologies (e.g., BIM, AI, IoT) in project management
- Stakeholder management and collaboration
- Regulatory compliance and standardization issues

Exclusion criteria:

- ❖ Publications focused solely on technical aspects without project management considerations. For example,
 - Articles solely discussing concrete mix designs without addressing their impact on project planning or execution.
 - Studies focused exclusively on the mechanical properties of printed structures without considering project management implications.
- ❖ Non-academic sources like blogs or news articles.
- ❖ Publications not available in full text.

3.2.3 Literature Review Process

Initial Screening

- ❖ Review titles and abstracts summaries of the papers that have been identified.
- ❖ Apply inclusion/exclusion criteria.
- ❖ Record the factors leading to exclusion.

Full-Text Review

- ❖ Read full papers that pass initial screening
- ❖ Further implement inclusion/exclusion criteria
- ❖ Assess quality and relevance of studies

3.2.4 Data Extraction and Analysis

The extracted data will be categorized and coded according to the following themes:

- ❖ Project planning and scheduling in 3D concrete printing.
- ❖ Resource management and supply chain considerations.
- ❖ Quality control and assurance strategies.
- ❖ Risk management approaches.
- ❖ Sustainability integration in project management.
- ❖ Digital technology adoption in project management.

- ❖ Stakeholder management and collaboration.
- ❖ Regulatory and standardization impacts on project management.

To find trends, patterns and gaps in existing knowledge a thematic analysis will be conducted (see Appendix B for Thematic analysis coding). Where available, quantitative data on project performance metrics will be summarized using descriptive statistics. Additionally, the research will seek for innovative approaches and new standards for overseeing 3D concrete printing operations.

(See Appendix A for Data Extraction Form)

3.2.5 Software Tools Analysis

This research will focus on software applications that integrate design capabilities, with analysis and project management functionalities for supervising 3 printing tasks. The software options selected for evaluation have been highlighted due to their usage, in existing literature and their ability to address project management challenges related to 3 dimensional concrete printing processes. The assessment will cover aspects including. Not restricted to:

- ❖ BIM-integrated tools: Building Information Modeling (BIM) software tailored for printing play a significant role in enhancing the design to print process and facilitating better project coordination as highlighted in the work Paolini, Kollmannsberger & Rank (2019).
- ❖ Specialized 3D printing software: Tools like the Slicer software from Witteveen+Bos, a Rhino/Grasshopper plugin plays a role in enhancing the quality and efficiency of

printing processes by enabling precise control over 3D concrete printers and converting 3D models into robot-readable files (Witteveen+Bos n.d.).

- ❖ Project management platforms: These refer to cloud based tools that incorporate design features and structural analysis capabilities along with printing simulations and project management functions as outlined by Zhang et al. (2019). These platforms are chosen for their ability to enhance collaboration among team members.
- ❖ Simulation and optimization tools: These tools are essential for anticipating structural stability problems and improving printing processes; for example the Buckling Simulation software referred to by Witteveen+Bos (n.d.) plays a role in risk assessment and ensuring quality control measures are met.
- ❖ Digital Twin technologies: Tools that create virtual representations of the physical construction process, as discussed by Xiao et al. (2021). They are valuable as they enable project managers to simulate scenarios and make well informed decisions.

The assessment will primarily consider on how these technologies work with project management processes and how they affect precision and effectiveness. In particular, the analysis will focus on:

- ❖ The tool's ability in tackling hurdles encountered in 3D concrete printing tasks like predicting material behaviour accurately and optimizing the print path, for better results while ensuring top notch quality control throughout the process.
- ❖ The ability to integrate with software and hardware commonly utilized in 3 concrete printing projects.

- ❖ The tool's contribution in managing risks while also taking into account sustainability factors and meeting regulatory requirements.
- ❖ How it effects the project timeline, cost, and resource allocation.
- ❖ User-friendliness and the learning curve for project teams.

This comprehensive analysis of software tools is crucial because:

- ❖ It addresses a significant issue in current project management practices for 3D concrete printing, as identified by Wu, Wang & Wang (2016), highlighted the necessity for specific tools to manage the distinct aspects of this technology.
- ❖ It aligns with the shift towards using digital technology in managing construction projects, as highlighted by Ter Haar, Kruger & van Zijl (2023) in their discussion of integrating AI and ML.
- ❖ It contributes to the development of standardized processes in 3D concrete printing, addressing the challenge of lack of standardization noted by Siddika et al. (2020).
- ❖ It supports the implementation of sophisticated quality control and risk management techniques, which Buswell et al. (2018) identified as critical for the success of 3D concrete printing projects.

While this analysis focuses on specific types of software tools it does not exclude the possibility of identifying and evaluating other relevant tools that emerge during the research process. The objective is to give a thorough grasp of how software tools can improve 3D concrete printing project management, boosting the overall efficiency, quality, and success of these cutting-edge building initiatives.

3.3 SCHEDULE

	Month 1	Month 2	Month 3-4		Month 5-6		Month 7-8		Month 9-10	
	January	February	March	April	May	June	July	August	September	October
Task										
Finalize research plan and begin literature search	■									
Conduct initial screening of papers		■								
Full-text review of selected papers			■	■						
Data extraction and analysis					■	■				
Synthesis of findings							■	■		
Report writing and final revisions									■	■

Figure 1 Gantt Chart for Research Project Timeline

This Gantt chart illustrates the planned timeline for the 10-month research project on project management in 3D concrete printing. It visually represents the schedule of key activities, including literature search, paper screening, full-text review, data extraction and analysis, synthesis of findings, and report writing. The chart provides a clear overview of the project's progression, showing the duration and sequence of each task. This visual representation aids in project planning, resource allocation, and tracking progress throughout the research process.

3.4 RESOURCE REQUIREMENTS

- ❖ Access to academic databases through the university library.
- ❖ Organizing references through management softwares (e.g. Mendeley or EndNote).
- ❖ Qualitative data analysis tools (e.g. NVivo).
- ❖ Word processing and spreadsheet software.
- ❖ Personal computer with access to the internet.

3.5 RISK MANAGEMENT PLAN

This study, about "Project Management in 3D Printed Concrete Structures and Buildings" focuses on reviewing existing literature without conducting any hands on experiments or visits to sites involving construction work or physical testing activities. Therefore it does not necessitate the approval of risk assessment from the ethics committee at the University of Southern Queensland. The main risks associated with this project pertain to handling data effectively managing time allocation and ensuring that the information collected remains accurate and up, to date. Necessary measures to address potential risks have been implemented as detailed in the risk assessment table provided on in this document. The researcher (myself) commit to follow the university's protocols regarding ethical research conduct which includes citing sources correctly and managing data appropriately.

Table 3 Risk Assessment Table for Literature Review-Based Research Project

Risk Category	Potential Risk	Likelihood	Impact	Mitigation Strategy
Data Integrity	Outdated or inaccurate information in literature	Medium	High	Use recent publications (within last 10 years) and cross-reference multiple sources
Scope Creep	Research expanding beyond project boundaries	Medium	Medium	Clearly define research objectives and regularly review progress against them
Time Management	Delays in literature review completion	High	Medium	Create a detailed timeline with milestones and allocate buffer time
Bias	Unintentional bias in source selection or interpretation	Medium	High	Use systematic review methods and seek peer review of findings
Technology Issues	Loss of data or access to digital resources	Low	High	Regularly backup data and ensure access to multiple research databases

Risk Category	Potential Risk	Likelihood	Impact	Mitigation Strategy
Ethical Concerns	Unintentional plagiarism or improper citation	Low	High	Use reference management software and carefully document all sources
Language Barrier	Misinterpretation of non-English sources	Medium	Medium	Use professional translation services when necessary or focus on English-language sources
Limited Access	Inability to access key research papers	Medium	High	Utilize university library services and interlibrary loan options
Regulatory Changes	Changes in 3D printing regulations during research	Low	Medium	Monitor industry news and update literature review as necessary
Health	Eye strain or posture issues from extended computer use	Medium	Low	Take regular breaks and ensure proper ergonomic setup

3.6 RESEARCH PROCESS FLOWCHART

The research process involves an approach to conduct a detailed examination of the literature regarding project management, in 3D concrete printing. It starts with conducting a search, across databases and using defined search terms. Titles and abstracts are initially screened to pinpoint studies. Selected papers undergo a detailed review to apply inclusion and exclusion criteria. Important data is extracted. The gathered information is then synthesized to highlight themes, patterns and areas where the literature lacks sufficient coverage. The results are compiled together in a report addressing the goals of the study and adds valuable insights, to the existing knowledge, in this area.



Figure 2 Research process flowchart

This study methodology seeks to offer an, in depth examination of project management elements in 3D printed structures and buildings that emphasizes construction automation specifically. By systematically analysing the available literature and reviewing real world examples this study will synthesize current knowledge, identify best practices, and highlight areas for future research in this rapidly advancing field. The conclusions from this research will contribute to the development of effective project management strategies for 3D concrete printing projects while potentially leading to improved efficiency, sustainability, and innovation in the construction industry.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 REVOLUTION OF PROJECT MANAGEMENT IN 3D CONCRETE PRINTING

4.1.1 Transition from Traditional to 3D Printing-Specific Approaches

The use of 3D printing in the construction industry has led to notable changes in how projects are managed effectively prompting a shift from conventional 'waterfall' strategies to better suit the specific demands of 3D printing initiatives Buswell et al. (2018). This transition calls for a more flexible and repetitive method in mapping out and carrying out projects.

In the construction industry today, Lean Construction draws from manufacturing principles to integrate 3D printing effectively. The approach emphasizes boosting value and cutting down on wastage throughout the building process (Paolini, Kollmannsberger & Rank 2019). By applying lean principles to 3D printing, it becomes possible to enhance material efficiency, minimize delays between print cycles and elevate the overall operational effectiveness.

Agile project management methods are now being applied to 3D printing projects well. The iterative and repetitive nature of 3D printing fits nicely with the principles of agility by enabling lessons to be learned from each round (Paul et al. 2018). In construction projects utilizing 3D printing technology with this agile method might entail the integration of short sprint cycles, frequent team meetings and diverse feedback channels to guarantee that the printed structures satisfy changing stakeholder needs.

Some project management methodologies are tailored for 3D printing; however these modifications might not entirely cater to the unique characteristics of the technology as mentioned by Wu, Wang & Wang (2016). Conventional project management strategies find it challenging to account for the continuous nature of the printing process and the interdependencies between material properties, printing speed, and structural integrity. The layer, by layer building technique of 3D printing demands a scheduling and resource allocation strategy compared to traditional construction methods according to Xiao et al. (2021).

4.1.2 Integration of Digital Technologies

One important discovery is the growing use of technology, in managing projects involving 3D concrete printing technology. Building Information Modeling (BIM) has become an instrument that fosters collaboration among stakeholders in these projects by enhancing project visualization capabilities while also enabling accurate estimations of costs and timelines (Li, Li & Zou 2023). Despite these benefits of BIM in 3D concrete printing projects being evident there are still obstacles to overcome in creating tools for optimizing print parameters (Robayo-Salazar et al. 2023).

Lately there have been developments in combining Building Information Modelling (BIM) with 3D printing techniques. AMC Bridge showcased a method for 3D printing using concrete that can simplify production processes and improve printing accuracy while reducing construction timelines. This was achieved by examining and presenting the 3D printing of designs created in Autodesk Revit software (AMC Bridge, n.d.). In addition to that presentation by AMC Bridge highlights functionalities like producing route data for robotic arm cement 3D printers and carrying out collision analysis while also crafting visual representations of the printing procedure (AMC Bridge n.d.). This range of abilities implies that supervisors could gain advantages in terms of strategizing risk mitigation, and quality control through the use of specialized software tools.

The use of 'Digital Twin' technology is on the rise in monitoring 3D printing construction projects. This virtual representation of the physical construction process, consistently updated with data from sensors and monitoring systems, allows project managers to simulate scenarios, refine processes, and make informed decisions using up-to-date information (Xiao et al. 2021).

The analysis of software tools specific to 3D concrete printing reveals their significant impact on project management processes. The Slicer software from Witteveen+Bos, a Rhino/Grasshopper plugin, demonstrates the potential for seamless control of 3D concrete printers and efficient conversion of 3D models to robot-readable files (Witteveen+Bos n.d.). This integration helps simplify the process from designing to printing which could potentially decrease errors and enhance project schedules.

4.2 KEY CHALLENGES IN MANAGING 3D CONCRETE PRINTING PROJECTS

4.2.1 Resource Management and Skill Development

Managing resources in 3D printing projects poses distinctive challenges that involve specialized staff and equipment requirements which create a demand for individuals skilled in both construction and 3D printing technologies (Wu, Wang & Wang 2016). The existing skills gap acts as an obstacle for project leaders which highlights the necessity for tailored training programs and educational campaigns within the sector.

The application of the Just in Time (JIT) approach is now being utilized in the field of 3D printing in the building industry. This strategy revolves around creating components precisely when required to diminish surplus inventory and cut down on waste as highlighted by (Rahul & Santhanam 2020). Incorporating JIT concepts into the production and delivery of 3D printing materials can effectively organize these actions by reducing the need for storage space and improving overall project efficiency.

4.2.2 Quality Control and Assurance

Quality control becomes an obstacle in 3D concrete printing projects. Traditional testing methods are often inadequate for 3D printed structures, necessitating the need to create innovative quality control procedures (Sanjayan et al. 2018). Novel methods of quality supervision are under development to address the hurdles of 3D printed structures by introducing monitoring systems that utilize sensors and computer vision technology for identifying and fixing printing imperfections in real-time (Buswell et al. 2018).

Project managers are delving into non-destructive testing methods tailored for 3D printed components to ensure their quality assurance. This involves devising testing protocols establishing monitoring systems onsite and employing non-destructive testing techniques to validate the dependability and performance of 3 dimensional printed components (Robayo-Salazar et al. 2023).

4.2.3 Risk Management in an Evolving Technological Landscape

Managing risks in 3D printing projects involves assessing not only the typical hazards found in construction projects but also those specific to this innovative technology. Perkins and Skitmore (2015) identify technological uncertainties, variability in material performance and adherence to regulations as crucial risk areas.

Managing risks in printing projects requires a strategy as project managers face distinct obstacles such as unpredictable material behaviour and the possibility of equipment malfunctions or printing errors. To effectively address these risks thorough testing must be conducted, backup systems for components should be in place and comprehensive contingency plans need to be developed backup systems for critical components and create detailed contingency plans (Shakor et al. 2019).

New approaches in managing risk involve using risk assessment models that target the uncertainties associated with this domain with the goal of assisting project managers in effectively identifying and managing risks throughout their projects (Ziejewska et al. 2022).

The QOROX 3D printing technology case study on Construction Accord (n.d.) illustrates the significance of robust quality control systems and backup procedures to mitigate risks in large-scale printing projects.

Strategies to reduce the impact of 3D printing projects include:

- Enforcing quality checks, on materials and printed components.
- Developing contingency plans for equipment malfunctions and variations in materials.
- Early project engagement with regulatory bodies to resolve compliance issues.
- Investing in the growth of project team members, through training and skill development opportunities.

4.2.4 Long-term Durability and Maintenance Considerations

Project management methods today often prioritize the immediate construction phase over planning for the entire life cycle of the printed structure. This gap could lead to unforeseen maintenance issues and potential structural problems in the future (Shakor et al. 2019). Addressing the long-term durability and maintenance of 3D printed structures poses a challenge in project management strategies (Sustainability 2023).

4.3 SUSTAINABILITY CONSIDERATIONS IN PROJECT MANAGEMENT

4.3.1 Environmental Impact Assessment

The environmental impact of 3D concrete printing is an aspect that needs consideration and evaluation to analyse the potential effects on the environment caused by proposed projects

or developments. Alami et al. (2023) highlight the positive impact of 3D printing on Sustainable Development Goals by minimizing material wastage and energy usage, however they stress the importance of thorough life cycle evaluations to grasp the complete environmental consequences of printed structures.

Green-focused project management techniques are becoming more popular in the field of 3D printing for construction projects. These methods seek to improve the efficiency of material usage and save energy while minimizing waste during the printing phase. Projects leaders are investigating methods to integrate tools for assessing the life cycle into their planning efforts to guarantee that 3D printed structures are not just economical but also environmentally sustainable (Alami et al. 2023).

4.3.2 Integration of Sustainable Materials and Practices

Project managers are increasingly required to integrate eco-friendly materials and methods into their 3D concrete printing projects. Bhattacharjee et al. (2021) examines materials suitable for 3D concrete printing such as industrial by-products and recycled aggregates. This shift towards sustainability brings forth both possibilities and obstacles for project managers who must weigh material characteristics alongside with printing parameters and long-term durability concerns.

Dey et al. (2022) specifically focus into the utilization of industrial materials in crafting sustainable concrete using 3D printing technology to lessen environmental impact in construction activities by minimizing waste and carbon emissions. Their analysis indicates that integrating substances like fly ash and slag alongside recycled concrete aggregates into mixtures shows promise, however achieving uniform quality and lasting strength poses ongoing challenges.

4.4 REGULATORY AND STANDARDISATION IMPLICATIONS FOR PROJECT MANAGEMENT

4.4.1 Navigating an Evolving Regulatory Landscape

The rules and regulations governing 3D printed construction are continuously developing as new technology emerges in jurisdictions without guidelines in place yet for this innovative approach to building structures Siddika et al. (2020) highlight the difficulties that arise due to the lack of standardised regulations pointing out how this could result in uncertainty when it comes to approving projects and ensuring their quality.

Some countries and regions have begun to develop guidelines for 3D printed construction as seen in the case of the Dubai Municipality that has established regulations for 3D printed buildings, paving the way for other jurisdictions (Parametric Architecture n.d.).

4.4.2 Impact of Standardisation Efforts on Project Practices

Efforts are being made to establish standards in 3D concrete printing with various stakeholders working to develop guidelines and best practices. Jipa and Dillenburger (2022) discuss the state-of-the-art technologies for 3D-printed formwork, emphasize the importance of standardized methods to guarantee uniform quality and efficiency. They point out that although there have been advancements in creating materials and techniques the absence of industry-wide standards within the remains a barrier to widespread adoption.

The establishment of standards is met with obstacles because of the progress in 3D concrete printing technology and the various methods under development pose challenges. The regulatory bodies and industry groups must carefully weigh the importance of implementing standards against the desire to encourage creativity and advancement in the field.

4.5 FUTURE TRENDS IN PROJECT MANAGEMENT FOR 3D CONCRETE PRINTING

4.5.1 Automation and AI Integration

The literature suggests a trend towards increased automation and AI integration in project management for 3D concrete printing. Ghafur (2023) discusses the potential of AI in optimising printing parameters and resource allocation. This trend indicates a future where project managers will need to be adept at leveraging advanced technologies for decision-making and process optimisation.

To boost effectiveness in managing 3D printing projects it is beneficial to merge Artificial intelligence and machine learning technologies. This method focuses on improving productivity and minimizing mistakes by adjusting printing settings, forecasting material performance ahead of time and spotting problems before they escalate (Ter Haar, Kruger & van Zijl 2023).

4.5.2 Off-Site Construction and Modular Approaches

An emerging trend identified in the literature is the potential for off-site 3D concrete printing. Ter Haar, Kruger and van Zijl (2023) explore the obstacles in terms of logistics management and ensuring quality and coordination in projects. This trend suggests that future project management approaches may need to integrate principles from manufacturing with traditional construction practices.

The concept of 'Agile Manufacturing' is now being applied to 3D printing in the construction industry. This method combines project management with manufacturing techniques to enable projects to swiftly adapt to alterations in design or specifications by employing modular printing systems that can be readily reorganized to manufacture different components as required (Bhattacharjee et al. 2021).

4.5.3 Specialized Scheduling Systems and Lifecycle-oriented Management

Future project management approaches should focus on developing and implementing scheduling tools that can accurately model the unique timing and resource allocation requirements of 3D concrete printing projects (Ter Haar, Kruger & van Zijl 2023). Additionally future frameworks should embrace a lifecycle focused approach that takes into account the lasting durability and potential flexibility of 3D printed structures. This strategy will help ensure the sustainability and durability of 3D printed buildings, beyond their construction phase (Li, Li & Zou 2023).

4.6 EMERGING PROJECT MANAGEMENT METHODOLOGIES

4.6.1 Agile and Lean Approaches in 3D Concrete Printing

Agile project management frameworks are increasingly being adapted for 3D printing projects. The cyclical and repeatable nature of 3D printing aligns well with agile principles, allowing for learning from one series to the next (Paul et al. 2018). In construction projects involving 3D printing technology, this agile approach could involve incorporating short sprint cycles, regular team meetings, and various feedback mechanisms to ensure that the printed structures meet the evolving requirements of stakeholders.

4.6.2 Digital Twin Technology and Virtual Project Management

'Digital Twin' technology is gaining traction as a tool in monitoring 3D printing construction projects. A digital twin acts as a model of the actual construction process regularly updated using sensor and monitoring setup data. This advancement empowers project supervisors to simulate scenarios improve workflows and make informed choices based on up-to-date information (Xiao et al. 2021).

4.7 SUPPLY CHAIN MANAGEMENT IN 3D CONCRETE PRINTING PROJECTS

Managing the supply chain for 3D printing in the construction industry presents challenges and complexities of its own nature. It involves working with suppliers to coordinate the procurement and transportation of printing materials that have particular storage and handling requirements. Establishing logistics systems is crucial to guarantee a continuous supply of materials to the construction site as highlighted by (Siddika et al. 2020).

One of the evolving approaches involves setting up on-site production facilities to cut down on transportation costs and improve the reliability of the supply chain operations. The application of blockchain technology is being considered to improve traceability and quality control of materials across the supply chain (de Schutter et al. 2018).

Overall 3D printed concrete construction management emerges as a dynamic and developing sector blending construction, technology and sustainable consciousness. With the advancement and widespread embrace of this technology, project managers will have a part to play in bridging the gap between construction methods with real world applications. The effectiveness of 3D printed concrete in tackling construction

issues like housing shortages, sustainability concerns and construction productivity will primarily hinge on the creation of flexible project management plans.

4.8 MATERIAL CONSIDERATIONS IN PROJECT MANAGEMENT

The process of choosing and getting materials for 3D concrete printing plays a crucial role in managing projects effectively. According to Ma and Wang (2018) adjusting concrete mix designs for 3D printing is key as it impacts project scheduling and resource distribution directly. The need for precise control over material properties, as discussed by Paul et al. (2018), introduces new quality control challenges that project managers need to address.

The use of eco materials like recycled aggregates and industrial by products as discussed by (Bhattacharjee et al. 2021), introduces challenges to procurement processes and requires project managers to consider long-term performance alongside immediate printing requirement as this balance between sustainability goals and project constraints represents a new dimension in construction project management.

4.9 COLLABORATIVE WORKFLOWS IN 3D CONCRETE PRINTING PROJECTS

The use of 3D printing technology has a notable effect on how different parties work together in construction projects. The necessity for designers and engineers to collaborate closely with constructors on creating 3D printed structures is highlighted by Witteveen+Bos (n.d.). This multidisciplinary method demands that project managers oversee communication and blend skills, across the projects life-cycle.

Incorporating resources like BIM and digital twin technologies improves teamwork by offering a shared platform for designing, analysing and managing projects (Xiao et al. 2021). However, the adoption of these technologies also necessitates new skills and processes, which project managers must oversee and integrate into existing project management frameworks.

4.10 SPECIALIZED SOFTWARE TOOLS FOR PROJECT MANAGEMENT

Software applications are being created specifically to assist with managing projects involving 3D printing technology. These applications offer functions such as generating path data for robotic arm concrete 3D printers, conducting analysis to prevent collisions, producing visual representations of the printing procedure and generating technical documents like G-code and 3D PDF reports (AMC Bridge, n.d.).

4.11 CASE STUDIES AND REAL-WORLD APPLICATIONS

Studying case studies reveals practical insights on how to manage 3D concrete printing projects effectively. The Project Milestone in Eindhoven, Netherlands (Parametric Architecture n.d.), the significance of teamwork and continuous design improvements in overseeing 3D printing projects. The project faced key challenges including coordinating multidisciplinary teams and adjusting to changing rules and regulations

The Huia Bay Private House Development in West Auckland, New Zealand (Construction Accord n.d.), highlights the critical role of early stakeholder engagement and adapting

project management strategies to suit the requirements of 3D printing technology effectively. This case study also underscores the significance of combining construction practices with 3 printing methods and calls for project managers to facilitate knowledge gap sharing and coordinate various expertise within the project team.

4.12 KEY RESEARCH QUESTIONS IN 3D CONCRETE PRINTING PROJECT MANAGEMENT

After conducting a review of existing literature and analysis in the field of 3D concrete printing project management, a number of crucial areas for investigation have emerged. These questions reflect the current state of the technology and the challenges faced by project managers in implementing in integrating this cutting-edge construction approach.

The key research questions are as follows:

- ❖ What are the effective management strategies for projects that incorporate 3D printed concrete structures?
- ❖ What main barriers and limitations are commonly encountered in the field of 3D printing concrete?
- ❖ How can project management methods be enhanced to improve the efficiency and effectiveness of 3D printed concrete construction?

4.13 EFFECTIVE MANAGEMENT TECHNIQUES

The literature reveals a shift from traditional project management approaches to more adaptive methodologies suited to the unique challenges of 3D concrete printing. The utilization of Lean Construction principles has demonstrated potential, in enhancing material efficiency and minimizing wastage in 3D printing projects (Paolini, Kollmannsberger & Rank 2019). Agile techniques emphasize progress and adaptability which harmonize

effectively with the nature of 3D printing procedures enabling ongoing learning and adjustments (Paul et al. 2018). The Just-in-Time (JIT) approach has been effectively applied to 3D concrete printing, helping to minimise inventory and improve project efficiency (Rahul & Santhanam 2020). This technique is especially advantageous when it comes to handling the materials needed for 3 concrete printing.

4.14 BARRIERS AND LIMITATIONS

Several key challenges have been identified in the implementation of 3D concrete printing:

- ❖ **Material restrictions:** Creating mixes that can be printed while ensuring they retain their strength, and functionality poses a difficulty as pointed out by (Ma & Wang 2018).
- ❖ **Lack of standardisation:** The lack of guidelines in the 3D printing industry leads to uncertainties regarding quality assurance and adherence to regulations as highlighted by (Siddika et al. 2020).
- ❖ **Regulatory uncertainties:** In some places regulations are unclear about using 3D printing in construction projects which can cause delays and issues with getting approvals for the projects (Parametric Architecture n.d.).
- ❖ **Quality control:** Ensuring consistent material properties throughout the printed structure presents unique challenges compared to traditional construction methods (Shakor et al. 2019).

4.15 PROPOSED IMPROVEMENTS AND INNOVATIONS

To address these challenges and improve project management in 3D concrete printing, several strategies and innovations have been proposed:

- ❖ **Integration of AI and ML:** These technologies can boost productivity by tuning printing settings and forecasting material characteristics (Ter Haar, Kruger & van Zijl 2023).

- ❖ Digital Twin technology: This enables project managers to monitor construction processes in real-time and simulate them for making decisions and improving workflows (Xiao et al. 2021).
- ❖ Specialised software tools: Tools in development to improve collaboration and streamline workflows by combining design capabilities with analysis and project management functionalities (AMC Bridge n.d.).
- ❖ Sustainable practices: Integrating life cycle assessment tools and sustainable materials during project development can enhance the impact of 3D printed buildings according to research by (Alami et al. 2023).

These research questions are interconnected, forming a comprehensive framework for understanding and improving project management in 3D concrete printing. It is important for the applied management methodologies to tackle the recognized barriers and limitations while integrating suggested improvements and innovations. In the evolving landscape of this field of study answering these inquiries will play a role in formulating project management strategies that can effectively harness the capabilities of 3D concrete printing technology within the domain of construction. By addressing these important research inquiries project leaders can create improved strategies for implementing and overseeing 3D concrete printing undertakings which in turn contributes to the acceptance and success of this groundbreaking construction technique.

CHAPTER 5 CONCLUSIONS

After examining project management in 3D printed structures in detail it is evident that this field is experiencing an evolution due to technological progress and the need for efficient and sustainable construction methods. The adoption of 3D printing in construction projects offers prospects along with unique challenges that call for creative project management strategies.

Key findings from this review include:

- ❖ The critical need for adapting traditional project management methodologies to suit the unique requirements of 3D concrete printing projects. Lean Construction methodologies and Agile frameworks are being customized to boost effectiveness and adaptability in projects.
- ❖ The increasing significance of digital technologies in project management, particularly the integration of Building Information Modeling (BIM) with 3D printing workflows. This integration simplifies the design-to-print procedure and improves overall project coordination.
- ❖ The rise of new challenges in ensuring quality and managing risks linked to 3D printed constructions requires the creation of tailored testing methods, on-site monitoring systems and strategies to reduce risks.
- ❖ There is a growing focus on sustainability in 3D concrete printing projects as project managers integrate life cycle assessments and sustainable material choices into their planning procedures.
- ❖ The development of supply chain management to cater to the material needs and logistics involved in 3D concrete printing projects.
- ❖ The creation of software applications and the use of cutting-edge technologies such as Digital Twins and AI to improve project management skills
- ❖ The significance of setting standards and adherence to regulations to ensure the widespread adoption and success of 3D concrete printing within the construction sector.

The results emphasize the aspects involved in managing projects related to 3D concrete printing emphasizing the importance of a comprehensive approach that combines technical expertise with traditional project coordination skills.

Looking ahead, several areas require further research and development:

- ❖ Refining project management frameworks designed specifically for 3D printing projects by integrating insights gained from pioneers in the field and real world examples.
- ❖ The establishment of quality control and assurance measures, for 3 printed constructions to guarantee reliability and consistency across various projects and areas.
- ❖ Exploring the long-term durability and effectiveness of 3D printed structures, informing project lifecycle management strategies.
- ❖ Exploring the potential of expanding 3D printing, for bigger construction projects and how it affects managing such projects.
- ❖ Integrating sustainability measures and circular economy concepts into project management methods for 3D printing.
- ❖ Further investigation is ongoing regarding the feasibility of utilizing 3D concrete printing in contrast to conventional building techniques, taking into account short-term project expenses and long-term advantages.

Summary of Key Findings from Case Studies

Case studies of 3D concrete printing projects highlight key factors for successful project management:

- ❖ The importance of early stakeholder engagement and collaborative workflows.

- ❖ The need for flexible project management approaches to accommodate evolving technology.
- ❖ The critical role of integrating traditional construction methods with 3D printing techniques.
- ❖ Exploring the significance of utilizing design methods in overseeing 3D printing projects.

Implications of Software Tool Analysis for Project Management Practices

The analysis of specialized software tools for 3D concrete printing suggests that project managers can benefit from:

- ❖ Improved planning and risk mitigation through advanced simulation and visualization capabilities.
- ❖ Improved quality assurance by monitoring and analysing printing operations in real-time.
- ❖ Enhanced efficiency by combining design elements with analysis and project management functions
- ❖ Increased precision and efficiency in translating designs into printable structures

Recommendations for Improving Collaborative Workflows

To enhance collaboration in 3D concrete printing projects, we recommend:

- ❖ Creating platforms that allow communication among all stakeholders involved.
- ❖ Providing cross-disciplinary training to connect the knowledge gap between construction methods and 3D printing techniques.
- ❖ Developing standardized protocols for data sharing and project documentation specific to 3D printing projects.

- ❖ Fostering a culture of innovation and ongoing education among project groups to tackle the changing demands of the 3D printing technology.

In summary managing projects related to 3D printing of structures is a dynamic and evolving domain that intersects construction practices with technology and sustainability efforts. As this technology advances and gains wide acceptance, project managers will have a responsibility in connecting cutting edge construction methods with real world application. The effectiveness of 3D printing in addressing worldwide construction hurdles like housing shortages, sustainability issues and construction productivity will mainly rely on the creation of robust and flexible project management approaches. The future for managing construction projects using 3D printing seems positive as it offers opportunities for enhancing efficiency and sustainability while reducing costs effectively in the run. This progress hinges on teamwork among researchers and professionals, in the construction industry alongside policymakers to tackle existing obstacles and leverage possibilities effectively. As the industry progresses ahead in its development journey it becomes increasingly crucial for project managers to keep themselves updated on the technological innovations, regulatory modifications and best practices. This will enable them to lead 3D concrete printing projects and play a significant role in transforming the landscape of the construction sector.

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APPENDIX A – DATA EXTRACTION FORM

This is a summary of key breakdowns used for my data extraction process.

- ❖ Title of Paper:
- ❖ Authors:
- ❖ Year of Publication:
- ❖ Journal/Conference:
- ❖ Research Objectives:
- ❖ Methodology:
- ❖ Key Findings Related to Project Management:
- ❖ Identified Challenges:
- ❖ Proposed Solutions/Recommendations:
- ❖ Project Performance Metrics (if available):
- ❖ Technologies/Tools Discussed:
- ❖ Relevance to Research Questions (High/Medium/Low):
- ❖ Additional Notes:

APPENDIX B – THEMATIC ANALYSIS CODING SCHEME

The following is the coding scheme that assisted in reviewing the literature systematically.

- ❖ Project Planning and Scheduling (PPS)
 - PPS1: Lean Construction principles
 - PPS2: Agile methodologies
 - PPS3: Just-in-Time (JIT) approach

❖ Resource Management and Supply Chain (RMSC)

- RMSC1: Material coordination
- RMSC2: On-site production facilities
- RMSC3: Blockchain for traceability

❖ Quality Control and Assurance (QCA)

- QCA1: New testing procedures
- QCA2: On-site monitoring systems
- QCA3: Non-destructive testing methods

❖ Risk Management (RM)

- RM1: Specialized risk assessment
- RM2: Contingency planning
- RM3: Equipment reliability

❖ Sustainability Integration (SI)

- SI1: Life cycle assessment
- SI2: Material efficiency
- SI3: Energy conservation

❖ Digital Technology Adoption (DTA)

- DTA1: BIM integration
- DTA2: AI and ML applications
- DTA3: Digital Twin technology

❖ Stakeholder Management and Collaboration (SMC)

- SMC1: Cloud-based platforms
- SMC2: Interdisciplinary integration
- SMC3: Team communication

❖ Regulatory and Standardization Impacts (RSI)

- RSI1: Lack of standardized regulations
- RSI2: Guideline development
- RSI3: Industry standardization efforts