Exploring Digital Collaboration across Knowledge Boundaries: A Case Study of the BIM-Enabled Construction Project

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

The University of Sheffield
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August 2023

Declaration

I hereby declare that this thesis is entirely my own work and effort. Parts of this thesis have been submitted for publication prior to this submission. I have obtained permission from the publisher's website and through the Copyright Clearance Centre to re-use content from the publication.

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August 2023

Acknowledgements

First, I wish to convey my heartfelt gratitude to my supervisors, Dr Pamela Abbott and Dr Efpraxia Zamani. Throughout my PhD journey, I have often felt truly fortunate to be under the guidance of such great mentors. Their meticulous approach to research has been a consistent source of inspiration. Beyond academic advice, they also uplifted me with patience, instilling in me the courage and motivation to persevere. Whenever I doubted myself, they always offered pertinent and sincere counsel. Without them, I would never have come this far.

From the depths of my heart, I thank my beloved parents for their unconditional support. Their trust, encouragement, and understanding during the challenging times, fortified me to confront any obstacle.

I extend my thanks to my dear friends who consistently offered their selfless help and bolstered me through many tough moments. A special thank goes to my partner, who has walked this journey together with me. As my most trusted confidant, he has supported me during many of my vulnerable times, bringing numerous positive influences into my life.

Lastly, I also wish to recognise the participants of my research. In spite of the impact of the pandemic, they engaged with my study wholeheartedly, making notable contributions. Their insights have been crucial in deepening my grasp of the subject.

I am so grateful for the challenges and difficulties I experienced during my PhD journey. They have changed my view of this world and also my life. Because of them, I believe I have become a better version of myself.

Abstract

Project collaboration, particularly in the field of Architecture, Engineering and Construction (AEC), involves a complex process primarily driven by bridging knowledge boundaries between various stakeholders from varying organisational and disciplinary backgrounds. Through digitalisation in the AEC industry, digital technologies, such as Building Information Modelling (BIM), are being implemented to varying degrees within organisations and used by individuals for facilitating construction project management. Recent research taking a practice-based approach to study digital technology-enabled collaboration provides insights into how digital collaboration may occur in cross-boundary collaborations. Most existing studies, however, have mainly focused on the role of digital technology in mediating individual collaborative practice which lacks a holistic understanding of the contextual conditions shaping the roles of digital technology during the entire collaboration process. Such a perspective could consider the interplay between organisational, cultural, and other contextual dimensions and digital technology-enabled knowledge practice in collaboration.

By building on the practice-based approach and incorporating the contextual dimensions mentioned above, this research aims to explore how collaboration occurs across knowledge boundaries in BIM-enabled construction projects from different levels. As part of this objective, the study examines three sub-questions: 1) How are collaborative activities across knowledge boundaries organised in the construction project? 2) How is BIM technology implemented and used to enable these collaborative activities? 3) How does the arrangement of collaborative activities shape BIM implementation and use over time?

To achieve this aim, this research adopts a qualitative, interpretative, embedded case study as the methodology. The embedded case is the BIM technology-enabled collaborative construction project comprising four types of major stakeholders: the owner organisation, design organisation, construction organisation, and sub-contractor organisation. Data was collected through multiple resources, with semi-structured interviews being the primary data source supported by data from field observations and document analyses. Using reflexive thematic analysis, data were analysed at three levels: the individuals' daily use of BIM technology for cross-boundary collaboration; the organisation’s strategic implementation of BIM technology; and the situated practice and experience at the construction project level.

The multi-level analysis reveals three dimensions of the phenomenon of BIM-enabled cross-boundary collaboration namely, the configuration of collaborative activities, the role of BIM technology, and the contextual conditions of BIM collaboration. It was found that collaborative activities are co-configured by individuals' motivation and work relations, the organisation's digital innovation strategy, and project-based collaboration. BIM technology was found to play a multifaceted role evolving from enabling individual practice, to influencing the organisations' digital transformation processes, and perceived changes to project goals. Further, within the dimension of contextual conditions of BIM collaboration, we observed temporal changes based on patterns of BIM use centred on digital artefacts, strategic adoption of digital innovation-driven BIM, and stage-based project management, which may influence the boundaries of BIM collaboration at different levels.

This research builds a practice-based and contextual-related understanding of the BIM-enabled construction project. It enhances the theoretical understanding of digital collaboration across boundaries at individual and collective levels by conceptualising these as dynamic relationships between different activity systems and identifying boundary work mechanisms at different levels. The adopted embedded case study and multi-level data analysis also introduce an innovative qualitative research design based on activity theory that enhances dominant extant single-level analyses in the literature. In addition, the study unpacks the black-box of BIM technology by detailing its roles in the individual's practice, organisational digital innovation strategies, and project lifecycle-based collaborations, and the evolutionary nature and mediating effect of the roles. Finally, the study contributes to the understanding of the temporal and permeable conditions of the context for BIM collaboration. It provides practitioners with a comprehensive understanding of how organisational digital innovation strategies and project management objectives combine with BIM-enabled practice to shape BIM-enabled project collaborations.

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- Wang, J., Abbott, P. Y., & Zamani, E. D. (2021). BIM as a Boundary Object in Construction Projects: A Knowledge-as-Practice Perspective. In D. Dennehy, A. Griva, N. Pouloudi, Y. K. Dwivedi, I. Pappas, & M. Mäntymäki (Eds.), *Responsible AI and Analytics for an Ethical and Inclusive Digitized Society* (pp. 371–382). Springer International Publishing.
- Wang, J., Abbott, P. Y., & Zamani, E. D. (2022). Exploring boundary theory and activity theory as theoretical basis within the Project-based Digital Collaboration: a synthesized conceptual framework. The 21st IFIP Conference e-Business, e-Services, and e-Society I3E2022, Research in progress

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List of Abbreviations

AEC Architecture, Engineering, and Construction

AT Activity theory

BIM Building Information Modelling

BO Boundary object

CMT Construction Management at Risk

CAD Computer-aid-design

DBB Design-Bid-Building

DB Design-Building

IPD Integrated Project Delivery

IS Information system

IT Information technology

MEP Mechanical, electronical, pluming

1 Introduction Chapter

1.1 Research background

As global digitalisation trends increasingly influence various contemporary industries, they alter traditional patterns of industrial production and organisational business management. In this ever-evolving business environment, numerous enterprises and organisations are transitioning their operations and management to digital formats, aiming to sustain their capacity for organisational innovation and maintain a competitive edge in inter-organisational collaboration (Kotlarsky & Oshri, 2005). In such a digitalised milieu, effective inter-organisational collaboration becomes even more crucial as it signifies a collaborative approach to achieving shared objectives (Patel et al., 2012). This is particularly evident in project-based collaborations spanning multiple disciplines and organisations, such as the Architecture, Engineering, and Construction (AEC) industry (Mignone et al., 2016). Such project-based collaborations involve professionals with different expertise from various organisations, working together for shared objectives within a project network (Boh et al., 2007; Hilbolling et al., 2022; Schilling, 2015).

Collaboration inherently necessitates individuals to communicate, coordinate, and share knowledge (Neff et al., 2010; Patel et al., 2012), especially for project-based collaboration. Interaction among diverse knowledge practices is seen as a catalyst for achieving superior collaboration outcomes (Hendriks, 1999). At the current intersection between the fields of information systems (IS) and organisational study, numerous academics are interested in studying the essence of effective and efficient collaboration, focusing on its ability to enhance performance by sharing expertise across sections and companies, thereby improving decision-making through the mutual exchange of knowledge and ideas (Patel et al., 2012). However, with the evolution and adoption of digital technology in collaboration, emerging challenges and conflicts have arisen between these varied knowledge practices. With the ongoing digitalisation process within organisations, digital technology plays a pivotal role in collaborative activities, continuously transforming collaboration patterns both within and between organisations (Bailey et al., 2022). As these patterns of collaboration evolve and remain dynamic due to interactions among organisations at different stages of digitalisation, uncertainties and potential challenges arise in the collaboration process. When individuals from different professional backgrounds, possessing varied knowledge, collaborate (Berente et al., 2010), digital technology-supported work practices and communication can be affected by the differing degrees of digitalisation they each bring.

With the advance of digital technology in the AEC industry, the introduction of Building Information Modelling (BIM) technology is viewed as a significant step for digitalisation in traditional AEC organisations. An increasing number of scholars have an interest in the essence of transformation to construction projects and AEC organisations/industries brought by BIM technology. Volk et al. (2014) delineate BIM from both narrow and broad perspectives. In the narrow sense, BIM is the digital model of a building crafted through architectural or engineering software tools specific to a construction project (Volk et al., 2014). It is not only about BIM technology offering digital representations that integrate both the physical and functional properties and characteristics of buildings but also functions as an information management repository. BIM models can house one or several virtual building models with the geometric data of buildings (Eastman et al., 2011), and serve as a platform for information sharing and facilitating decision-making throughout the project lifecycle (L. Ding et al., 2014). In a broader sense, BIM is seen as a digital collaborative process addressing the informational, functional, technical, and organisational aspects (Volk et al., 2014). BIM technology-engaged collaborative process also encompasses an interplay of policies, processes, and technologies (Bryde et al., 2013). The British National Building Specification (NBS) (2019) defines BIM as a process for creating and managing information within a construction project, where the resultant digital building information model aids participants in their interactions as it transforms the collaborative practices of construction project teams, along with the delivery approaches employed in construction (Hardin & McCool, 2015). Viewed as a significant transformation in the digitalisation of the AEC industry, in recent years BIM technology is increasingly seen as the primary digital technology for construction project collaboration (Monson et al., 2015; Saka & Chan, 2019). In short, BIM technology is widely recognised as a transformative collaborative process, leveraging a suite of 3D-integrated modelling tools to enhance construction project outcomes and the collaboration process.

1.2 Problem statement

The effective and efficient implementation and use of digital technologies in practice are always important but difficult in terms of facilitating collaboration among groups with different knowledge backgrounds. This is especially true for certain traditional industries, including the

AEC industry, and such difficulties are related to the tremendous change from a conventional paperwork-based collaborative process toward transformative digital technology-enabled collaborative patterns. Focusing on the intersection of the field of IS research and organisation studies, this research is interested in changes in collaboration brought about by the use of new digital technology (e.g., BIM) as this is an area that still requires more exploration. This is particularly relevant as, in recent years, some digital technologies have disrupted conventional activities and management in the AEC industry from a practical view (Marocco & Garofolo, 2021), and it is this that leads the researcher to reconsider the role of digital technology and its transformative influence in collaboration. As hinted at above regarding the implementation and use of digital technology within and across organisational collaboration, there is insufficient extant research looking at how the organisational digitalising process accompanies and influences collaborative activities. Some proximate studies explore this phenomenon from different perspectives, such as the strategic perspective (Chen et al., 2021; Lindblad, 2019; Ma et al., 2020) or the project network perspective (Cao, Li, Wang, Luo, et al., 2017; Mignone et al., 2016; Oraee et al., 2021). Moreover, there is a lack of research offering a more comprehensive view to observe the interplay between the collaborative process and its digitalising context, especially for AEC organisations involved in project outcomes, during the collaborative process, how people from different backgrounds understand the role of BIM technology. This understanding has become particularly important in the context of the ongoing transformation of the construction project industry by BIM technology.

Despite the emergence of BIM technology being seen as causing a revolution in the AEC industry, with a lot of the research in the construction management field exploring the practical aspect (Azhar, 2011), a lot of challenges remain for BIM-enabled collaboration regarding the implementation and use of BIM technology in construction projects. For example, as mentioned previously, the reduction of integration flexibility of BIM hinders people from communicating across different disciplines (Neff et al., 2010). There is also little clarity on how to promote the collaboration process by introducing BIM technology, particularly entangling with varying digitalising processes within AEC organisations. Researchers are therefore calling for more socio-technical systems perspectives to observe the implementation and use of BIM technology (Olofsson Hallén et al., 2023; Saka & Chan, 2019).

For construction projects which aim to apply BIM technology to the project lifecycle, the configuration of the team always involves multiple disciplines and organisational stakeholders, which increases the challenge of collaboration among these different experiences, backgrounds and values. Collaboration as the interaction approach for construction team members is the main way to share knowledge (Nissen et al., 2014). However, the innovation of collaborative practice in construction projects has developed slowly due to the complexity and fragmentation of the AEC industry (Oesterreich & Teuteberg, 2019). Construction projects, like all types of transient projects, are ad hoc and the ephemeral nature of project transactions inevitably complicates collaborative relations between project actors (Dietrich et al., 2010). Multiple phases of the project lifecycle and temporary relationships between team members also increase the difficulty and challenge of knowledge sharing in collaboration (Dave & Koskela, 2009). As collaboration in a construction project involves multiple parties, such as the owner, contractors, designers, and suppliers, who are from different organisations and disciplines, the diverse professional backgrounds cause challenges and conflicts in understanding others' work and values among the construction team members (Berente et al., 2010). The different disciplines thus present 'knowledge boundaries' when employees share knowledge with each other (Carlile, 2004). Therefore, for BIM collaboration across different knowledge boundaries, the question arises regarding how to organise collaboration across knowledge boundaries; this has also gained increasing attention recently in the construction project management research field (Doolin & McLeod, 2012; Hsu et al., 2014).

1.3 Research motivation

Current IS research is highlighting the need to understand the organisational phenomenon from the technology perspective. This involves considering the emerging phenomenon from a technology perspective, rather than taking it for granted (Barrett & Orlikowski, 2021). This motivates researchers to deliberate the practical relations between AEC professionals and BIM technologies in the situated context, especially for those emerging activities that shift beliefs/values regarding digital technology transformational change in traditional practices and collaborative form. For the AEC industry, on the one hand, BIM technology is regarded as related to innovative collaborative processes among professionals from different backgrounds, requiring the researcher to adopt boundary theory to observe the role of BIM technology across knowledge boundaries in the context of construction projects from a practical view. On the other hand, the numerous problematic situations in BIM-enabled cross-boundary collaboration imply the challenges of the collaboration process relating to the interaction(s) between the AEC digitalising organisations.

While many extant studies are focusing on BIM technology-enabled collaboration, the majority are more concerned with BIM technological performance in construction projects (Boland et al., 2007) or the challenges of integrating BIM technology in collaboration (Zomer et al., 2021). Few studies consider the dynamics of BIM technology implementation and usage among different individual practices and organisations and how this is reflected in project-based collaboration. These dynamics and complexities are closely related to the effectiveness of BIM-enabled collaboration (Akintola et al., 2020) and are assumed to relate to both the individual perceptions and collective perceptions of BIM collaboration (Chen et al., 2022), which motivates the researcher to explore how different AEC organisational changes shape and are themselves shaped by the BIM-enabled collaborative activities from a systemic perspective. Therefore, the two streams of theoretical perspectives adopted to synthesise the theoretical lens in this study are boundary theory and activity theory as the study's theoretical foundation.

1.4 Research questions and objectives

Given the research gaps and research motivation identified above, this research explored BIM collaboration across diverse knowledge boundaries within construction projects. This study will take the exploratory qualitative approach to explore the BIM collaboration-enabled construction project across knowledge boundaries. As a result, the primary research question of this thesis is as follows:

- **How does digital collaboration occur across knowledge boundaries in BIM-enabled construction projects?**

In line with this central query, the exploration of BIM collaboration has been formulated to delve deeper into three sub-questions, which also informs the research design:

- How are BIM-enabled collaborative activities across knowledge boundaries organised in construction projects?
- How is BIM technology implemented and used to enable these collaborative activities?
- How does the arrangement of collaborative activities shape BIM implementation and use over time?

The objective of this investigation is to establish a comprehensive understanding of BIM collaboration across knowledge boundaries, considering the perspectives of professionals from diverse organisations in the construction sector. Therefore, the following research objectives define the specific goals pursued throughout the research process:

1) To explore how knowledge boundaries manifest in the collaboration process within construction projects.
2) To investigate the methods by which BIM technology is implemented and utilised for collaboration across various AEC organisations.
3) To comprehend the interplay between BIM-enabled collaborative activities and professional knowledge boundaries.
4) To evaluate the role of BIM technology in shaping knowledge practices in construction projects.
5) To understand how the dynamics of BIM-enabled collaborative activities shape/are shaped by different knowledge boundaries.

The first objective was achieved through both a literature review and an empirical case study. The theoretical framework established insights into how to identify knowledge boundaries from a knowledge-as-practice perspective. By investigating different professionals' work practices, knowledge boundaries have been manifested in various boundary work to deal with diverse sense-making, values, and beliefs in collaborative activities. With BIM technology involving their knowledge practice, different organisational actions on BIM implementation are reflected in inter-organisational collaborative activities.

The second objective was achieved primarily via data collection and data analysis regarding how professionals interact with BIM technology in their work practices and collaborations. Specifically, it was accomplished by collecting and analysing reflections from professionals about their daily work practices with BIM technology, and comparing their organisational digital innovation strategies regarding BIM implementation and usage.

The third objective was completed by analysing the interconnection between BIM-enabled collaborative activities and their manifested knowledge boundaries among professional interactions. Relevant data was collected and analysed through the first two objectives.

The fourth objective was met by classifying the different roles of BIM technology reflected in professional practice and perceptions, before subsequently analysing the rationale behind these varied roles and their interactions and implications.

The fifth objective was achieved by analysing the context in which BIM-enabled collaboration occurs. The features of this context and these collaborative activities were identified and their relationships analysed.

1.5 Significance of the study

The outcomes of this research aim to elucidate the BIM collaboration process among professionals from diverse disciplines and organisations involved in construction projects. The findings are multifaceted, promising contributions to both academic research and practical application. By delving into the varied knowledge practices of professionals from different AEC backgrounds, this study seeks to provide a comprehensive understanding of knowledge boundaries in construction project-based collaboration, an area that has been underexplored in the extant literature.

This enhanced comprehension of the dynamics in digital technology-enabled collaborative activities provides insights into how BIM technology-enabled collaborations can influence individual and collective values, interests, and sense-making. This is particularly evident in the interplay of different BIM technology implementations and uses, especially in the context of inter-organisational collaborative relationships. Additionally, by examining the role of BIM technology in collaborative endeavours within construction projects, this study offers deeper insights into how digital collaboration impacts the management of diverse knowledge boundaries. It is anticipated that this research will pave the way for further developments in the theoretical frameworks of relevant fields and lay the foundation for future studies, especially those at the intersection of technology, collaboration, and construction management.

Further, this study has the potential to bolster understanding of making informed industrial policy decisions. The implementation and application of BIM technology in construction projects has and continues to prompt various organisational stakeholders to strategically navigate BIM-related business and management transformations. The effective management of BIM-centric innovations and partnerships, especially for inter-organisational collaboration in construction project management, necessitates governmental or institutional guidance and a standardised procedure. By investigating BIM collaboration from multiple perspectives, representing different knowledge groups, the insights gleaned about the dynamics and challenges of evolving practices among organisations will be invaluable for enabling relevant policymakers to grasp the full scope of BIM collaboration.

The empirical work based on the case study contributes to the existing body of knowledge in several areas, including the fields of IS, organisational studies, and construction project management. This theoretical advancement broadens the potential for guiding knowledge development and cross-fertilisation in interdisciplinary research fields between the IS domain and other digitising industries. In the realm of IS research, the study underscores the multifaceted role of BIM technology, revealing that actors possess varied and evolving perceptions of BIM in their individual work practices. This enriches our understanding of the concept of ‘boundary object-in-use’ (Levina & Vaast, 2005). Furthermore, the trajectory of actors’ perceptions regarding BIM technology broadens our comprehension of the process in which actors engage with digital technologies for collaborative endeavours. Emphasis is placed on actors’ unique objectives, experiences, and sense-making processes as they adapt BIM technologies for collaborative tasks. Another pivotal revelation is the mediating effect(s) of BIM technology in various activities, such as BIM model presentation in coordination meetings between clients and contractors, detailing how BIM influences the outcomes of these activities and the subsequent ramifications of doing so.

Moving on to organisational studies, this research is illuminative in deciphering the intricate relationship between boundaries and different types of activities. It sheds light on the multifaceted dynamics of cross-boundary collaboration driven by myriad factors. Findings regarding the BIM collaboration context are particularly enlightening, as they unveil the subtle influences embedded within the structural and cultural constructs of digital technology-enabled collaboration. One such nuanced insight suggests that BIM experts harbour the belief that decision-makers should have a ‘sufficient’ knowledge base. This stems from the perception that armed with such knowledge, decision-makers would exhibit a higher degree of autonomy, potentially reducing their reliance on BIM experts in specific scenarios.

In the expansive domain of construction project management, this research provides an insight in identifying pivotal drivers and determinants influencing the role of BIM technology.

Particularly, it zeroes in on the facets related to the adoption of digital technology in the construction milieu. As such, this research accentuates the profound significance that professionals attach to BIM technology in their daily practices, which invariably moulds their collaborative dynamics. Delving deeper, this study explores the symbiotic interplay between professionals and BIM technology. By considering the influence of organisational digital innovation strategies and project management paradigms on this dynamic, the research fills an existing void. Adopting a systemic vantage point, it offers insights into BIM technology's implementation and collaborative utility from both user and organisational perspectives (Olofsson Hallén et al., 2023).

1.6 Thesis Structure

This thesis is organised into six chapters, followed by the bibliography and appendices:

Chapter 1: Introduction

This chapter (of which this section is a part of) presents the research background and identifies the research gap based on a review and critical analysis of extant literature sources. Based on the problem statement and current research status to relevant fields, this chapter sets out the aims of the study and the research questions and research objectives. Furthermore, the expected contributions of this research are presented to show the significance of this multidisciplinary study.

Chapter 2: Literature Review

This chapter conceptualises the central concepts of the research and develops a theoretical framework based on prior studies. The first section reviews the extant literature concerning collaboration, and the key concept of digital collaboration to pinpoint the primary research focus. The second section presents knowledge and boundary in collaboration and the existing theoretical perspectives on studying the management of knowledge boundaries in collaboration. The third section presents the construction project within the AEC industry, providing context for the research and highlighting the primary features of digital collaboration in construction projects and the AEC sector, and elaborating on the activity systemic view of the digitalising AEC organisations. The fourth section provides an overview of BIM technology, including its adoption in the Chinese AEC industry. The last section establishes an integrated theoretical framework based on boundary theory and activity theory, presenting and justifying the main theoretical lens employed in this research.

Chapter 3: Theoretical Foundations

This chapter discusses the theoretical foundations of this study by elaborating on the boundary theory and activity theory. The first two sections discuss each theory's theoretical origins, focus and implications for digital collaboration. Further, it reconciles how this study applies plural theoretical perspectives from boundary theory and activity theory to investigate digital collaboration, and the ontological and epistemological assumptions of the practice view of boundary theory and the system view of activity theory.

Chapter 4: Methodology

This chapter delineates constructivism and interpretivism as the philosophical stands and qualitative strategy adopted in this study. Further, it details the adoption of the embedded single case study approach, presenting the rationale behind the research design. Besides, it also presents the research design and implementation in the context of the Chinese AEC industry. Ethical considerations pertaining to the research are also addressed, along with the consideration of the influence of the pandemic on this study. Last, the chapter demonstrates the consideration of research design quality and the role of the researcher in this study.

Chapter 5: Findings

The findings are presented in this chapter, based on a multi-level analysis at the individual, organisational, and project levels. Each level offers a comprehensive perspective of BIM-enabled cross-boundary collaboration, elaborating on the configurations of collaborative activities, the role of BIM technology in collaboration, and the contextual conditions influencing BIM-enabled collaboration.

Chapter 6: Discussion

This chapter interprets the findings in light of theoretical underpinnings and contrasts the research outcomes with existing studies. It posits that collaborative activity configurations are rooted in various systemic structures. It also underscores the multifaceted nature of BIM technology and its transformative effects on collaboration. Furthermore, the temporal and permeable nature of the contextual conditions impacting BIM-enabled collaboration is highlighted.

Chapter 7: Conclusion

This final chapter offers a summary of the research, reflecting on the research questions and objectives. It elaborates on the empirical, theoretical, and methodological contributions of the study. Based on the results, practical implications and recommendations are provided for relevant stakeholders. The chapter also addresses the study's limitations and suggests directions for future research. A concluding summary wraps up the chapter.

2 Literature Review

2.1 Introduction

This chapter aims to elaborate on theoretical perspectives and provide a comprehensive academic context for this research by evaluating and analysing current theoretical debates and research work relevant to this study. It organises the main research fields related to the study's phenomenon and research questions. The chapter progresses from a broad overview of the research phenomenon towards the focal research interests, presenting research work and theoretical perspectives on relevant research fields such as digital collaboration, construction project management, knowledge boundaries, and Building Information Modelling (BIM). Thereafter, it narrows the focus to core research problems and gaps by identifying main theoretical debates in this research. It clarifies the theoretical understanding of the research questions and conceptualises the research focus.

Collaboration, the main research phenomenon in this study, is ubiquitous and permeates various fields. The advent of digital technology has disrupted traditional forms of collaboration, especially when different stakeholders engage in digital technology-enabled collaboration. When the proliferation of new digital technologies across industry, it triggers organisational transformation, fostering the role of digital technology in inter-organisational collaboration, especially for project-based collaboration. However, it also presents new challenges and barriers due to the interplay between collaboration and digitalisation processes across organisations (Riemer & Schellhammer, 2019). As a result, the use of digital technology in collaboration has attracted the attention of many researchers (Davidekova & Hvorecky, 2017; Marion et al., 2016; Salganik, 2019).

In a project-based industry, collaboration is highly complex as it involves multiple stakeholders from different disciplines and temporary relationships within project teams. Currently, in the Architecture, Engineering, and Construction (AEC) industry, the implementation and use of BIM technology has triggered emerging digital transformation in the industry and altered work practices of construction projects. The degree of digitalisation in relevant construction organisations leads to varying levels of engagement in digital collaboration within a construction project.

The definition of BIM is also complex and multidimensional; it is related to the evolving technology-based collaboration process throughout the lifecycle of a construction project. Figure 2.1 shows the problematised research issues related to this study, including cross-boundary knowledge practice, digitalising context, and project-based collaboration. These issues are interrelated in this study and determine the theoretical foci to be explored through the literature review.

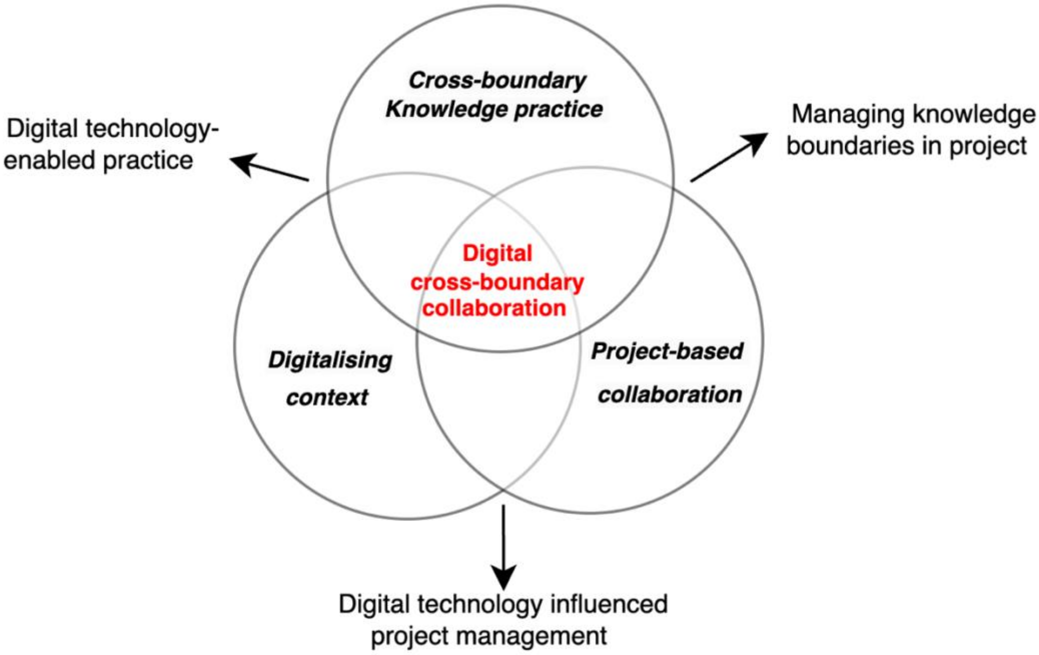

Figure 2.1: the scope of the phenomenon in this study

This chapter is organised into six main sections, progressing from broad concepts about collaboration to the focused research topic of BIM-enabled cross-boundary collaboration in construction projects. Section 2.2 reviews the literature related to collaboration, the primary phenomenon of this study, and identifies the main factors influencing collaboration from existing research. The aim is to define the scope of collaboration and understand the factors that shape its process. Section 2.3 introduces the theoretical concept of knowledge boundaries as a focal issue in collaboration. It reviews relevant literature on the nature of knowledge sharing and the relationship between knowledge sharing and boundaries in collaboration. Section 2.4 introduces the emerging research interests in digital technology-enabled collaboration in recent years, focusing on the theoretical understanding of the role of digital technology in collaboration and the evolution of views about studying the digital collaboration process. Section 2.5 introduces construction projects in the AEC industry as the context of this study. It explores the relationship between emerging digital collaboration and the relevant organisational stakeholders in the AEC industry. Section 2.6 focuses on the implementation of BIM technology in the AEC industry and construction project management, discussing its role in facilitating collaboration across different stakeholders.

2.2 The concept of collaboration

2.2.1 Definition and perspectives of collaboration

The definition of collaboration is elusive due to the lack of consensus among researchers in different research fields. Many studies explore or investigate the nature of collaboration in different domains, such as organisational studies (Bucher et al., 2016); communication studies (Fu et al., 2019); public administration studies(Morris & Miller-Stevens, 2015; Rhymer, 2023); business and management studies (Riemer & Schellhammer, 2019). Understanding and distilling the main features of collaboration from different research studies help to provide a working definition of collaboration that can be applied in this research. The early organisational theorist, Gray (1985, p. 912) has proposed a useful basis for an academic definition of collaboration, emphasising the aim and format of collaboration among people, defining collaboration with three characteristics: 'a. the pooling of appreciations and/or tangible resources, b. by two or more stakeholders, c. to solve a set of problems which neither can solve individually'. This suggests that the essence of collaboration is the interactions among various parties. Based on Gray's definition, Kramer (1990, p. 546) proposed that collaboration is a process and summarises three phases of any collaboration: 1) identifying the problems and legitimate parties and getting them together; 2) establishing the ground rules and negotiating agendas, negotiating for agreements; and 3) 'dealing with constituencies, building support for the agreement, and ensuring compliance'. It requires people involved in this process to rely heavily on negotiation to create a shared understanding of the same objective. Therefore, during the collaborative process, new ideas may be created by a group of people together and they are generally constructed through a multidimensional process, such as coordination and communication (Kotlarsky & Oshri, 2005).

With the increasing attention on the broader contextual influence, collaboration has been regarded as inter-organisational issues or multiparty-related social performance. Wood and Gray re-clarify, 'collaboration occurs when a group of autonomous stakeholders of a problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain'. It emphasises that these interrelated stakeholders from respective organisations need to use a set of shared frames to increase the efficiency of collaboration. This has been especially emphasised by researchers who study project-based work; developing a partnering relationship has been regarded as an important strategy for collaboration across organisations to achieve common targets (Ungureanu et al., 2020; Zhao et al., 2010).

Current discussion on collaboration mainly focuses on three perspectives. Strategy-oriented perspectives are led by discussion about collaborative strategies and relationships to establish well-developed preconditions for collaboration. This stream of discussion is mainly based on the work of Hardy and Phillips (1998). They discuss four strategies: collaboration, compliance, contention, and contestation. From a strategic perspective, collaboration, cooperation, and coordination are regarded as different approaches to govern relationships and management (Gulati et al., 2012; McNamara, 2012). Thomson and Perry (2006) propose five dimensions for managing collaboration actions, including governance, administration, autonomy, mutuality, and reciprocity:

- Governance: Jointly make rules to govern the collaborative behaviour and build a structure for determining consensus on collaborative activities and consequences。
- Administration: manage collaborative relationships in coordination through assigning different administrative roles for the functioning of interpersonal relationships or inter-organisational partnerships.
- Autonomy: encourage distinguishing individuals' interests and control from collective action
- Mutuality: forge mutual benefits among the parties to the collaboration to create commonalities from differences
- Reciprocity: build a common belief or culture among individuals' or groups' trust and obligation on reciprocity in the long-term view of collaboration

Another strand of literature adopts a process-oriented perspective on collaboration, where researchers delve into collaborative practices and behaviours. Ring and Van De Ven (1994) formulated an iterative and cyclical framework for the collaboration process, illustrating the dynamics among collaborators. They depicted collaborators as intentionally "doing" collaboration by negotiating congruent expectations, forging mutual commitments for collective actions, and subsequently executing these commitments. Both efficiency and equity serve as guiding principles to assess the execution phase, after which renegotiations or adjustments to commitments may occur (see Figure 2.2). Literature that views collaboration from a process perspective argues that collaborative working is intricately tied to a series of episodes of interactive processes such as learning, coordination, communication, and decision-making (Lavikka et al., 2018). Based on these definitions and explanations by numerous researchers, it is evident that collaboration is not only associated with interactions among individuals but is also influenced by the organisations from which the stakeholders originate. This is especially pertinent to project-based collaboration, as the aim of such collaboration is to achieve a shared goal by exchanging resources and information among team members from each organisation. Therefore, the working definition of collaboration in this research is as follows: collaboration is a process in which more than two individuals with different assets work together, making decisions interactively to form a shared understanding in order to achieve common final goals.

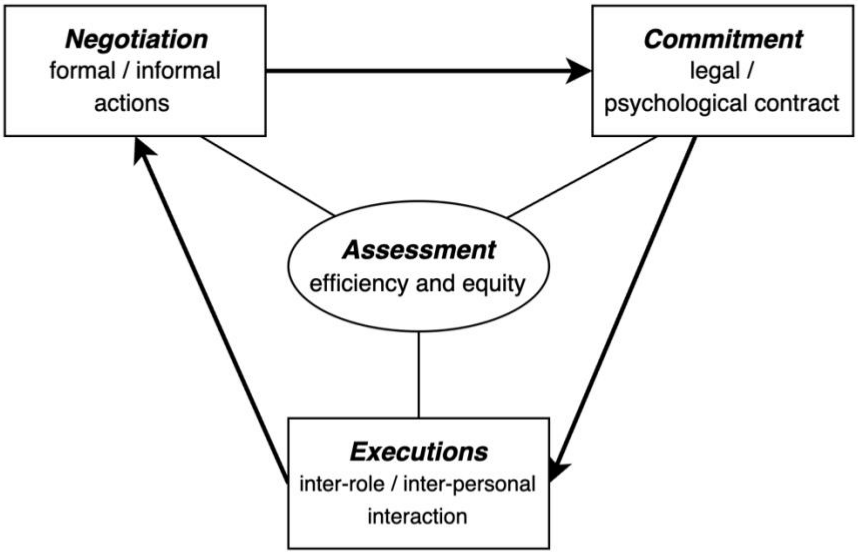

Figure 2.2: A framework of collaboration process (source: Ring & Van De Ven, 1994)

Another stream of research approaches collaboration from a network perspective. These scholars have identified the structural nature of collaborative settings, highlighting that collaborative activities occur at various levels and mutually influence each other (Bardach, 2001; Imperial, 2005). The underlying assumption of this perspective is that the performance of collaborative activities is interconnected with the nature and characteristics of the level at which it occurs, as well as the interrelationships among the different levels.

The various perspectives discussed form the foundational theoretical understanding of collaboration for this study. Recent research has reached a consensus to some extent that collaboration is 'a highly flexible, adaptable, and fluid form of interaction' (Morris & Miller-Stevens, 2015, p. 8). Organisational strategic planning for collaboration will directly influence the interactions among individuals and the consequences of collaborations. Taken as a whole, these observations lead to the conclusion that collaboration is influenced by multiple mechanisms and will evolve in the interaction process among individuals, groups or organisations.

2.2.2 Key factors affecting collaboration

Collaboration is a complex interaction process that is shaped by many factors. Patel et al. (2012) broadly identifies seven comprehensive categories of factors related to collaborative performance: context, individual, tasks, interaction processes, support, teams, and overarching factors. Oraee et al. (2017) further analyse the barriers to effective collaboration and identify five aspects: process, actor, context, team, and task. Riemer and Schellhammer (2019) emphasise that currently, collaboration is under the influence of individual, team, organisation, environment, business, and market factors. It is evident that individual participants in the interaction process integrate their ideas with others', which is the basis of collaboration (Majchrzak et al., 2005), and is also regarded as an important factor of collaboration by many researchers, as mentioned above. In addition, for team-level collaboration, which is the main focus of this research, researchers find that team effectiveness significantly influences employees' collaborative performance (Peters & Manz, 2007). The role of organisations is increasingly regarded as a factor influencing the behaviour of team members (Siakas & Siakas, 2008). The collaboration environment, as the context in which interaction occurs, determines the types of individuals and teams involved in collaborative work, as well as the types of tasks that need to be carried out, which have an impact on the process of collaboration itself (Patel et al., 2012). These considerations of factors identified by different researchers as influencing the collaboration process form an understanding of team collaboration, which synthesises five main factors that shape team collaboration: individual factors, team factors, organisational factors, environmental factors, and technological factors (Table 2.1).

2.2.2.1 Individual factors

Individuals, who are the 'actors' involved in collaborative practice, form the foundation for the collaboration process by actively providing their necessary skills for collaborative work. In other words, an individual's performance can affect social and interactive activities, such as teamwork performance (Oraee et al., 2019). An individual's performance is defined by their professional competence in their specific roles, i.e., expertise performance (Papadonikolaki et al., 2019). Apart from their professional expertise, an individual's collaborative expertise is also emphasised in collective work, as it influences communication (Craig et al., 2020).

Various individual factors have been identified as influential, including attitude (Ahmad et al., 2010), motivation (Clifton et al., 2019), and level of professional skill and knowledge (Gal & Berente, 2008; Johnson & Hyde, 2003). Individual perception, which focuses on the social representation of constituting the world, influences collaborative behaviour (Ahmad et al., 2010).

The objective of people working together is to harness their personal skills and knowledge to engage in collaborative work and accomplish tasks in collaborative activities (Johnson & Hyde, 2003). Furthermore, the reciprocity of knowledge can motivate individuals to collaborate with each other to share knowledge (Ipe, 2003).

2.2.2.2 Team factors

Three aspects of team factors contribute to collaboration performance: team configuration, team relationships, and knowledge sharing in teams (Oraee et al., 2021). Team configuration is considered a primary factor in collaborative group work (Riemer & Schellhammer, 2019). The first aspect, team configuration (roles and responsibilities), requires team members to determine and understand the roles and responsibilities of participants from different organisations for better information sharing. The second aspect, relationships in work practice, refers to the relationships between participants and the actual work carried out (A. Robson et al., 2016). Effective team communication is believed to provide a foundation for team members to establish a shared goal in their teamwork (Bjørn & Ngwenyama, 2009). The third aspect is ensuring knowledge sharing. Structured work teams and purposeful learning channels facilitate knowledge sharing (Ipe, 2003). However, collaboration among teams is thought to be influenced by organisations (Patel et al. 2012).

2.2.2.3 Organisational factors

Organisations shape individuals' experiences and influence their interpretation of and behaviour in situations (Bjørn & Ngwenyama, 2009), specifically, collaborative behaviour in the organisational environment can be affected by organisational culture, structure, and strategies. Organisational culture comprises the attitudes, beliefs, and values shared among employees, which can impact their attitudes towards collaboration (Bresnen & Marshall, 2002; Hardin & McCool, 2015; Patel et al., 2012). For example, a corporate vision of organisational culture influences employees' behaviour and values regarding knowledge sharing (Ipe, 2003). Apart from cultural factors, organisational structure can impact collaboration within and between firms, determining partners' relationships and interaction rules (Thomson & Perry, 2006). Diverse organisational structures can affect task delivery and power dynamics among employees (Patel et al., 2012).

Organisational strategy dictates how to achieve organisational goals; it determines not only how a firm engages in collaborative activities but also what kind of support it provides to employees for collaborative processes, such as technical assistance (Morris & Miller-Stevens, 2015). A high degree of harnessing distinctive resources is regarded as enhancing high-level collaboration (Hardy et al., 2003). Firms that strategically manage and operate current trainings and resources required by markets or industries will help employees improve their acquisition of new skills, consequently enhancing productivity during collaborative work. It is important to consider allowing key resources identified by collaborating partners to enhance their core competencies and distinctive advantages (Hardy et al., 2003; Patel et al., 2012).

2.2.2.4 Environmental factors

The environment is an important factor for collaboration. Environmental factors refer to the context in which collaboration is carried out, consisting of the setting and social context (Mattessich & Monsey, 1992). The setting focuses more on the location or surroundings of collaborative work. Actors involved in collaboration across physical distances often rely more on asynchronous communication, leading to more formal coordination (Patel et al., 2012).

Meanwhile, the social context emphasises the conditions for information sharing through communication and cohesion among employees (Harvey & Koubek, 2000). For example, in team collaboration, the social context is more important for building relationships amongst members (Clifton et al., 2019). Co-working spaces are regarded as a strategy to build a more collective social context that facilitates collaborative work (Patel et al., 2012). These spaces link people, ideas, and physical space, and are seen as social infrastructure (Merkel, 2015). A co-working space is not only a physical space but also a collaborative community, providing a shared context for team members' collaborative practice (Waters-Lynch & Potts, 2017). It offers an opportunity for people in the same social surroundings to build relationships and improve their communication (Merschbrock & Munkvold, 2015). They can be more creative through active information flow and sharing of common core objectives and values between members(Clifton et al., 2019). Through collaborative activities, the perception and interpretation of group tasks can be shared in individual interactions, which is vital for increasing the understanding of common goals (Johnson & Hyde, 2003).

2.2.2.5 Technological factors

With the development of digitalisation, digital technology is regarded as a critical factor for collaboration (Orellana, 2017). In collaboration, digital technology serves as a medium that influences collaborative working among participants. The role of digital technology, its characteristics, and its interoperability influence the effectiveness and efficiency of collaboration. The role of digital technology refers to how it engages in collaboration. Digital technology can be used as a collaborative tool for pure collaboration, such as digital model-based tasks (Olesen & Myers, 1999; Patel et al., 2012). The characteristics of digital technology are defined as the features of digital technology, namely the capability of digital technology, which responds to the requirements of collaboration functionally (Shafiq et al., 2013). Due to the complexity of collaboration, the interoperability of digital technology should also be considered when introducing new technology into current work practices or changes (Grilo & Jardim-Goncalves, 2010).

Table 2.1: Key factors affecting collaboration

Main factors	**Sub-factors**	**Key points**	**Reference**
Individual	Social factors	Professional expertise/skills	(Papadonikolaki et al., 2016)

		Collaborative expertise can contribute to the collaboration	
	Psychological factors	Perception of collaborative activities Motivation to collaborate Objectives in collaboration	(Ahmad et al., 2010; Oraee et al., 2017)
Team	Team configuration	Team members' responsibility Understanding team members' roles and responsibilities	(Oraee et al., 2021)
	Team relationships	Relationships in work practice determine personal collaborations	(C. Robson, 2002)
	Knowledge sharing in teams	Helps team members to improve their capability and influences the efficiency of collaboration	(Ipe, 2003)
Organisation	Organisational culture	Organisational culture has an influence on initiative actions for organisations Differences in organisational culture makes partnering challenging	(Bresnen & Marshall, 2002; Hardin & McCool, 2015; Kostis et al., 2021; Patel et al., 2012)
	Organisational structure	Influences the delivery of tasks and power among employees	(Thomson & Perry, 2006)
	Organisational strategy	Training/resources: High-level collaboration will involve a high degree of use of distinctive resources	(Chen et al., 2021; Hardy et al., 2003)
Environment	Setting	People involved in collaborations working separately across physical distance often place more reliance on asynchronous communication, which leads to more formal coordination	(Patel et al., 2012)

	Social context	A co-working space is not only a physical space, but also a collaborative community that provides a shared context for team members' collaborative practice	(Merkel, 2015)
Technology	The role of digital technology	Digital technology can be a collaborative tool for pure collaboration	(Olesen & Myers, 1999; Patel et al., 2012)
	The characteristics of digital technology	Respond to the requirements of collaboration functionally	(Shafiq et al., 2013)
	The interoperability of digital technology	The interoperability of digital technology should also be considered when introducing a new technology into current work practice or change, including data interoperability and framework interoperability	(Grilo & Jardim-Goncalves, 2010; Shen et al., 2010)

Collaborative processes are influenced by a myriad of factors, which enriches the depth of this study. In the current digital era, the profound impact of digital technology is acknowledged across many disciplines. However, while its role in the research field of collaboration has attracted increasing attention, it remains underexplored, especially regarding the interplay between digital technology adoption and the dynamics of collaboration. Some studies have begun to highlight the significant influence of digital technology on collaborative processes, emphasising the transformative changes it instigates. Yet, there's a burgeoning body of literature that underscores the intricate, and sometimes volatile, relationship between digital technology and both individual and collective activities. For instance, the materiality and affordances of digital technology are intimately linked with its role and implications in collaborative endeavours (Leonardi & Treem, 2020). The growing discourse on digital technology underscores the importance of the emergent phenomenon of digital technology-enabled collaboration. The following section will delve deeper into a pivotal concept central to this study: digital collaboration.

2.3 Knowledge boundary in Collaboration

In the collaboration process, information is shared among different parties and used to make agreed decisions to complete a series of creative tasks. Knowledge is created in this collaborative process, in which team members engage in shared work, support each other, and build on individual expertise through shared experiences (Orellana, 2017). Hardy et al. (2003) identified that organisations have different patterns of involvement and embeddedness in the collaboration process, leading to diverse strategic, knowledge creation, and political effects. Additionally, Dietrich et al. (2010) suggest that the ability to integrate knowledge into a project team affects the performance of team members and translates knowledge into action. Therefore, effective knowledge management can empower individuals' handling and sharing of information efficiently (GhaffarianHoseini et al., 2017). A primary element of knowledge management is knowledge sharing, which involves the knowledge being successfully transferred from the owner to the receiver (Hendriks, 1999). Effective knowledge sharing is seen as a facilitator for stakeholders to make agreed decisions in collaborative practice (Pittz & Intindola, 2015). Furthermore, the collaboration also provides a context for occurrences of knowledge sharing (Yang & Chen, 2008). Collaboration, as a form of interaction, is regarded as beneficial in managing how knowledge is shared in a heterogeneous team (Nissen et al., 2014).

The modern division of labour encourages individuals to focus on their specific professional tasks, often delineated based on various knowledge domains. Such compartmentalisation can lead to different functional groups being unfamiliar with each other's work content, each possessing their own codes of practice (Howard-Grenville & Carlile, 2006). For effective collaboration and satisfactory work performance, these diverse professions, disciplines, and organisations must cooperate, despite their differing knowledge bases and practices. In the current digital age, digital technology not only enhances the collaboration process but also introduces unexpected challenges, particularly as digitisation progresses across various industry organisations (Cozzolino et al., 2018; Noesgaard et al., 2023). Differences and boundaries between implicit and explicit knowledge coexist with digital collaboration and can also challenge its process. This section will explore critical issues concerning digital collaboration by unpacking current findings from the literature and related insights.

2.3.1 Definition of knowledge

The definition of knowledge is a continuous debate in the literature among scholars from different perspectives. Most discussions about types of knowledge include both tacit and explicit knowledge. Explicit knowledge is easy to transmit through language; in contrast, tacit knowledge is related to personal experience and rooted in action, a commitment that is difficult to formalise and communicate (Ipe, 2003). Explicit knowledge and tacit knowledge are interconvertible (Nonaka, 1994). In addition, tacit knowledge is referred to as sticky knowledge as it is difficult to move it from the knowledge owner to the knowledge receiver (von Hippel, 1994). The tacit and sticky nature of knowledge increases the difficulty of sharing knowledge (Carlile, 2002). However, explicating the tacit knowledge can contribute to the knowledge shared (Nonaka, 1994). Furthermore, sometimes, even if the tacit knowledge is explicated, the shared meaning of knowledge can still not be transferred, particularly for projects involving different expertise and experience (Bechky, 2003). This requires people to consider how to share knowledge through these differences.

Knowledge sharing is defined as ‘the process by which knowledge held by an individual is converted into a form that can be understood, absorbed, and used by other individuals’ (Ipe, 2003, p. 341). The process of knowledge sharing ‘is a mutual exchange of ideas and information that could influence the way teams learn in organisations. It involves the capturing, organising, reusing, and transferring of tacit knowledge, often characterised as the implicit knowledge of one’s practices’ (Hong et al., 2017, p. 52). To be specific, since knowledge cannot be delivered directly from one person to another person, the knowledge sharing process is divided into two forms: externalisation by the knowledge owner, such as speech, writing and explaining; and internalisation by the knowledge acquirer (or knowledge reconstructor), such as listening, reading and imitating (Hendriks, 1999). The existing barriers ‘may distort the internalisation of externalised knowledge’ (Hendriks, 1999, p. 92). It is believed that inadequate representations of knowledge are detrimental to knowledge sharing among people. Therefore, knowledge sharing is more than transferring knowledge (van den Hooff & Huysman, 2009). Knowledge is transferred when the same meaning is delivered from the person who expresses it to the person who receives it. While the problem is that sometimes, the expression of knowledge might mean something different to the receivers, and then it is not clear if the knowledge is transferred (Bechky, 2003). Therefore, knowledge sharing focuses more on the interaction among individuals who have diverse knowledge and contribute to both knowledge distribution and knowledge acquisition (Ipe, 2003).

Theoretical perspectives of knowledge in academic debates, can mostly be divided into either a knowledge-as-possessed-asset perspective or a knowledge-as-practice perspective (Wang et al., 2021). While the two perspectives come from different worldviews, Cook and Brown (1999) suggest that possessed knowledge can be regarded as a tool to serve knowing as a process (i.e., part of action). From the perspective of knowledge as an ongoing process, knowledge is an ongoing action embodied in what actors do every day to get their work done (Orlikowski, 2002). Similarly, in other forms of work such as project-based organisational forms, e.g., in product development projects, Carlile's view (2002) on knowledge also supports this perspective, i.e., that knowledge is not a static entity or stable disposition, but an ongoing and dynamic production among actors in innovative settings.

Knowing calls for an epistemology of practice, where practice implies doing the real work itself. Practice, here, refers to "action informed by meaning drawn from a particular group context" (Cook & Brown, 1999, p. 387). We understand knowing as the practice or 'doing' of actions using knowledge to seek a solution to a problem. To shed light on knowing in practice, Carlile's pragmatic view (2002) suggests knowledge is localised, embedded, and invested in practice articulated from experience and know-how. Similar to this perspective, Ryle (1945) proposes that know-how can be described as when a person knows how to do, and that knowledge is manifested in their practice/action rather than in their statement.

2.3.2 Knowledge boundary

Levina and Vaast (2005, p. 307) suggest that boundaries in practice emerge as some people are 'distinguished from others who are not engaged in a similar pursuit' when they 'act knowledgeably in a given material, historical, and social context'. Diverse professional and organisational settings are the two main reasons for the boundaries that exist in organisations. Multiple organisations and multiple disciplines make knowledge sharing across the heterogeneous context more complex and dynamic. The embeddedness and tacitness of knowledge are the main issues to deal with to integrate various expertise (Levina & Vaast, 2005). The biggest challenge is to share with others and assess from others domain-specific knowledge at a boundary (Carlile, 2004). During the process of collaboration and communication, the organising and managing of explicit knowledge, such as datasheets or reports, are mostly routine for organisations as they are easy to transfer through regular work practice. As Carlile (2002) states, however, the difficulty in transferring knowledge is the tacit nature of knowledge and its stickiness, and these characteristics of knowledge that hinder knowledge creation across functions are just the driver of innovative problem-solving within a function. Berente et al. (2010) describe 'object world' of designers from separate disciplinary specialities as the unique, personal context within which a designer engages in the practices of design. This 'object world' is made up of physical artefacts, tools and instruments, as well as abstract formalisms, design principles, methods and associated practices. 'The characteristics of knowledge that drive innovative problem solving within a function actually hinder problem-solving and knowledge creation across functions', which is at the knowledge boundaries (Carlile, 2002).

Carlile (2002) identifies three types of knowledge boundaries, namely syntactic knowledge boundaries, semantic knowledge boundaries and pragmatic knowledge boundaries (Figure 2.3). 'A syntactic knowledge boundary occurs when knowledge is low in novelty, specialisation and dependence' and requires people to build a shared and stable syntax to cross this boundary (Hsu et al., 2014, p. 284). A semantic knowledge boundary is when there is a shared syntax but different interpretations or understanding for actors (Yates & Paquette, 2011). This boundary requires to translate a tacit and context-specific knowledge to explicit to ensure common and shared meanings (Hsu et al., 2014). A pragmatic knowledge boundary occurs when the goals of knowledge delivery of actors contradict with each other but require common knowledge regarding a specific practice (Yates & Paquette, 2011). This boundary considers presenting current knowledge and generates and learns knowledge from other functions and then transforms knowledge accordingly (Hsu et al., 2014) . 'The knowledge boundaries are not only a critical challenge but also a perpetual necessity because much of what organisations produce has a foundation in the specialisation of different kinds of knowledge' (Carlile, 2002, p. 442). A 'knowledge boundary is specifically concerned with the barriers caused by local knowledge itself in the process of knowledge delivery and sharing' (Hsu et al., 2014, p. 284).

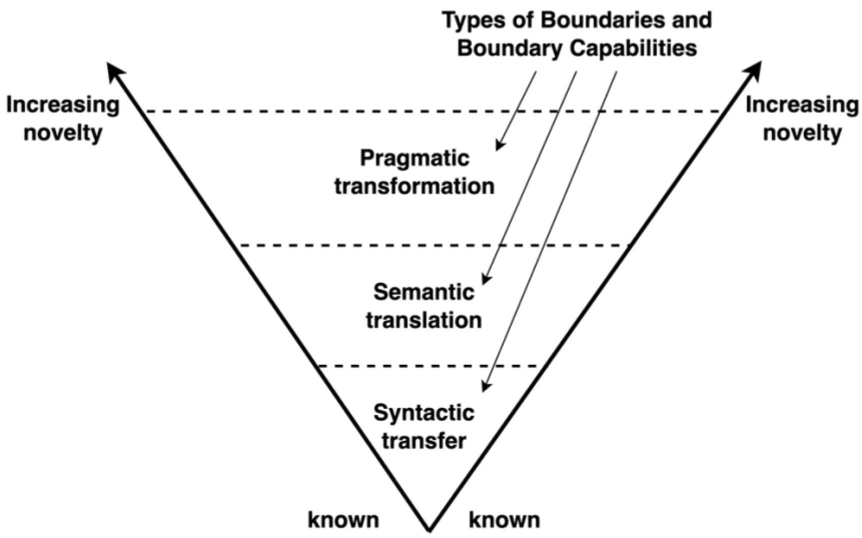

Figure 2.3: An integrated/3-T framework for managing knowledge across boundaries (Source: Carlile, 2004)

2.4 Digital technology and the emergence of digital collaboration

With the progression of technology integration, a growing number of technologies aimed at enhancing collaboration are being incorporated into work practices. The introduction of new technologies invariably causes significant disruptions within existing work practices and business models (Cozzolino et al., 2018; Lavikka et al., 2018), leading to the creation of new tasks and roles (Hollnagel, 2003). As a result, a new form of network, underpinned by these technologies, is established to support the changes brought about by technology adoption (Oraee et al., 2021). During the adoption and diffusion of new technology, it becomes evident that numerous challenges related to collaboration based on new technologies need to be addressed. Therefore, how to incorporate technologies into collaboration to achieve effective digital collaboration is a prominent topic in many domains, particularly for project-based work. Given the diverse roles of digital technology in interaction, digital technology leads to the emergence of different collaborative formats in intra- and inter-organisational collaboration (Riemer & Schellhammer, 2019) such as spreadsheets, ICT, or digital platforms. However, due to the hyperconnections and mutual dependencies between digital technology, human actors, and contexts, the emergence of digital collaborative formats is a dynamic and complex process involving interactions among multiple entities that evolve over time (Benbya et al., 2020). To conclude, recent studies suggest that the evolution of digital technology-enabled collaboration is shaped by interactions at both the individual and group levels and is further associated with the characteristics of the broader socio-technical system structure embedded within interconnected collaborative practices. This provokes further contemplation on the potentialities brought about by the incorporation of digital technology into collaboration, given the dynamic evolution processes and complex contexts.

2.4.1 Role of digital technology in collaboration

Digital technology has varied influences on the collaboration process across different research domains. In innovation research, with the dramatic rise of ICT innovations, the technological aspect has become a critical and essential factor in promoting digital collaboration within organisations, particularly those collaborating with Information Systems (IS) (Olesen & Myers, 1999; Yoo et al., 2012). In network research, information technology bolsters collaboration by fostering trustworthy relationships among agents, especially for employees working from dispersed locations (Hossain & Wigand, 2004). In supply chain research, IT-enabled collaboration leads to "better quality, lower inventory levels, faster new product development cycles, higher productivity, lower materials and manufacturing costs, and shorter delivery lead times" (Fawcett et al., 2011, p. 41). Communication theory suggests that digital technology can enhance communication by mediating both asynchronous and synchronous communication (Sofia Pereira & Soares, 2007).

The roles of digital technologies in organisational work vary and have been discussed from multiple perspectives. Orlikowski and Gash (1993) propose that individuals' interpretations of technology are vital for their interaction with it. Different groups within organisations possess distinct assumptions and understandings of technology, referred to as technological frames (Orlikowski & Gash, 1993). Incongruent technological frames among members can lead to conflicts and challenges in implementing and using technology. They posit that congruent technological frames in members' collaboration entail similar expectations regarding the role of technology, the technical strategy, and the nature of technology use in business processes. As previously highlighted, digital collaboration technology plays a pivotal role in digital collaboration. IT types, based on functionalities, can be categorised as '1. overcoming constraints, 2. increasing the range and speed of information access, 3. improving task performance' (Hendriks, 1999, p. 93). However, many researchers approach information technology from a sociotechnical standpoint, emphasising not just technological aspects, but also social ones. Drawing on structuration theory, Orlikowski and Robey (1991) propose two roles of information technology in an organisational context: one as a consequence of subjects' actions within structural and cultural contexts, and the other as an antecedent, providing conditions of interaction to create or transform these contexts, illuminating the dynamic relationships between digital technology and its context.

As the form of collaboration evolves, an increasing number of digital technologies have been introduced in various industries and fields. Team members' positive attitudes towards new technologies can motivate novices of technology usage to learn more knowledge and skills (Merschbrock & Munkvold, 2015). Furthermore, when actors need to receive instant messages or rapid feedback, synchronous communication is crucial for organisations or project members. Understanding how factors and relationships between digital technology and participants are changing in organisational collaboration is the focus of the attention of current research. The development of digital technologies is shaping the evolution of digital collaboration. With the increasing digital characteristics of collaborative tools, digital technology-enabled communication may become more effective and structured, but sometimes, information richness is declining due to less informal conversation for "messy talk", which is important for those open-ending problem-solving (Dossick & Neff, 2011). Moreover, from a sociotechnical perspective, IT-enabled collaboration can have unsatisfactory effects due to limited interpretability in communication (Neff et al., 2010).

2.4.2 Different views of studying digital technology in collaboration

Few scholars have provided explicit definitions of digital collaboration, largely due to the inherent difficulties in delineating its scope and pinpointing the beginning of a digitalised collaborative process. However, some explanations related to information systems (IS) might offer insights into the nature of digital collaboration. Recent research study digital technology from different views. In the field of Computer-supported Cooperative Work field (CSCW), some studies explore the implementation and use of digital technology in collaborative practice from a design and practice view (Bjørn et al., 2021; Paavola & Miettinen, 2019, 2023)For example, to create a virtual or more synchronous collaborative environment by applying digital technology (e.g. BIM) with integrating professional workflow, cooperation work practice (e.g., the design of articulation work), and spatiotemporal consideration (e.g., mobility) (Bjørn et al., 2021). These studies emphasise individual behaviour with digital technology in collaborative activities or the functionality of digital technology in collaborative processes.

Aside from focusing on individual behaviour with digital technology in collaboration, some studies focus on the organisational process of digital collaboration. The digitalisation of collaboration has evolved into what we know as digital collaboration, which has become a staple for organisational business. Oraee et al., (2017) describe the digitalisation of collaboration as using digital tools to replace physical information with digital versions, supporting the core business, and then reshaping the business to extract value from the digitalisation itself. This suggests that the digital information derived from technology should directly benefit the core business to generate value. Recognising the growing significance of digital collaboration, Kock (2005) posits that electronic collaboration enables individuals to utilise technologies to complete shared tasks. Building on the early definition of technology-enabled collaboration, Madlberger and Roztocki (2009) view e-collaboration as synonymous with digital collaboration, emphasising its inter-organisational nature involving multiple partners. Peansupap and Walker (2005) suggest that ICT enhances collaboration by fostering communication and information sharing. Merschbrock and Munkvold (2015) further study effective digital collaboration, defining it as collaboration through IT among inter-organisations or within project teams. They identify specific ICTs that unify users to undertake digital and networked work practices as being integral to digital technology. Thus, digital collaboration hinges on digital technology with a focus on task-related collaborative tools.

Within organisations and enterprises, the depth and scope of digital technology adoption vary. This evolution isn't just a technological shift but fundamentally transforms organisational operations, profoundly impacting management and business practices, especially in project-based collaborative activities. In both academia and industry, the nature of digital collaboration adapts based on digital technology's integration level. Three primary levels of digital technology adoption are discerned: digitisation, digitalisation, and digital transformation.

- Digitisation is the process of turning activities or information previously restricted by physical constraints into digital formats, liberating them from the confines of time and space.
- Digitalisation encompasses more than just technological advancement. It signifies a shift in social interactions, with digitised work and communication fostering innovative organisational and collaborative approaches. Some scholars link digitalisations with the impact of digital technology on business operations.

- Digital transformation encapsulates comprehensive organisational change. As entities embrace digitalisation, there's a pronounced alteration in their operational strategies, affecting competencies, alliances, and even overarching business models. This profound shift is termed digital transformation (Leonardi & Treem, 2020). A crucial component of this transformation is the evolving rapport with customers or clients, marking a comprehensive change in how organisations function in the digital era.

Thus, in this context, digital collaboration refers to collaborative activities within an ongoing digitalising environment. Compared to traditional face-to-face collaboration, emerging technologies herald new collaborative processes and networking reconfigurations among organisations (Riemer & Schellhammer, 2019). Electronic communication fosters decentralised networks among individuals, sculpting virtual relationships, especially beneficial for building rapport among dispersed organisations and teams (Rutkowski et al., 2002). However, when these relationships hinge on technology-enabled collaboration, a shared understanding becomes crucial, considering the potential lack of a shared language and nuanced social sensitivity in electronic platforms (Qureshi et al., 2006).

The management of knowledge boundaries signifies the underlying strategies and relationships among individuals and groups, particularly when digital technology is introduced to traditional collaboration patterns. In the fields of information systems and organisational studies, two perspectives have garnered considerable attention in recent years with respect to managing knowledge boundaries: the boundary object perspective and the boundary work perspective. Digital technology, often seen as a critical factor impacting knowledge sharing across boundaries due to its relationship with actors who act on them, is addressed differently in these two perspectives in the context of collaboration. The chapter 3 theoretical foundation will continue discuss the boundary issue and the role of digital technology in managing knowledge boundary in collaboration.

2.5 Digital collaboration in Construction projects

2.5.1 Project management and AEC industry

Collaboration, as an approach for sharing information across organisations, is embedded within a project. The project is defined as the achievement of a particular goal by completing a set of tasks or activities by allocating and using certain resources (Munns & Bjeirmi, 1996). Manning

(2008) abstracts the elements into three project properties that should be recognised to guide a project embedded in a collaborative context: task specifications, project constraints, and team relations. Team integration is also considered important to build team collaboration and it is necessary to improve project performance (Franz Bryan et al., 2017).

2.5.1.1 Collaboration in construction projects

As a project-based industry, the AEC industry consists of many disciplines and organisations, which require project management to assemble these separate players to work together on a construction project. However, during a construction project, many risks, such as design change, are usually encountered; however, high-quality and responsive project management of collaboration among team members can reduce the possibility of failure of the project. The focal collaboration with multiple actors in a project team is viewed as the key success factor for a project (Dietrich et al., 2010).

The construction project in the AEC industry is a temporary multidisciplinary organisation, assembling a variety of firms (Sackey et al., 2015). Succar (2009) conceptualises the life cycle of a construction project into three phases (Figure 2.4). The whole construction project lifecycle includes the design phase, construction phase and operations phase, and each phase is related to multiple activities.

Design phase	Construction phase	Operations phase
D1 Conceptualisation, programming, and cost planning	C1 Construction planning and construction detailing	O1 occupancy and operations
D2 Architectural, structural and system design	C2 Construction, manufacturing, and procurement	O2 Asset management and facility maintenance
D3 Analysis, detailing, coordination, and specification	C3 Commissioning, as-built ad handover	O3 Decommissioning and major re-programming

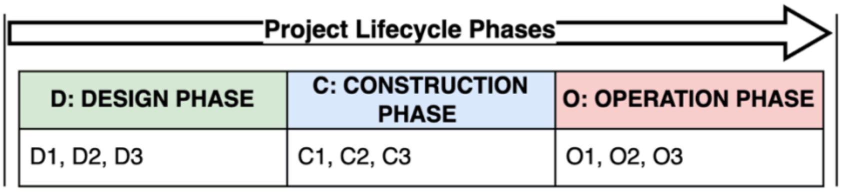

Figure 2.4: the collaborative activities in different construction project phases (Source: Succar, 2009)

Chan et al. (2004) developed a conceptual framework including five critical success factors for a construction project based on previous studies: project-related factors, project procedures, project management actions, human-related factors, and external environment, with the project management actions being the most critical for project success. Applying an information system in the construction project process can improve the effectiveness and efficiency of construction management by developing the information quality, systems quality, user satisfaction, and intention of project management on the information system use (S.-K. Lee & Yu, 2012). However, the fragmented nature of the AEC industry is the primary barrier to improving the productivity and performance of a construction project (Baiden et al., 2006; Lee & Yu, 2012). The fragmented nature of the AEC industry is due to three main reasons, namely, multiple stakeholders from different disciplines, collaborative relationships built across organisations and multiple project phases, which lead to a series of communication and information processing problems in the collaboration process (Singh et al., 2011).

From the organisational perspective, the fragmented nature is related to the fact that each organisation involved in a common project has different organisational values. The organisational value depends on the objective of the project, which might influence the attitudes of employees towards the collaborative process (Gal et al., 2008). For some organisations, different behaviours may lead to practitioners' inertia to change and make collaborative practice in the AEC industry difficult to achieve (Abdul & Ahmed, 2014). Adversarial relationships between parties in a project are also a major factor against organisations retaining a common objective, which leads to low productivity in the construction project (Nitithamyong & Skibniewski, 2004).

The multiple phases of a construction project make the information discrepancy of each participant in different construction phases more obvious, which heavily influences the efficiency of project change. According to the Construction Industry Institute's (CII: https://www.construction-institute.org/resources/knowledgebase/project-phases) knowledge database, a construction project is divided into eight phases: feasibility, conception, detailed scope, detailed design (engineering design), procurement, construction, commissioning & start-up, and handover & closeout. The phases of design and construction include the most information during the whole project life cycle. How to manage information flow in multiple project phases is the core issue in construction management for project performance (Hu, 2008).

Additionally, the multidisciplinary nature of a construction project contributes greatly to its fragmentation (Neff et al., 2010). The integration of multiple disciplines becomes the focus for dealing with these problems and enhancing productivity in the AEC industry (Gu & London, 2010; Neff et al., 2010). The fragmentation of the professional capability of different participants results in them working together inefficiently (Baiden et al., 2006). According to Shelbourn et al. (2007) propose that the planning and implementation of effective collaboration in a construction project should balance and synthesise business, technology, and people. However, team members have diverse special expertise and backgrounds, which may lead to the discrepant understanding of the transferred information (Neff et al., 2010). In addition, operating different tools and producing distinct models for multidisciplinary parties increase the difficulties of interoperability (El-Diraby et al., 2017).

This fragmented context adds heterogeneity and complexity to knowledge-based production (Bresnen, 2016). Alashwal et al. (2011) state that the impact of fragmentation of construction projects includes: eliminating learning and innovative solutions; hampering knowledge sharing and capturing; hindering members' mutual sharing of information and knowledge; inhibiting relevant knowledge production about the project; making information integration complex. Besides, members of the same team have different backgrounds and experience, which leads to a different understanding of expression between members (Nicolini et al., 2012).

2.5.1.2 Knowledge boundaries in AEC industry

In the AEC industry, diverse practices emerge due to the involvement of multiple disciplines and organisations. Individuals from different organisations often embody distinct organisational cultures and strategies, leading to the formation of organisational boundaries. Similarly, various disciplinary backgrounds contribute to disciplinary boundaries. These boundaries become significant obstacles to knowledge sharing within projects. The difficulties in knowledge sharing are deeply rooted in differences in language, locus of practice, and understanding of objectives (Bechky, 2003). Moreover, the multitude of actors from varying disciplinary and organisational backgrounds have their own unique social worlds and purposes. Yet, they are required to establish a shared understanding to maintain a level of coherence and consensus for ongoing collaboration (Gal & Berente, 2008; Star & Griesemer, 1989). Within the AEC industry, particularly in construction projects, stakeholders such as architects, engineers, construction managers, facilities managers, and owners possess specialised knowledge from different professional fields. This diversity makes mutual understanding a considerable challenge (Kalay, 2001).

Knowledge boundaries become evident in project-based collaboration within the construction industry when multiple organisations and disciplines are involved. The AEC industry requires a vast amount of knowledge, due to the various disciplines and organisations that contribute distinct functions throughout a construction project's lifecycle. Kasvi et al. (2003) suggest that there are three main types of knowledge related to a project: technical knowledge about the product, procedural knowledge regarding production, and organisational knowledge concerning communication and collaboration. Within a construction project, Rezgui (2001) categorises knowledge in the construction domain to include domain knowledge, organisational knowledge, and project knowledge. Domain knowledge forms the overall informational context, including administrative information, standards, technical rules, and product databases. Organisational knowledge is company-specific, encompassing personal skills, project experiences of employees, and cross-organisational knowledge. Project knowledge refers to the potential for usable knowledge created through interaction, encompassing project records, solutions, and memories of processes. Since AEC projects involve multiple disciplines, knowledge sharing in a construction project is 'distributed (designed and constructed by multiple, autonomous actors), heterogeneous (composed of communities with distinct skills, expertise, and interests), and sociotechnical (requiring trust, values, and norms, as well as IT capabilities and complex fabrication processes)' (Boland et al., 2007, p. 633).

Managing knowledge boundaries is crucial for construction project management as it fosters improved project performance. Throughout the collaborative process in construction projects, knowledge is shared via the interaction of different object worlds (Berente et al., 2010). These include physical artefacts and tools as well as discipline-specific guidelines and associated practices. The transformation of various sharing pathways for explicit and tacit knowledge also indicates the inseparability of knowledge and practice (Berente et al., 2010). According to Woo et al.(2004), shared knowledge in a construction project is largely reliant on AEC professionals possessing tacit knowledge and experience from related projects, with explicit knowledge playing a supporting role. Furthermore, within a project, knowledge is dynamic, varying based on problem-solving requirements and the tasks to be performed. Therefore, in the AEC industry, knowledge is viewed as a tool facilitating a dynamic knowing process aimed at resolving issues to enhance project progression. This implies that, during the ongoing process of a construction project, knowledge can be effectively shared when it is applied towards achieving practical objectives and tasks in the actors' practice. A diverse knowledge practice perspective is the approach adopted by current researchers to view knowledge across boundaries. The know-how practice/actions should be reasonable under the required principles of their work setting for performing their tasks. Majchrzak, Malhotra, and John (2005) propose collaboration know-how in teams to refer to knowledge about how to communicate and integrate ideas with others and how to coordinate others' work and actions in the team.

2.5.2 Digital collaboration among AEC organisations and construction projects

With digital transformation happening in AEC organisations, digital technology is adopted to facilitate their intra- and inter-organisational collaboration. The purpose of adopting new digital technology for AEC organisations includes improving their competitive advantage and business performance. The process of implementing and using digital technology within and between AEC organisations benefits the management of knowledge boundaries in construction projects. But various digitalisation processes in organisations demonstrate diverse influences on project-based collaboration across boundaries.

Researchers believe that as a complicated and traditional industry, project performance within the AEC industry can be significantly enhanced through the use of advanced and efficient digital technologies (Froese, 2010). Froese (2010) classifies three main types of construction ICT according to the degree of digitalisation of construction project management. The first type is standalone tools for a specific task, such as computer-aided design (CAD). The second type is computer-based tools to assist communication, such as emails and document management systems. The last type is the type which has received the most focus in research over the last decade, which is integrating all these types of IT as a cohesive overall system through model building to promote whole project collaboration. Project management is affected by the introduction of ICT. Technological innovation in project management leads to increasing complexity of work practice (Froese, 2010). Baccarini (1996) proposes that project complexity is a significant criterion for determining the objective, requirements, and eventual influence of project management. However, change based on the innovation of technologies in the AEC industry sometimes increases challenges to manage when being implemented in a construction project (Travaglini et al., 2014). Dubois and Gadde (2002) suggest that the complexity in construction has two determinants, uncertainty, and interdependence. They believe that uncertainty is caused by four aspects: 1) management is unfamiliar with local resources and the local environment; 2) the lack of a complete specification for the activities at the construction site; 3) the lack of uniformity of materials, work and teams regarding place and time (every project is unique); 4) the unpredictability of the environment.

Interdependence includes technological interdependence and the interdependence of various work tasks and the overlap of construction project stages. With interdependence in construction, emerging ICTs require more integration and collaboration across project tasks, which can make it easy to fit into previous work practice (Froese, 2010).

Digital collaboration happens in a construction project facing many challenges. As discussed above, the causes are due to the fragmented nature of the construction project and the impact of digital technology innovation in the construction project. In the AEC industry, instead of mitigating fragmented features, digital technology may highlight the difference between users across different disciplines (Neff et al., 2010). From the socio-technical perspective, Shelbourn et al. (2007) studied the planning and implementation of effective collaborative work in construction projects and summarised the different forms of collaborative work illustrated in Table 2.2.

Table 2.2: Different forms of collaboration and typical uses in construction projects (Source: adapted from (Shelbourn et al., 2007)

Type of collaboration	Description of collaboration	Typical uses
Face-to-face collaboration	Same time – same place	Information centres Team rooms
Asynchronous collaboration	Different time – same place	Task delegation e-mail Computer conferencing
Synchronous distributed collaboration	Same time – different place	Data sharing Tele-conferencing Video-conferencing
Asynchronous distributed collaboration	Different time – different place	Conference publishing Electronic meeting rooms Design conferences Project management

Improving information and knowledge sharing is always the focus of the collaboration process. With the development of digital technology, patterns of collaboration display remarkable innovation in information and knowledge management. In terms of organisational collaboration, differences among organisations and disciplines are inevitable. The existing discrepancies have a negative impact on building a shared understanding, assumptions, and expectations in collaboration among people, especially when digital technologies change. For the construction project, considering knowledge management within collaboration during the project life cycle can promote project performance (GhaffarianHoseini et al., 2017). Nevertheless, Neff et al. (2010) propose that crossing knowledge boundaries is still regarded as the most vexing issue for the collaboration process in the construction project. Therefore, it is crucial to have a better understanding of digital technology's relationship with knowledge sharing across boundaries.

Overall, the impact of digital technology on construction project management often leads to changes in collaboration based on digital collaborative technology. It requires more interdependence among project tasks; however, the uncertainty caused by innovation makes project management more complicated. Conflicts increase the challenge of digital collaboration in the construction project. The nature of the construction project is related to the multiple firms and disciplines involved in the whole project, which affect the effectiveness of collaboration with IT from different dimensions. The incongruence of organisational culture or value on adopting IT in collaboration has an influence on team members.

2.5.2.1 Systemic view of the digitalising context of AEC organisations and the project-based collaboration

In the IS research field, researchers explore organisation-related phenomena based on the view of the activity system, especially regarding technology-mediated organisational activities (Allen et al., 2013). The key elements underpinning this activity system view are primarily derived from Engeström's third generation of activity theory, especially the interaction between multiple activity systems. This includes components like activity, mediator, subject, object, community, rules/norms, and division of labour (See Figure 2.3).

Table 2.3. Activity system view and implications for the digitalised AEC organisations

Constructs	Definitions	Implications for the digitalised AEC organisations
Activity	An activity is a form of "doing" directed to an object, and activities are distinguished from each other according to their objects. Transforming the object into an outcome motivates the existence of an activity.	Implementing and using digital technology in inter- or intra-organisational practice
Mediators	It can be anything used in the transformation process, including both material tools and tools for thinking (e.g. (Cole, 1998)); "social objects with certain modes of operation developed socially in the course of labour" (e.g. (Verenikina, 2001); Collective use of tools integrates different collaborative activities and the shifting roles of objects (e.g. (Belmondo & Sargis-Roussel, 2015))	Different digital innovation strategies and initiatives to promote digital technology implementation and use
Subject	Individuals or groups in organisations involved in the activity.	Project manager, coordinator architect, engineer, MEP manager, on-site construction manager etc

Object	An object can be a material thing, but it can also be less tangible (e.g. (Nicolini et al., 2012))	Within an organisational activity system, their objects are following their organisational business goal
Community	Knowing manifests itself by practice and locates both in the doings and sayings and in the body, artefacts, habits of groups (e.g. (Nicolini, 2011))	Different professional groups
Division of labour	The explicit and implicit organisation of the community as related to the transformation process of the object into the outcome.	The work assignment in technology-assisted activities among participants
Rules	Both explicit and implicit norms, conventions, and social relations within a community.	The organisational institutionalised standards, Laws, agreements, codes of practice, general specification and guidance
Outcome	The shared goal among different organisations (e.g. (Lu et al., 2018))	Complete the construction project goals

Beyond merely identifying the elements related to organisational phenomena, the activity system view offers a cultural-historical perspective. This allows for a deeper understanding of inscriptions from organisational norms in digital technology-related actions. Leveraging this perspective, researchers have shown that technologies can reinforce organisational structure through tensions or contradictions, leading to emerging actions that achieve congruence. Such cultural-historical insights facilitate exploration into how organisations transition from traditional processes to digital technology-enabled processes, like those seen in digitalised AEC organisations.

However, in recent years, some scholars have suggested that the conceptualisation of interactions between activity systems still requires further exploration. Moreover, the role of technology within the activity system should be better illuminated through empirical studies on emerging technologies such as AI and big data. This necessitates a reconsideration of the relationship between technology and humans. Within the context of this study, construction project-based collaboration pertains to interactions occurring between various digitalising AEC organisations, all of which are united by project goals. The ties between digitalised AEC organisations are inextricable. Information and knowledge sharing in project-based collaboration have been enhanced through improved communication and coordination within collaborative networks (Bajwa et al., 2005; Oraee et al., 2017). Some research indicates that digital technology, used as collaboration tools, exerts varied influences on different types of collaboration. Discussions in these studies consider different levels of collaboration, including inter-personal, intra-organisational, and inter-organisational collaboration (D. Scott, 2005). Such intertwined and nested collaborative activities within a construction project can be understood as the inter-activity system.

Conversely, it has been observed that collaboration and communication through digital technology in construction projects can sometimes hinder cross-disciplinary knowledge sharing. Digital technology integrates different experts into the same project process using a suite of digital objects, all stemming from a specific digital representation due to the shared digital tools. To effectively collaborate, all involved parties must form a unified cognition concerning this shared digital representation, a requirement that can clash with their varied professional knowledge backgrounds. In this context, digital technology complicates collaboration among team members (W. J. (Wanda J. Orlikowski & Gash, 1993). Therefore, when aiming to enhance collaboration performance through digital collaborative tools, it's crucial to consider the interpretive flexibility and stability of the tools in use (Neff et al., 2010). The role of digital technology in project-based interactions between evolving organisations becomes multifaceted and dynamic. Thus, the intricate role of digital technology within digitalised AEC organisations draws attention to the dynamics of project-based collaboration, which might manifest in emerging tensions and contradictions during collaborative activities.

2.6 BIM technology-enabled collaboration in construction projects

2.6.1 Definition of BIM

BIM, i.e., Building Information Modelling, is an emerging digital technology in the AEC industry. This section presents the current academic definition of BIM technology, and different perspectives on the influence of BIM technology in collaboration. In addition, due to the evolving nature of digital collaboration in the AEC industry, BIM technology has been continuously adopted for intra- and inter-organisational collaboration and for facilitating organisational transformation in the long-term and while enabling project management in the short-term. Various factors thus influence the development of digital collaboration processes across different knowledge boundaries. The concept of BIM was first used by an auto CAD staff member to describe a new generation of design software developed after object-oriented CAD (Ghaffarianhoseini et al., 2017). Before BIM, object-oriented CAD had been traditionally used to produce 2D/3D-based modelling in the AEC industry. It allowed different disciplinary designers, such as architects, structural engineers, mechanical engineers and electrical engineers to communicate and co-coordinate through sharing information from their own discipline-specific field (Neff et al., 2010; Singh et al., 2011).

Currently, in the AEC industry, there are generally two types of definitions for BIM: 'little' BIM and 'big' BIM. 'Little' BIM refers to a virtual information model for simulating building information (Azhar, 2011), which is used for practitioners to understand the characteristics of building and achieve project goals during the different phases of the project lifecycle, such as architecture design, engineering design, construction, fabrication, and maintenance (Eastman et al., 2011). Generally, all BIM models are completed by multiple authors from different organisations who have diverse roles in a construction project (Christodoulou & Scherer, 2017). In these BIM models, there is a large amount of information, for example, building geometric information, quantities, and properties of building elements, mechanical, electrical, plumbing (often referred to as MEP), fire and life safety systems, cost estimates, material inventories, and project schedules, represented in different models and completed by different BIM software elements. In contrast, 'big' BIM refers to a model-based collaboration process, which involves various stakeholders and occurs throughout the entire lifecycle of the building construction (Azhar, 2011). The process includes communication about data and information exchange and the coordination of a model-based workflow in 'big' BIM, in other words, 'big' BIM process.

According to research on BIM, four perspectives of BIM are generally discussed in academic contexts: technological perspective, process-based perspective, strategy-based perspective, and behaviour-based perspective (Eastman et al., 2011; Grilo & Jardim-Goncalves, 2010; Hardin

& McCool, 2015). These four perspectives comprise the four areas affected by the emergence of BIM and are currently the main aspects of BIM focused on by researchers.

2.6.1.1 Technological perspective of BIM

From a technological perspective, BIM has always been a significant focus for researchers and practitioners, especially regarding the influence of BIM technology on the quality of building models and the project team's performance (Grilo & Jardim-Goncalves, 2010; Shafiq et al., 2013). The technological aspects of BIM include a set of modelling software, required hardware infrastructure, and a network to develop a systematic environment for operation amongst design and construction practitioners (Succar, 2009).

The early conception of BIM, based on the development of Computer-Aided Design (CAD), was designed as a tool to be used for integrated analysis and parametric modelling (Volk et al., 2014). BIM models contain 3D data and object attributes, which allow designers to define the object and adjust the positioning or scale using parametric modelling. Four dimensions are denoted in BIM technology: property, relation, standards, and utilisation (Jung & Joo, 2011).

The property of BIM refers to the objective of the BIM model and any geometric or non-geometric data-related building elements, such as the size of a wall. The relation depicts the relationship between the created properties of building information, including physical and logical interdependency among these properties. These relations imply the knowledge-based reasoning of BIM technology. The standard mainly focuses on the rules of interoperability of different BIM models across organisations and disciplines. The utilisation focuses on the advancements from using BIM technology, and manipulation of BIM elements and databases, such as using graphic information for scheduling or BIM analysis for cost estimating. This technological perspective in existing research mainly explores the potential effectiveness and development of BIM technology from a functionalist perspective.

2.6.1.2 Process-based perspective of BIM

BIM is not only seen as a model created by multiple professionals but also a dynamic collaborative process (Grilo & Jardim-Goncalves, 2010). In a project, implementing BIM technology can affect different stakeholders. For designers, it improves the visualisation and building simulation of the BIM model. For contractors or sub-contractors, they can understand the constructability and construction sequence by increasing the communication efficiency and the collective understanding of project information. The quantitative information drawn from a complete visual 3D BIM model can be a fundamental source for the project schedule and project cost estimation that can be used for project phases, such as the project concept design phase and construction phase (Grilo & Jardim-Goncalves, 2010). BIM technology provides a collaborative space for improving information documentation, data integrity, distributed access, and project information retrieval (Gu & London, 2010).

The adoption of BIM changes the work practice based on the digital models in the construction process. The creation of an integrated and accurate BIM model for a project needs to consist of work from multiple sectors in the AEC industry. The adoption of BIM requires to a certain extent a relevant shift of roles and work practice in a new collaborative way for a multidisciplinary team because of the fragmented nature of the AEC industry. In a single construction project, many participants engage in the same BIM collaboration process. The owner organisation communicates mainly with the designer and builder, with the construction manager playing a liaison role in the project. External organisations provide some support for the industry, for example, the establishment of industry specifications (Figure 2.5.2.2). In the process of a construction project, a set of 3D building models is designed through the architect, designer and structural engineers designing applications. Based on the geometric models, building organisations create a project schedule and integrate costs into the models by using their own BIM application. Subcontractors can also gain access to the models and integrate with other participants based on the BIM process (Eastman et al., 2011).

A ‘deep’ application of BIM is seen as enhancing the collaboration and integration of different stakeholders in a construction project. A clear and specific definition of the required BIM-based collaboration level in a project or organisation can facilitate the management of project performance and guide the direction of BIM development in organisations. Currently, the level of using BIM is not completely specified by this industry. However, one can identify the extent or degree to which BIM is involved in a project, which is based on the level of collaboration within a project team. To specify the degree of the collaboration process, the National Building Specification (NBS) (2018) in the UK defines levels of BIM maturity from Level 0 to Level 3 and beyond. Level 0 involves zero collaboration. Level 1 involves the creation of concept work, such as 3D CAD modelling and electronic sharing of data. Level 2 of BIM maturity is related to some form of collaborative working, such as information exchange among different systems and various participants. However, Level 3 of BIM maturity is yet to be described and implemented in the construction industry. Level 3 of BIM maturity is considered as consisting of more collaborative working than level 2. It would be explored to establish more consistent international standards on collaborative working and build an open cultural environment that encourages learning and sharing among team members (NBS, 2018).

2.6.1.3 Strategy-based perspective of BIM

The strategy-based perspective of BIM refers to BIM implementation strategy. The separate use of a set of digital technologies by multiple organisations makes the connections to each functional system difficult (Narasimhan & Kim, 2001). IS strategy implementation in an organisation influences IT/IS performance and the future development of organisations. Gottschalk (1999) states that IT strategy is used to plan IT applications to help organisations to achieve their goals. Khosrowshahi and Arayici (2012) propose that BIM implementation requires a fit between technology and the business process, organisational culture, education and training, and information management. The coupling of BIM with the project process depends on the contractual arrangement and current industry principles. Good coupling of IT with the business process can reduce change and conflict and facilitate coordination and project performance. Berente and Yoo (2011) propose that the strategy of coupling IT and the work process should consider human factors and local practice. Moreover, policies, standards and principles are fundamental for implementing successful BIM strategies in a construction project (Howard & Björk, 2008). For efficient collaboration, the rules and structure should be jointly created, which involves negotiations among multiple parties (Thomson et al., 2009).

2.6.1.4 Behaviour-based perspective of BIM

Regarding the adoption and diffusion of BIM, some studies in the literature discuss the attitude and intention of employees to engage in BIM collaboration and change their previous work practice. Hardin et.al.(2015, p. 22) states that ‘BIM is 10 per cent technology and 90 per cent sociology’. The cultural shift in mindset is the core of BIM implementation in construction team collaboration (Hardin & McCool, 2015). Based on the opinions of Hardin and McCool, personal behaviour and organisational behaviour can impact the integration of IT adoption, which might depend on whether an innovation culture and a nimble attitude towards process change exist in companies. Compared with the technological perspective, human resource is regarded as a significant mismanaged perspective for observing the implementation of an information system in the construction industry (Jung & Joo, 2011). The main factors impacting on the performance of BIM technology include organisation size, users' habits, capabilities of used tools, nature of project team, modelling information accuracy, and technical training (Gu & London, 2010). In addition, based on sociotechnical theory, Oesterreich and Teuteberg (2019) suggest that employees' attitude and belief regarding the expected consequences from the IT performance affect IT adoption.

2.6.2 BIM adoption and construction project lifecycle management

The adoption of BIM technology requires not only skilled practitioners and the innovation of the collaborative process, but also more integrated, central relationships in the project. The level of BIM collaboration interacts differently with different types of construction project. Different delivery methods determine distinct collaborative relationships which influence BIM engagement in the project team. In turn, the fit between the BIM application and project relationships affects project performance, including project quality and efficiency.

The four most common delivery methods employed in the construction industry are identified in the literature as Design-Bid-Building (DBB), Design-Building (DB), Construction Management at Risk (CMR) and Integrated Project Delivery (IPD). 'The selected delivery methods have a significant influence on team integration' in diverse forms, for example, the interaction among different level roles and the understanding of the usage of BIM (Franz Bryan et al., 2017, p. 1). The business model or project delivery system determines the main collaborative and cooperative approach among various stakeholders and parties of a project during the project progress. The contracts for a project generally differ due to the different business models chosen, which have diverse requirements on the stakeholders' time for engaging in the designing or implementation processes of a building facility and the level of collaboration with other participants (El Asmar Mounir et al., 2013). Performance metrics have been divided into different categories. El Asmar Mounir et al. (2013) quantify the performance of the project and provide the statistical inference based on the survey on IPD projects and non-IPD projects and identify the benchmarks for IPD performance based on collected data. Team integration and group cohesion are considered as the main forms of integration for a construction project team when mediating the relationship between delivery method and project performance (Franz Bryan et al., 2017). DB is the most traditional delivery method; however, there is currently a large amount of interest in a new alternative method in a large, complex, or small project. For this type of method, the contractor needs to be responsible for the whole project and assign tasks to the chosen designer and constructor. It is observed that the owner is less involved in conveying information and their need to the contractor during the designing process (Ibbs et al., 2003) Under the IPD business model, major stakeholders, including owners, architect, contractors, subcontractors, supplier, and consultants, will commonly get involved in the same contract before the start of designing; in this type of collaborative method, all stakeholders will share project risk and rewards (El Asmar Mounir et al., 2013). The popularity of the IPD business model is increasing in the AEC industry.

BIM collaboration practice is around the digital models to integrate multiple disciplines, Shafiq et al. (2013, p. 149) propose that there are four categories of functional requirements in the BIM collaboration, including 'model content management, model content creation, viewing and report, and system administration', and each discipline has various roles and views in the collaboration practice.

The use of BIM in construction projects is more and more universal. Liu et al. (2017) propose that the effects of BIM collaboration are reflected in technology management, communication, trust, role-taking, leadership, learning and experience. For example, BIM is positively impacting construction in terms of quality and on-time completion (Suermann & Issa, 2009). In addition, digital representation of physical and functional characteristics of the building enables users to share and transfer information by different software applications within a multidisciplinary team and provide a collaborative platform for different stakeholders involved in a project through an integrated approach (GhaffarianHoseini et al., 2017).

However, even though BIM usage is dramatically increasing and fostering collaboration in theory, collaborative work practices based on BIM that support knowledge sharing across organisations and disciplines are slowly emerging (Neff et al., 2010). It is well-known that BIM can provide opportunities for collaboration and integration of multiple disciplines in a project, but the connections among project members seem not as close as expected (Liu et al., 2017). The nature of multidisciplinary construction projects is reflected in the differences in digital, cognitive and representational models generated from each discipline (Berente et al., 2010). Moreover, digital technology has difficulties in bridging these distinct disciplinary knowledge boundaries. IT used to increase collaboration will make organisational and cultural differences between participants explicit (Neff et al., 2010) since the tools reflect and amplify disciplinary representations due to knowledge boundaries. The discontinuity of virtual construction teams (organisational and geographic) has resulted in technology-based dependencies for these teams, for example, communicative technology (Mignone et al., 2016). However, Neff et al. (2010) propose that digital models from BIM cannot provide enough interpretative flexibility in communication. Therefore, relevant collaborative practice around BIM is needed to improve information and knowledge sharing among team members. The characteristics of organisation and projects have also been thought to influence BIM implementation and use (Hong et al., 2019).

2.6.3 Emerging digital collaboration and BIM technology in the Chinese AEC industry

In China, BIM is propelling digital transformation in the Architecture, Engineering, and Construction (AEC) industry, becoming a dominant trend in recent years (Ma et al., 2020). BIM technology has drawn attention from diverse stakeholders, including policymakers, investors, and practitioners. Successful projects have demonstrated the benefits of adopting BIM technology, yet a considerable number of projects have either failed or partially succeeded. This has led to a re-evaluation of how to effectively implement and utilise BIM technology for optimal performance. While most managers and employees within AEC organisations concur that incorporating BIM technology into their business and work practices is a crucial and necessary transformation, challenges, and barriers, particularly those related to coordination and communication within a BIM-involved project, often deter this digital adoption (Oesterreich & Teuteberg, 2019). BIM-related project collaboration remains a significant concern within the Chinese construction industry. Implementing an effective BIM execution plan in the AEC sector is vital for integrating BIM technology successfully into project-based collaboration across organisations (Zhou et al., 2019). This plan plays a critical role in both internal and external coordination processes (Jin et al., 2017). Hong et al. (2019) identified that the challenges and benefits of BIM adoption are primary considerations for Chinese AEC organisations seeking to integrate BIM technology into their projects. Moreover, they concluded that relevant BIM knowledge and technical support facilitate BIM implementation and adoption. This subsection will examine the social, cultural, economic, and political environmental factors in China that may influence digital collaboration, especially in the AEC industry.

Since the implementation of open-door policies in the late 1980s, China has aimed to develop its economy and transform various industries. The government has influenced industry transformation by issuing numerous policies and guidelines (Chan & Suen, 2005). Governmental and institutional innovation initiatives play a critical role in enhancing the motivation for BIM adoption and cultivating a BIM-use culture in the Chinese construction industry (Qin et al., 2020). The Chinese construction industry, under the government institute—Ministry of Housing and Urban-Rural Development of the People's Republic of China—published the guidance to guide and encourage BIM implementation in 2015. However, insufficient financial support and a lack of standardised BIM implementation guidelines are still regarded as the main challenges for organisations engaging in BIM transformation and adopting BIM technology in construction projects across the industry (Zhou et al., 2019).

Therefore, governmental policies and institutional rules shape the context of BIM implementation and use in the Chinese construction market. According to the guidelines published by the Chinese Ministry of Housing and Urban-Rural Development in "The 14th Five-Year Plan for Housing and Urban-Rural Construction Technology Development", the emphasis on BIM development in the AEC industry is clear. Politically, China's status as a civil law country emphasises written contracts and codified legislation, particularly in the Chinese construction industry, as these directly relate to risk and cost management in construction projects (Chan & Suen, 2005).

From an economic perspective, in Chinese construction market, financial support from the owner is seen as the primary factor influencing BIM implementation and use in projects (Wu et al., 2021; Zhang et al., 2020). The success of BIM adoption in a project is largely dependent on funding support from owners since senior management decision-making relies heavily on this financial backing (Wu et al., 2021). While designers' acceptance significantly influences the economic benefits of BIM adoption (Z. Ding et al., 2015), organisational sizes and types are also related to resource support, operational risk, and benefits received from BIM adoption (Y. Hong et al., 2019).

Culturally and politically, the traits of Confucianism, embedded in Chinese society and history, nurture respect and the pursuit of harmony in interactions among people. This ethos is also manifested in management and communication within and across organisations. Chan and Suen (2005) indicate that such cultural traits incline project members to increase interactions to synchronise their mutual expectations and objectives in collaboration. These interactive activities help them build trust and avoid disputes. This is also reflected in leadership's emphasis on people management rather than technology management, which lacks precise technological management and focuses more on envisioning, coupled with the insufficient BIM knowledge of organizational leaders (Li et al., 2017). Moreover, it is believed that government-led markets also influence the external environment of organizational digital transformation in China (Tiangang et al., 2018).

3 Theoretical foundations

Choosing a theoretical perspective is crucial for facilitating knowledge production, guiding inquiry, research design, and the interpretation of observed phenomena (Collins & Stockton, 2018). This study investigates the phenomenon of digital collaboration, which is complex since it involves crossing different boundaries and adopting digital technology in various contexts to facilitate the collaboration process. The guiding question of this study is: How does digital collaboration occur across knowledge boundaries in BIM-enabled construction projects? – it requires a theoretical lens to support the interpretation of digital collaboration ontologically and epistemologically. This section explains the study's theoretical foundations by applying plural theoretical perspectives from boundary theory and activity theory. First, section 3.1 discusses boundary theory as one theoretical lens of this study, discussing its theoretical origins, focus and implications for project-based digital collaboration. Then, section 3.2 presents activity theory as another lens following a similar structure. The practice view of boundary theory contributes to theorising the dynamic roles of digital technology in practice and the collaborative interaction among project team members, encompassing organisational and disciplinary knowledge. Activity theory provides a system view to theorise the digitalising context of AEC organisations and its interconnection within construction projects. The last section, 3.3, explicates the adoption of the synthesised ontological and epistemological assumptions derived from the practice and the system views and how these are reconciled to theorise digital technology-mediated, project-based, cross-boundary collaboration.

3.1 Boundary theory

Boundary or cross-boundary collaboration usually attracts much attention in social science research. The notion of boundary theory stems from an established conceptual toolkit used by some social scientists, e.g., Marx and Weber, to account for the dynamics between boundaries in social processes across a variety of social, cultural or structural levels (Lamont & Molnár, 2002). Recent applications of boundary theory have been made towards illuminating similarities and differences in organisational studies (Carlile, 2002; Langley et al., 2019; Levina & Vaast, 2005). Digital collaboration involves collaboration from disciplinary and organisational backgrounds, particularly in construction projects. These differences impact knowledge practice and collaborative processes, especially with digital technology use. Boundary theory, as a theoretical lens, provides the analytical language to express an ontological and epistemological view of the phenomenon. In particular, the practice view of boundary theory, provides a lens through which to observe the interaction dynamics and the role of digital technology with entangled knowledge practice in cross-boundary interaction. The following section introduces boundary theory derived from existing scholarly discussions of the practice view of boundary theory. It also suggests how this perspective can be applied in this study by focusing on digital collaboration in construction projects.

3.1.1 Practice view of boundary theory

Boundaries, rooted in organisational psychology and behaviour, concern the demarcation lines that differentiate between entities, practices, or social positions within and across organisations (Star & Griesemer, 1989). Scholars engage in ongoing debates regarding the nature of boundaries, exploring two primary epistemological streams: the materiality of boundaries and the interactivity of boundaries. Proponents of the materiality view see boundaries as existing within historical and institutional contexts, manifesting symbolically to delineate social groups (Pelizza, 2021). Conversely, the interactivity perspective argues that boundaries emerge from social interactions, reflecting and shaping social positions (Lunkka et al., 2022). Both streams highlight performed knowledge differences through boundary enactment, suggesting that various boundaries manifest among different groups' knowledge practices (Carlile, 2002, 2004). Through research on knowledge sharing among different groups who interact with each other across boundaries, the literature seems to agree on the boundaries' inherent instability and susceptibility to change (Leonardi et al., 2019). Therefore, the discourse has evolved from focusing on boundaries as barriers to a broader consideration of their practical implications and focusing on boundary dynamics in organisational and disciplinary collaboration.

Within this context, some scholars view boundaries as junctures facilitating collaboration through boundary objects (Quick & Feldman, 2014). Star and Griesemer proposed the concept of a boundary object (1989), which refers to an entity that can bridge interaction among different groups with its plastic structure to localise each group's needs and its flexibility to build a common identity across groups. In other words, the boundary object serves as a translation or interpretation tool for communication and understanding, facilitating interaction among individuals or group members, originating from various social worlds with different viewpoints and interests (Uppström & Lönn, 2017). Star and Griesemer (1989) identified the following four types of boundary objects:

- Repositories: This type of boundary object should be modular so that people from different social worlds can use it directly for their own purposes without considering the needs of others.
- Ideal types: These boundary objects are fairly vague and abstract, serving as a means of negotiation and communication across different social worlds (e.g., two-dimensional building models).
- Coincident boundaries: These objects are common across different sites over a large-scale geographic area, each with different perspectives. They have the same boundaries but varied internal content, allowing cooperating parties to share a common reference.
- Standardised forms: These serve as methods of common communication across different groups.

From the perspective of managing boundaries, Carlile defines a boundary object as 'a means of representing, learning about and transforming knowledge to resolve the consequences that exist at a given boundary' (2002, p. 442), according to Papadonikolaki et al. (2019), boundary objects can be physical or virtual, such as drawings, emails, or online transactions. Additionally, boundary objects carry explicit or implicit information. Boundary objects are regarded as the shared understanding that facilitates communication, information, and knowledge sharing (Azzouz & Papadonikolaki, 2020).

Some researchers examine the role of digital technology by interpreting it as a boundary object. Digital technology in work practice is typically considered as a boundary object for collaboration across different functional groups, where it is used for bridging knowledge (Carlile, 2004). It plays a role in bridging divisions and fostering the re-evaluation of boundaries' functions in organisational settings (Gal et al., 2008; Huvila, 2011; Levina & Vaast, 2005; Nicolini et al., 2012). For example, Forgues et al. (2009) delineates digital technologies as boundary objects that can be used in projects encompassing different generic types, such as repositories, standardised forms and methods, objects and models, and maps of boundaries. Taking this perspective, digital technology as a boundary object can influence collaborative activities within a construction project, facilitating information searching and delivery, providing adaptable and universal elements to teams, aiding balanced discussions and coordination, and clarifying the roles and responsibilities of project members (Phelps & Reddy, 2009). Digital artefacts may also sometimes transition into boundary objects in a construction project due to being designed to bridge knowledge boundaries between diverse professions (Berente et al., 2010). Based on existing research, effective knowledge boundary objects require the encapsulation of shared meanings and values from different professions (e.g., clinician and nurse) (Star, 2010; Levina & Vaast, 2005).

However, research also indicates that a knowledge boundary object is not stable between professionals but exhibits emerging dynamics in practice. Different boundary objects may be developed from artefacts produced in ongoing practice, for example (Levina & Vaast, 2005). These changes in boundary objects in use are associated with changes in organisational boundary practice and relationships (Gal et al., 2008; Barrett & Oborn, 2010). For example, the object can co-evolve with changing boundaries (Leonardi et al., 2019). These dynamics, arising from the instability of boundary objects, suggest that intertwined changes in digital artefacts' roles are emerging with the transformation from digital artefacts to boundary objects. These boundary objects are likely to act in different modes, influencing subsequent collaboration and even generating certain structural influences on boundaries (Nathues et al., 2024) Despite extensive research on digital technologies within the context of project-based collaboration in particular, the role of these technologies has been perceived differently within situated collaborative conditions, which suggests a practice view would be useful to theorise the role of digital technology in cross-boundary collaboration (Leonardi et al., 2019).

In addition to examining the nature and role of boundary objects, other scholars examine boundaries in interaction through the concept of **boundary work**. Boundary work is firstly defined as the purposeful effort, practice and consequence involving a change in boundaries (Gieryn, 1983). Lindberg (2017) frames boundaries as iteratively and recursively shaped in practice through boundary work, where this purposeful interaction across boundaries proactively shapes the boundaries (Langley et al., 2019). Lindberg’s (2017) study into boundary work identifies different types of practices which span, cross and change boundaries.

Boundary work is seen as important for managing collaboration, especially among multiple organisations and disciplines, since it influences collaborative relations and management performance (Langley et al., 2019). By identifying the varying and processual organising activities, Langley et al.'s (2019) clarification on the status quo of boundary work defines it as a purposeful individual and collective effort to influence the social, symbolic, material, or temporal boundaries, demarcations, and distinctions affecting groups, occupations, and organisations. They identified three types of boundary work: 1) Competitive boundary work, which involves mobilising boundaries to establish some kind of advantage over others; 2) Collaborative boundary work, which is concerned with aligning boundaries to enable collaboration; 3) Configurational boundary work, which involves redesigning boundaries to establish a pattern of working together among groups.

Recent studies examine the influence of boundary work on the material structure of boundaries in practice. For example, in their studies, Quick and Feldman (2014, p. 690) claim that boundary work should be oriented towards being open to the “ever-expanding sets of connections” to build flexible, porous, and tenuous boundaries to promote boundary resilience and adapt to changes in circumstances. Boundary work is viewed as intertwined with the visibility of boundaries through knowledge practice. Leonardi et al. (2019) state that boundaries are the enactments that occur in practice and define "Enactment" as a process of putting something that is believed to be right in practice, thus knowledge practice within the boundary is the enactment of what people know and do. Comeau-Vallée and Langley (2020) propose that "boundary work" refers to any effort to create, maintain, blunder, or shift boundaries. This also suggests that from a practical view, boundaries do not exist in an essentialist way but emerge from interactions supported by the efforts of institutions, organisations, and individuals (Abbott, 1995). These efforts are manifested as the " attempts of actors to create, shape, and disrupt boundaries” (Zietsma & Lawrence, 2010, p. 190). It reflects the activities that “establish and maintain boundaries and manage interactions across those boundaries” (Faraj & Yan, 2009, p. 604). These activities could be constructing, maintaining, buffering, reinforcing (Faraj & Yan, 2009), reconfiguring (Barrett et al., 2012), spanning (Levina & Vaast, 2005), and disrupting boundaries. These manifestations of boundary work provide a practice-based view of theorising how individuals and groups interact within and between their boundaries, which draws attention to the relation between their purposeful practice and the consequences of their boundary work.

3.1.2 Applying the practice view of boundary theory to digital collaboration

Digital technology-enabled boundary work involves the dynamic interaction between digital technology, collaborative practice, and boundary relations. For complex collaboration, such as project-based collaboration, this digital technology-enabled boundary work is embedded into various collaborative activities that span professional boundaries. For construction projects, collaborative interaction entails integrating building information and constructing building information models to share professional knowledge for problem-solving and decision-making within the project. Building models become important objects that bridge different professions to collaborate on different delivery dimensions, including building performance, building aesthetics and technical construction (Naar et al., 2016). This digital interaction within and across professions (e.g., architect, project manager) is dynamic owing to the long-term iterative modelling and recurrent shifts in needs or requirements among the different professions (e.g., architects, surveyors, bricklayers, plumbers).

Such model-based interaction in construction projects can be viewed from two angles: work practice within the professional boundaries (intra-professional boundary work) and work practice beyond the professional boundaries (inter-professional boundary work) (J. Wang et al., 2021). Within a profession, actors' work practices involve coordination and synchronisation, such as professionals developing models to meet other professionals' needs and requirements or policy stipulations. Intra-professional boundary interaction often involves explicit transformations (e.g., sorting records of on-site material usage) or tacit to explicit ones (e.g., architectural modelling). The variations, dependencies, and innovations can be revealed through how professions utilise relevant documents and protocols to accomplish tasks in their shared fields. Inter-professional boundary interaction predominantly involves tacit knowledge sharing (e.g., sharing project experiences) or explicit to tacit knowledge transformation (e.g., learning from discussions), where the variation, dependency, and novelty can be explained through conflict resolution and decision-making negotiations (Carlile, 2004).

This iterative modelling process reflects a recursive relationship between practice and boundary work (Lindberg et al., 2017). For example, BIM artefacts, produced as part of the model-based processes of construction projects, are created, utilised, or delivered between agents under contracts and related instructions (Papadonikolaki et al., 2019). Consequently, when actors use BIM tools to complete their professional work or achieve a goal, their know-how practice is influenced by the requirements and needs of other parties via policies and contracts. The know-how practice also represents the actors' process of transitioning their work from 'objects' (the artefacts that professionals work with) to 'ends' (the outcomes that validate the successful creation, measurement, and manipulation of the objects) (Carlile, 2002).

Previous studies have shed light on how the assignment of value and local relevance to digital artefacts can position them as boundary objects in general collaboration, aiding in effective knowledge boundary bridging (Hsu et al., 2014; Lindberg et al., 2017). Given the intertwined model construction process and model-enabled collaboration throughout a construction project's lifecycle, BIM plays important roles: for example, the BIM model as a boundary object and BIM-related software as a facilitator for actors to complete their tasks (Berente et al., 2010). Consequently, it is valuable to investigate how digital artefacts, as boundary objects, shape the dynamic interplay between practice and the boundaries.

3.2 Activity theory

This study uses activity theory as a theoretical lens, providing a system view of the investigation. Digital collaboration is an ongoing interactive process across the parties involved in its organising. This process implies that digital technology plays a role in collaborative activities and engages various organising entities to some extent. For digital collaboration across boundaries, different professionals enact practices knowledgeably derived from their given social, cultural, and historical contexts (Lave, 1988; Suchman, 1987). Activity theory is particularly relevant for examining technology-enabled activities to understand digitally related contexts by providing a systemic and critical view of how digital practices occur, especially regarding collaborative interactions within or across organisations. It offers valuable insights into the dynamics within organisational systems and interactions across organisational systems. This section explains the rationale for choosing activity theory in this study by introducing the origins of activity theory, its theoretical foundation underpinning the understanding of digital technology-mediated activity and system interactions, and its application to multi-organisational project-based digital collaboration.

3.2.1 System view of activity theory

Activity theory was initially developed to understand subjects' social actions on objects and evolved over three generational waves. The first generation of activity theory was introduced by Lev Vygotsky, who proposed that the focus of activity is based on the interplay between subjects (i.e. the actors), objects (i.e. the physical or virtual things acted on by actors) and tools (i.e. mediating mechanisms used by actors to achieve their objects). Engeström's work (1987) extends the understanding of the mediating process as part of the second generation. It proposes that there is considerable environmental influence on activities, as a result of norms/rules in departments/organisations, division of labour of subjects, and communities engaged in the activities. Engeström (2001) further extended activity theory, proposing a third generation of activity systems by introducing insights into interacting activity systems through shared objects and outcomes.

Activity theory emphasises hierarchical structures that describe the components of an **activity system**. Activity is defined as a form of "doing" directed to an object, and activities are distinguished according to their objects. Transforming the object into an outcome mobilises the activity. Mediators/tools can be anything used in the transformation process, including material and thinking tools (e.g. (Cole, 1998)). Tools are "social objects with specific modes of operation developed socially in the course of labour and are only possible because they correspond to the objectives of practical action (Verenikina, 2001). Collective use of tools integrates different collaborative activities and shifting roles of objects (Belmondo & Sargis-Roussel, 2015). Subjects are individuals or groups in organisations involved in the activity. An object can be material but less tangible (Nicolini et al., 2012). The differences in the use of objects have diverse influences on cross-boundary collaboration (Heldal, 2010). A community is formed by individuals or groups with shared general objects but may have distinct codes of practice among subjects. Division of labour describes the explicit and implicit organisation of the community as related to the transformation process of the object into the outcome. Rules are explicit and implicit norms, conventions, and social relations within a community. The outcome is the shared goal among organisations (Lu et al., 2018).

The system view of activity theory emphasises the internal relations of elements within the activity system and external relations with other systems. Several principles define the activity system’s scope (Engeström, 2001). Firstly, an activity system's artefact-mediated and object-oriented nature serves as the primary unit of analysis, interlinked with a network of activity systems. Secondly, the multiplicity of perspectives within an activity is revealed through the interplay between the community and the individual. Thirdly, the historicity of activity systems indicates that the activity and its objects are constructed locally and institutionally over a long time. The fourth principle is that contradictions within activity systems are recognised as drivers of change and development. When an activity system adopts new elements, such as new technology, it often raises contradictions within or between systems. Lastly, transformation may be accomplished in activity systems by rediscovering objectives and motivations within the system. In addition to the hierarchical structure of the activity system and its cultural-historical nature, the activity system has been seen as developmental over time (Spinuzzi, 2008).

With the development of activity theory, researchers have increasingly started to explore interactions between activity systems (Karanasios et al., 2021; Spinuzzi & Guile, 2019), especially the notion of an **activity network**, first forwarded by Engeström. Spinuzzi (2008) describe two forms of activity networks regarding the interactive relations of activity systems: 1) one is chained activity systems – activity systems are connected by the products from the elements of one activity system with the others; 2) the other one is overlapping activity systems – multiple activity systems converge on the same object through their combined work and influence each other. For complex multi-organisational project collaboration, the interaction of activity systems in the relational activity network lead to the featured landscape of polycontextuality (i.e., each activity system has its own internal rules, norms and expectations) and boundary crossing (i.e., the linked activity systems must collectively work in the developmental relations across system differences).

To date, scholars have applied activity theory to explore technology-related individual behaviour, such as Human-Computer Interaction (HCI) work (Nardi, 1995). Others have explored the interaction of digital technology with subjects and objects, or from a cultural-historical point of view, to examine technology-mediated processes (Allen et al., 2014; Karanasios, 2018). The accelerated pace of digitalisation and the role of digital technology within activity systems has drawn researchers' recent attention towards the use of digital technology across different activity systems (Karanasios et al., 2021), such as different departments or organisations (Pettersson, 2021). Thus, a more flexible application of activity theory has become the key theoretical focus for studying the intertwined relations between digital technology-mediated practice and systems.

3.2.2 Applying the system view of activity theory to the AEC industry's multi-organisational construction projects

For construction project collaboration, building models orient subjects' activity within and between systems. The model tools mediate the model co-creation process within and between organisations through collaborative activities. The system view of activity theory can facilitate the understanding of complex structures and dynamic organisational relations embedded in construction project collaborative activities. Collaborative activity is understood as historically embedded into conventional collaborative structures within activity systems and in the relationships between activity systems (Spinuzzi, 2008). A new collaborative practice might emerge from the development of activity systems and activity networks to formulate temporary and new relationships. AEC organisations and project networks constitute the elements of organising collaborative activities in a construction project collaboration. Different AEC organisations constitute the structural context of model development based on organisational roles and responsibilities, e.g. designing initial architectures and structures, integrating resources, and scheduling elements into the model. The entire building modelling process is segmented into an organisational modelling process in the different stages of a construction project. The project network constitutes the joint relations and structure for these organisations to integrate different facets of model building into holistic and comprehensive building information and construction project deliverables. Such processes and structures are embedded in the organisational collaboration and interactivity of organisational activity systems. For construction project collaboration, AEC organisational activity systems constitute the ultimate project outcome within an activity network according to splicing objects (e.g., different models) of each activity system together.

Such divergence marks a fundamental debate among theorists of activity theory in the IS field. It reveals the challenge of activity theory in the current digital age regarding the transformation of objects within such a complex collaborative context (Engeström & Sannino, 2021). Digital technology increases the dynamics of intra-and inter-organisational collaboration in construction projects. Organisational cultural influence and agential activity are believed to be inseparable (Allen et al., 2013), which means that collaborative activities are also embedded in the interactions among different activity systems. Such interactivity within and between the activity systems contains individual and collective interactions. A project-based collaboration requires interactions among different activity systems within the activity network based on the different teams and project goals. A project requires spatial and temporal considerations for collaboration, and implementing digital technology means implementing collaborative patterns among the different project teams.

In addition, digital technology plays different roles in construction project collaboration because it facilitates the model-development process throughout different project lifecycle stages. This process involves different professionals' objects and is intertwined with how the intermediary models created by different professionals can interact with each other and finally co-create ultimate objects (Miettinen & Paavola, 2018). The diverse roles of digital technology in construction project collaborations make the internal structure of organisational systems and external relations with other activity systems more dynamic and processual. On the one hand, digital technology can be a tool mediating object achievement, reflecting the different practices for establishing shared objectives (Miettinen & Paavola, 2018). On the other hand, digital artefacts themselves may be objects of activity produced from the collaborative practice of subjects.

3.3 Reconciling the practice and the system view

Digital collaboration across knowledge boundaries necessitates interactions across different digital technology-mediated practices. As such, this research synthesises digital technology-mediated collaboration, i.e., the changing role of digital technology in cross-boundary collaboration, the digital technology-mediated collaborative practice, and the complex and dynamic context of project-based collaboration. This section, therefore, discusses the ontological and epistemological assumptions of the practice view of boundary theory and the system view of activity theory, with the aim of synthesising and reconciling them. This is because it is posited that such a synthesised view helps explore the interaction of different digital technology-mediated practices and reveals the complexity and dynamics of collaborative interaction in a project context. The following sub-sections show the reconciliation of activity theory and boundary theory regarding their ontological and epistemological assumptions, the critical relevant notions in understanding collaborative activity, the role of digital technology, and the complex and dynamic context of collaboration.

3.3.1 Plural perspectives for examining digital technology-mediated, cross-boundary collaboration

The practice view from boundary theory and system view from activity theory has been plurally adopted to provide this study's ontological and epistemological assumptions. This application derives from the nature of digital technology-mediated collaboration - a practice-oriented, technologically mediated boundary issue. Such collaboration, particularly within project-based work, involves different professionals from multiple AEC organisations. Besides, in digital technology-mediated collaboration, the function of digital technology transcends mere task completion, such as using CAD to construct models. It extends to mediating human practices in knowledge-sharing, communication, and decision-making. From ontological and epistemological standpoints, plural perspectives in the same research project can lead to diverse possibilities for study (Collins & Stockton, 2018; Jones, 2019; Koro-Ljungberg, 2004) to understand the intertwined phenomena of digital technology-enabled contextual complexity and digital technology-mediated collaborative practice.

The practice-focused and system-focused perspectives are essential for observing the complexity and dynamism of interaction reflected in the different organisational contexts and project-networked collaborative relations. In digital technology-enabled interactions, professionals' digital practices are usually integrated within or by the same suite of digital technology (e.g., CAD) but can vary according to their distinct organisations and disciplines (e.g., Revit, AutoCAD), notably among AEC professionals. This variety is due to the different roles each profession has in terms of the project and to achieve collaborative goals collectively. For example, contractors might employ various modelling tools to translate model data into a format that facilitates time and cost-effective construction planning. Consequently, professionals' technology-mediated practices are often shaped by the cultural and structural implementation of digital technology within their organisations. Regarding digital technology-engaged collaboration across boundaries in construction projects, understanding and explaining boundary issues necessitates exploring organisation-based processes since the performed knowledge boundaries are embedded into individual and collective practices impacted by digital technology within an organisational context. This complexity requires a system view to understand the meta-theoretical context. In other words, the system view provides a structural proposition on what causes different individual/collective knowledge practices in digital technology-enabled collaboration. This study can investigate different digital technology-mediated patterns by revealing their strategic implementation and evolution in practice and interaction.

This study explores how digital collaboration occurs across knowledge boundaries in BIM-enabled construction projects. It addresses the multifaceted assumptions inherent in digital technology-enabled collaboration, particularly across organisational boundaries within industries transformed by new technologies. In the AEC industry, digital collaborations often occur within construction projects, such as building model co-creation. Integrating digital technology into a construction project requires professionals from different organisations to adapt their digital practices for collaboration, as these organisations strategically deploy technology to achieve their goals in the AEC market. The project collaboration patterns and practices evolve in response to intertwined organisational digital strategies and professional engagements. Such intertwining is inherent in qualitative research (Koro-Ljungberg, 2004), and continuous changes in the digital-social world, driven by technology, demanding multiple theoretical propositions to interpret the dynamics of digitally mediated phenomena (Mousavi et al., 2021).

For example, a digital model can visualise building information, and designers can use this to help clients understand how their requirements will be met in practice and what the final design may look like. Here, the digital model, an element of the modelling technology, will influence the outcome of designer-client collaboration by shaping communication practices through interpretive capacity. In the AEC industry, such scenarios often involve multiple stakeholders (e.g., fitters, contractors, engineers, architects, plumbers) who use or are affected by the same digital object (the digital model). For instance, contractors might use a digital model for construction plans, adjusting building details to fit on-site construction practices and material availability. When collaboration is orchestrated through a digital technology-enabled process, such as modelling, technology's role encompasses linking stakeholders together by mediating their collaborative practices via the co-creation of digital objects. Therefore, the interactions of stakeholders' or professionals' technology-mediated practices reflect the complexity and dynamism of boundary issues in cross-boundary collaboration. The integrated theoretical framework stresses the intersections of different focal phenomena, synthesising theoretical perspectives to form a novel integrative view in this research and connecting the fragmented topic into a more coherent whole (Jaakkola, 2020). Thus, a plural theoretical perspective can help understand practice-based, technology-mediated dynamic phenomena and explain in depth the system-oriented influences and forces on the interaction of cross-boundary practice.

3.3.2 Objective of Collaborative Activity

One analytical focus of this study is sub-question 1: How are collaborative activities across knowledge boundaries organised in a construction project? It is necessary to explore the organisation of collaborative activity among inter-professional, intra-organisational and inter-organisational stakeholders. Collaborative activities are constituted of professional practice and interactions among professionals. When digital technologies are integrated into the construction project, knowledge exchange among project members is promoted (Gal et al., 2008; Papadonikolaki et al., 2019). In construction projects, modelling processes are an integral part of the project process, facilitating collaboration among project members to deliver the project outcomes (Aibinu & Papadonikolaki, 2020; Cao, Li, Wang, & Huang, 2017). Professionals' boundary work has distinct 'inscribed' social contexts within digitalising organisations (Allen et al., 2013). Exploring professional knowledge practice, inter-professional technology-mediated boundary work and organisational technological implementation activities can help understand collaborative activities' purpose and direction. The plural perspective can enrich the understanding of collaborative activity by interpreting the boundary work and organising activities among actors with different knowledge practices who proactively shape boundaries in interaction through boundary work (Langley et al., 2019).

Ontologically, collaborative activities across boundaries are based on two interdependent objectives: professionals' objectives for the project's outcome and organisations' objectives for digital technology implementation. Professionals aim to act on their motivation and achieve the project objectives to deliver the outcomes. Within a project, the purpose of professional boundary work may coincide with various organisational and technological objects. For example, for a design organisation, the technological objective could be to employ BIM technology to create each disciplinary BIM model. For a contractor organisation, the technological objective might be to produce a BIM-informed construction plan and BIM collision detection report. Collaborative activities reflect the purposes of the professionals' actions and the interaction of their actions across knowledge boundaries. Within the ever-evolving context of digitalisation, various organisations adopt digital technology to enhance collaboration across knowledge boundaries. These interactions may be mediated by their perceived technological affordances and capabilities. Hence, the epistemological assumptions from activity theory can help to unpack the social contexts, structures, and cultures of the entire digital technology-focused organisation's digital technology implementation. These objects reflect each organisation's specific purposes and motivations within the collaborative activity. However, conflicts and tensions may arise within collaborative activities due to diverse organisational digitisation objectives, and these differences can exert a transformative influence within the project activities, thus prompting organisations to make adjustments (Karanasios & Allen, 2014).

3.3.3 Role of digital technology in practice

Another analytical focus of this study is digital technology's role in digital collaboration. The implementation and use of digital technology aim to facilitate cross-boundary collaboration in projects. In the collaboration process, professionals may use digital technology as a boundary object in their practice. As discussed in 3.1, the "object" is viewed as having directional influences from actions' agency and will also be perceived by receivers. Ontologically, the role of digital technology as a boundary object exists in practice, especially in collaborative practice between professionals.

Within construction projects, digital technology is a dynamic integration of modelling processes and technology (Papadonikolaki et al., 2019). For example, BIM technology serves multiple functions in a construction project, as evidenced by the BIM artefacts produced during the project's lifecycle, such as model integration and simulation. BIM artefacts can include 3D building models, procedural documents such as Gantt charts, specialised sessions, and more. Additionally, the use of BIM tools in the creation, use, and maintenance of BIM artefacts is throughout the whole lifecycle of a construction project. The material aspects of digital technology are perceived as useful and then enacted in collaborative practices. Through material enactments of the objects existing in interactive activity, the role of digital technology is objectified in practice. The perceived material affordance of digital technology may be developed in the ongoing interaction process (Barrett & Oborn, 2010; Leonardi et al., 2019). Therefore, ontologically, a technological object can be recognised as the "object in activity" in collaborative practice.

Epistemologically, the role of digital technology is part of the orchestration of professional collaborative purposes and project organising, inscribed in the organisational culture and institutional cognitions to mediate technology-enabled practice among professionals. Miettinen and Paavola (2018) emphasise the "construction of an object" and support the evolving nature of the object in practice, focusing on the "product of activity". In this sense, the object of activity is the result of the interplay of digitalising organisations in projects. Within digitalising organisations, professionals' perceptions of digital technology's role in their practice are influenced by implementing organisational technology. For example, in the project model co-creation process, understanding the role of digital technology may be related to the engagement of various stakeholders in the model-oriented interaction process. Modelling technology facilitates the development of the virtual representation of buildings (Paavola & Miettinen, 2019), which provides a means of working collaboratively. The digital model can be recognised as an "intermediate object" that is constantly amended in the design process and facilitates building information sense-making and decision-making in the construction process (Miettinen & Paavola, 2018). In this sense, the digital modelling technology bridges the outputs of individual work and mediates the members' construction simulation during project collaboration. With the evolving nature of the digital model within the construction collaboration process and in-depth collaborative activities happening within the construction phase, the model might join different phases of the construction project together, and the changing collaborative pattern is not only happening within the multidisciplinary design process but also across different project phases, such as the construction phase.

On the other hand, organisations that implement digital technology for cross-boundary collaboration may relate to the organisational strategical influence of digital technologies on intertwined social relations in projects, such as professional roles and identities (Comeau-Vallée & Langley, 2020). Regarding project collaboration, the different social positions could be influenced by organisational strategies (Comeau-Vallée & Langley, 2020). Emphasising the social context at various levels offers insights into how collaborative activities emerge from the interconnected relationship actors share with their tools. Regarding focusing on BIM-enabled cross-boundary collaboration within the project context, the mediating effect of digital artefacts is also considerable for people with different roles in using BIM technology in their collaborative practice, especially for how interconnected knowledge practices influence each other within the collaborative interaction. This study applies ontological and epistemological assumptions of objects to theorise the role of digital technology in dynamic interaction between professionals and organisations.

3.3.4 Context of digital collaboration

Another theoretical and analytical focus of this study is the status of boundaries in digital collaboration. The synthesised perspective contextualises digital collaboration by revealing the social context of activity and material aspects of the boundary. However, studies have accentuated the need to meld this practice-based perspective with multiple approaches (Nicolini et al., 2012; Orlikowski, 2016) since digital collaboration is a complex interplay between the different actors' actions and the inherent properties of digital technologies. It implies the potential interplay between organisations transitioning into digital units, particularly regarding different digital technology implementations. This captures the essence of digitalised, collective, collaborative practices. The continuous interactions amongst these organisations through professionals' collaborative activities may profoundly influence each organisation.

Ontologically, the context of collaborative activities can be seen as the manifestation of boundary status in interactive practice. This interactive practice is based on different individuals and groups communicating, negotiating, and integrating tools with different rules and norms. This implies not an entirely dynamic or stable context of digital collaboration but hierarchical conditions from a relatively dynamic to stable structure since the project-oriented, model-oriented interaction involves different layers of interactions and technological intervention. Actual collaboration practices among professionals can influence the wider organisational historical conditions in the construction project, which constitutes a network. For example, BIM technology innovation initiatives will facilitate organisations' digitisation process. These digital innovation endeavours include integrating BIM tools into the workflow, e.g., BIM design software, BIM viewer software, and software that integrates the building data to produce BIM artefacts, e.g., 3D models, mechanical, electrical, plumbing (MEP) clash detection reports. This technology-enabled collaboration can change the division of labour among organisations.

Epistemologically, digitalised organisations encapsulate the continuous implementation and usage of digital technology within organisations. When implementing digital technology in a project, differences are seen as immediate fluctuations that join differences among different cognitions, interests, purposes, and norms together and towards a relative harmony to push the project goals forward over time since the project has the ultimate goal -- project delivery in the cost-/time-constrained context. This context accommodates the changes in the implemented and used digital technology. Digital technology enables project members to convey project information in a manner that facilitates effective collaboration among various organisations and disciplines. Concerning project-based collaboration, the interaction of digitalised organisations fosters project-based collaborative relations. For example, these interactions could involve project coordination meetings for technology-related requirements and delivering the periodic deliverables stipulated in the contract.

Moreover, digital collaboration across knowledge boundaries is seen as intricate due to the evolving influence of digital technology in collaboration, a process without a straightforward trajectory. The collaborative practice's dynamic nature is inherent, likely influencing structural configurations. From a practice perspective, BIM can transform into a boundary object during cross-boundary activities. From a system perspective, BIM is seen as a digitising catalyst within AEC organisations, fostering project-based collaboration. Digital technology, when acting as a boundary object, can fortify the system's deep structure via boundary work (Thompson et al., 2019). Thus, the amalgamated theoretical perspectives illuminate the dynamic interplay between digitally enabled practices and evolving digitised organisational systems.

3.4 Summary

Stemming from existing studies on digital collaboration, knowledge boundaries, construction project-related digital collaboration, and BIM technology development discussed in earlier sections, the research phenomenon necessitates an ontological understanding encompassing two interrelated aspects. Firstly, it examines the management of knowledge boundaries in collaboration. Secondly, it delves into the emerging changes resulting from implementing and using digital technology within digital collaboration. This synthesis, informed by the literature review, aspires to deepen the comprehension of the role of BIM technology for individual users in their daily practice, the shifts it incites in organisational activity systems, and its transformative impact on project management through the rise of BIM-enabled collaboration. By melding the practice view from boundary theory with the system view from activity theory, the synthesised theoretical framework can enhance the understanding of BIM technology as it emerges, is implemented, and is used among individuals, organisations, and projects. Moreover, it elucidates the BIM-enabled collaborative activities required to manage boundaries across various knowledge practices.

4 Methodology Chapter

4.1 Introduction

This chapter sets out the research philosophy, research methodology and research design of the proposed study. This research will adopt constructivism as the ontological assumption and research design within this research. This chapter is divided into six main sections. The first section is the introduction. The second section discusses the different research philosophies, the philosophical stance held in this study, and the research approach and strategy. Subsequently, the third section comprises the research design and implementation, including qualitative, quantitative, and mixed-method paradigms. The fourth section discusses the ethical of this study. The fifth section contains how to ensure the research quality of this study and the researcher's reflection on this study. The last section gives a summary for this study.

4.2 Research Philosophy, Approach, Strategy

4.2.1 Research philosophical stances

Research philosophy is "a system of beliefs and assumptions about the development of knowledge" (Saunders et al., 2016, p. 124). It provides the foundation for research to be conducted in particular scientific specialisms (Benton & Craib, 2010). The philosophical issues of research include the ontological, epistemological, and methodological decisions. The researcher's view and assumptions about the nature of the social world and how knowledge should be produced will impact the research process (Bryman, 2012). In general, these are the two main systems for researchers to consider for their research, including ontology and epistemology.

4.2.1.1 Ontological assumption

Ontology is the way to answer "what kinds of things are there in the world" (Benton & Craib, 2010, p. 4). Orlikowski and Baroudi (Orlikowski & Baroudi, 1991, p. 8) described ontology as, "whether the social and physical world are objective and exist independently of humans, or subjective and exist only through human action". In other words, ontology is to consider the nature of existence. The social world can be viewed as exerting influence(s) on the behaviour of actors or as a constant process that the actors formulate and assess (Bryman, 2012). Therefore, ontology can shape the way that the researcher sees and studies the objects of the research (Saunders et al., 2016). Generally, there are two mainstream ontological positions: objectivism; and constructivism.

Objectivism implies that "social phenomena and their meaning have an existence that is independent of social actors" (Bryman, 2012, p. 33). In other words, objectivists think that the objects in the world and even the world itself originally and objectively exist even though human beings do not perceive it. Therefore, the social world is made up of relatively unchanging objects and is uninfluenced by the interpretation and experiences of social actors (Saunders et al., 2016). In social science, phenomena are generally related to organisational, cultural, and social 'things'. Based on the objective assumption, actors learn and apply rules and regulations existent in the organisational, cultural, and social environment (Bryman, 2012).

Constructivism is defined as "constructivism as a view in which an individual mind constructs reality but within a systematic relationship to the external world" (Talja et al., 2005, p. 81). Social interactions are a continual process; therefore, the phenomenon and realities are in a constant state of revision (Saunders et al., 2016). Constructivism holds the ontological assumption that human being is constructed, and is thus a social product based on the interrelation of social context and person (Packer & Goicoechea, 2000).

This research adopts constructivism as its ontological assumption. The objective is to study digital collaboration across knowledge boundaries within project teams. Different professionals hold diverse views on using BIM for collaboration due to their diverse knowledge backgrounds and roles in construction project. However, the nature of these differences is often not discerned by one another in practice, which cause different knowledge boundaries (Carlile, 2002). The challenges of digital collaboration can only be perceived through their interaction. From reviewing previous literature (Neff et al., 2010) regarding the use of digital technology in team-based collaboration, it has been demonstrated that actors have different social worlds that result in diverse understandings through which they shape the form of digital collaboration that they are involved in at any point in time. It might be difficult and challenging for communicating across boundaries. Objectivism holds the assumption that reality can be identified and remains constant, which is not suitable as the ontological basis of this research.

In contrast, constructivism is regarded as an appropriate ontological stance for studying how actors interact with others through BIM technology, which constructs the BIM collaboration process. The researcher explores the social reality by observing the interaction with team members by adopting the constructivist stance. The assumption inherent in constructivism provides the ontological foundation for "a deeper understanding of the practices of professional groups and scientific domains, and the tacit knowledge underlying these practices" (Talja et al., 2005, p. 88). In BIM collaboration, knowledge is shared through the collaborative practice across different disciplinary communities, and the team members from different disciplines have different interactions with BIM, which shapes the different nature of the actors. For example, such as juxtapose fitters and designers generally need to communicate the design of installing feasibility regarding the pipework. Therefore, this ontological assumption guides the researcher to establish an understanding based on the interaction between actors and social context.

4.2.1.2 Epistemological assumption

According to Bryman (2012, p. 27), "an epistemological issue concerns the question of what is (or should be) regarded as acceptable knowledge in a discipline". Epistemology determines how to understand and obtain knowledge from the world. Different epistemological assumptions influence the choice of research methods that, in turn, affects the subsequent research findings (Saunders et al., 2016). There are two main epistemological stances: positivism; and interpretivism (Bryman, 2012).

Positivists advocate applying research methods from the natural sciences to study social phenomena (Bryman, 2012). In other words, positivists believe that knowledge is existent in objects and that observable and measurable facts can be obtained through the scientific method (Saunders et al., 2016). Positivists believe that knowledge exists in social reality, and research needs to discover this knowledge through study. In a positivist's research, it is likely they will use existing theory to develop or test a theory or hypothesis (Saunders et al., 2016).

Compared with positivism, interpretivism holds the opposite philosophical stance. Interpretivism claims that social sciences differ from the natural sciences since the thinking of each human being and their social world are different. Therefore, researchers need to 'understand' the complexity and difference among actors, rather than explaining the phenomena based on a universal 'law' or 'principle' (Saunders et al., 2016). This consideration of interpretivism is derived from hermeneutics and phenomenology, which emphasises the understanding of human behaviour as one produced by how people interpret the world (Bryman, 2012). For social scientists, they "need to get access to people's 'common-sense thinking' and hence to interpret their actions and their social world from their point of view" (Bryman, 2016, p. 27).

This research employs an interpretivist epistemological consideration. In social sciences, when a researcher adopts interpretivism, they are concerned with the interpretation of human action and "seek to understand the subjective reality of those that they study to be able to make sense of and understand their motives, actions and intentions in a way that is meaningful" (Saunders et al., 2016, p. 131). This research needs to understand the interpretation of the collaborative practices among team members from different disciplines. A deep understanding of the actors' differences in knowledge is necessary for this research. Through interpreting the interactive behaviours of team members from different disciplines in the BIM collaboration, this study's research findings concerning the influence of BIM has been established.

4.2.2 Research approaches to theory development

It is necessary to consider which type of approach to the reasoning will be adopted when a researcher has selected the research aims and starts to obtain research findings by means of relevant theories (Saunders et al., 2016). The role of theory is distinctly varied in research, which can be applied in different positions in the whole research (Creswell, 2018). Creswell and others discussed the role of theory based on where it exerts influence to guide the research progression: 1) 'up-front explanation' refers to theory that provides a broad explanation before investigation; 2) 'end point' refers to theory that will be generalised as a model from data and observation; and 3) 'transformative-advocacy lens' refers to theory that provides an overall orienting lens or call for action(s) and change in research process.

Essentially, different research approaches are considered as the diverse relationship between theory and research. There are two predominant research approaches to the generation of knowledge and theory development, namely the deductive approach and the inductive approach. The deductive approach is understood as how theory guides research, whereas the inductive approach is concerned with how theory is primarily an outcome of the research

(Bryman, 2012). The two approaches to reasoning have a different logical flow for research design. Of note, the abductive approach has increasingly been discussed in recent years, which reflects a more complicated and back-and-forth relationship between theory and research (Saunders et al., 2019). The three approaches are as follows:

- **Deductive approach**: The deductive approach starts with a theory developed from the literature, which researchers then use as a research strategy to test the theory; in other words, the reasoning process travels from the general to the specific (Bryman, 2012; Saunders et al., 2019). Deductive research is suitable when researchers have a rich theoretical framework built from many pieces of literature (Creswell, 1994).
- **Inductive approach:** Adopting a reverse logical flow to the deductive approach, the inductive approach builds a theory or conceptual framework through data collection to explore a phenomenon; the reasoning process is from the specific to the general (Saunders et al., 2016). This does not mean that there is no theoretical underpinning for the research process in inductive research; rather, theory is often used to offer the background for an investigation (Bryman, 2012).
- **Abductive approach**: The abductive approach starts with the observation of 'supervising fact(s)', and the researcher may start based on a plausible theory but needs to move forward the research process to test these plausible theories. Deductive and inductive logics might be complementary for the abduction process (Saunders et al., 2019).

4.2.2.1 Choosing an approach to this study

An appropriate research approach to theory development enables the researcher to make informed decisions about the research strategies and design, and the choice of research approaches depends on the research philosophy, the emphasis of the research, and the nature of the research topic (Saunders et al., 2019). This research conducts an inductive studyexploring the influence of BIM-related collaboration practice on knowledge sharing at different knowledge boundaries. As discussed in 2.5 theoretical frameworks, two main theories can support the researcher to investigate BIM collaboration and knowledge sharing at different boundaries in the construction project. From the boundary object theory, IT artefacts are as the core subject of information technology (Orlikowski & Iacono, 2001), the BIM collaboration practice involves the BIM-related artefacts used in the collaboration process, such as the digital models. During the process of BIM collaborative practice, it is necessary to observe and analyse in the investigation that how BIM-related artefacts can be used as the boundary object to have a facilitator or hinder effect on the knowledge practice at different knowledge boundaries. In this inductive research, the boundary object theory fits nicely with this research aims and questions. This research aims to find out the influence of BIM collaboration on knowledge sharing across boundaries. The boundary object theory provides a background to view the data and generate ideas from the analysis of whether the BIM-enabled collaboration creates certain boundary objects for knowledge sharing across knowledge boundaries, which then generate from specific data to base on the inductive path.

4.2.3 Research Strategy

The research strategy is described as "a general orientation to the conduct of social research" (Bryman, 2012, p. 35). Pertaining to methodological considerations and the time horizon of the research process (Saunders, 2019), research strategies are typically classified into two main types: qualitative; and quantitative research (Bryman, 2012; Creswell, 2009). While these two strategies are not mutually exclusive; most studies tend to lean more towards either the qualitative or quantitative aspect (Creswell, 2009). Yet, in recent years, the mixed-methods research strategy, which incorporates elements of both qualitative and quantitative strategies, has been gaining in popularity. In any case, the choice of an appropriate research strategy should be guided by the research questions and objectives. It should also be consistent with the chosen research philosophy and research design (Saunders et al., 2019).

4.2.3.1 Quantitative Strategy

Quantitative research is often related to numeric data collection and analysis (Saunders et al., 2016). Based on structured data, from the research philosophical perspective, a quantitative strategy is mostly associated with the deductive approach, ontological objectivism and epistemological positivism for testing a theory (Bryman, 2012). However, if the data are used to build a theory, it may also be associated with an inductive approach (Saunders et al., 2016). For quantitative research, several methods are commonly used, including laboratory experiments and the survey method, even though these research methods may also be employed in qualitative strategies:

- **Experiments**: Experiments are derived from the natural sciences, and currently some researchers apply this method in sociology. In social sciences research, experiments are typically used to test the impact of particular factors on the results, either against, or to validate non-experimental research (Bryman, 2012; Creswell, 2009).
- **Surveys**: In survey research, a body of quantitative or quantifiable data is collected from a population to provide "a numeric description of trends, attitudes, or opinions of a population" (Creswell, 2009, p. 145). Survey research employs a cross-sectional research design or longitudinal design, which is designed to establish the detection of the variables in a population (Bryman, 2012).

4.2.3.2 Qualitative strategy

In simple terms, qualitative research emphasises words instead of structured numeric data (Bryman, 2012). Compared with quantitative research, a qualitative strategy is broadly associated with ontological constructivism and epistemological interpretivism (Bryman, 2012; Saunders, 2009). On occasion, researchers have not limited these features based on their research aims. There are five main types of qualitative methodology (qualitative inquiry) or paradigms in qualitative research, namely ethnography, action research, grounded theory, case study, narrative, and phenomenology (Creswell & Poth, 2016; Saunders et al., 2019). These are discussed as follows:

- **Ethnography** is a strategy in which researchers immerse themselves into the cultural and social lives of the people being studied, and the investigation lasts for a prolonged time period to collect data (Creswell, 2009). For example, it might require several years for a construction project. In addition, ethnography research requires the researcher(s) to immerse themselves into the social life of those being studied and interact with the participants (Bryman, 2012).
- **Action research** is used to develop solutions and interventions to real-world problems through participating and collaborating in the research project with participants (Saunders, 2019). Coghlan and Brannick (2005) claim that action research is about 'research in action'. As the purpose of action research is to identify a problem and working towards finding a solution to the problem together with the participating organisation and then deploying the solution. Addressing a practical problem is not the objectives of this research, which means this strategy is not fit for this study.

- **Grounded theory method** is applied to generate a theory or an explanation from a process, an action or an interaction from a large number of participants and analyse this information through a particular view. Grounded theory can also be used as a research design and mode of collecting and analysing data (Creswell & Poth, 2016). Generally, grounded theory research involves collecting data in multiple stages alongside refining the reflections to build a theory grounded on the data (Creswell, 2009).
- **Case study** can be regarded as a methodology and a method in social science research (Creswell, 2009; Yin, 2009). As a methodology, the case study is a strategy in which researchers investigate in-depth an event, programme, activity, process or individual by collecting detailed and comprehensive data with various methods (Creswell, 2009). When doing a case study, researchers can have a thorough understanding and comprehensive insight into the case. Consequently, the researcher builds an in-depth insight into the complexity and nature of the phenomenon under study within the real-life context (Yin, 2009). The case study can be a single community, organisation, person, or event (Bryman, 2012). Alternatively, sometimes, a multi-case study can be used in research, in particular for a comparison study (Bryman, 2012).
- **Narrative research** is a strategy to "explore the life of an individual through telling stories of individual experience" (Creswell & Poth, 2016, p. 110). This type of research focuses on studying one or two individuals and gathering data collected from their particular experiences.
- **Phenomenology** is a strategy to "describe the common meaning for several individuals of their lived experience of a concept or phenomenon" (Creswell & Poth, 2016, p. 121). The human experience is regarded as a phenomenon; this strategy is used to develop a composite description of the essence of the experience (Creswell & Poth, 2016).

4.2.3.3 Mixed-method strategy

The mixed-method strategy combines both qualitative and quantitative elements (Saunders et al., 2016). By combining the strengths of both strategies this approach can result in a study that is greater than sampling, collecting or analysing data with either qualitative or quantitative methods (Creswell, 2009). However, some researchers propose arguments against the combination of quantitative and qualitative strategies (Bryman, 2012; Smith, 1983). Two points should be considered when using a mixed-method strategy in research: the consistency between the research methods and the epistemological commitments; and the incompatibility of the two research strategies (Bryman, 2012).

4.2.3.4 Rationale of selection of qualitative case study as the research strategy

This research uses a qualitative case study as the research strategy. Qualitative research relies on human perception and understanding and emphasises personal experience, while quantitative research relies heavily on linear attributes and statistical analysis (Stake, 2010). Yin (2018) mentioned five important components to take into account for choosing the case study as the research design: research questions; propositions; cases; logic linking between data and propositions; and criteria for interpreting the findings. This research explores people's experience of BIM collaboration across boundaries, which relies on gaining understanding from their insights and views in the current Architecture, Engineering and Construction (AEC) context. In addition, the research question of this research is a 'how' question adopted to explore people's experiences of BIM collaboration and knowledge sharing across boundaries in order to generate an explanation of how BIM collaboration influences knowledge sharing at different boundaries. A 'how' question and the focus on examining contemporary events which are more explanatory fits with the case study strategy (Yin, 2009). The case study help the researcher drill down and look in-depth within a construction project to obtain evidence from every situation of the phenomena (Thomas, 2011). This digital collaboration is complex and related to the multiple activities inherent in a construction project; notably, BIM collaborative practice and knowledge sharing occur throughout the whole project lifecycle. Therefore, it is necessary here to carry out a multidimensional and in-depth investigation to understand the nature of the behaviour. Therefore, a case study has been applied to study this phenomenon.

Based on the subject of the research, the purpose of a case study is typically categorised into descriptive, explanatory, and exploratory research (Yin, 1994). The research is to answer, 'how does BIM affect (enable/hinder) knowledge sharing among construction project team members at different knowledge boundaries?', which involves the interaction among team members from different disciplines and working on the same project. Put succinctly, it requires the researcher to observe the interaction in a construction project team. There are a few specific frameworks to answer this question. The researcher explored BIM collaboration in the construction project, and then drill down into the situation to provide an understanding of the influence of BIM on knowledge sharing across different knowledge boundaries. Therefore, this research is primarily exploratory in nature.

As Bryman (2012) mentioned, a case can be an individual, an organisation, or an event. The single-case in this research is contextualised in a single BIM-enabled construction project. As a construction project generally involves multiple stakeholders, the case in this research is related to different organisations. A case study consists of two halves, namely the subject of the case study and the analytical frame (or object) (Thomas, 2011). The subject of a case study is the 'case' or 'practical, historical unity'. The analytical frame refers to the object of the case study or the 'theoretical, scientific basis'(Thomas, 2011). In this research, the unit or 'case' refers to the lifecycle of a BIM-enabled construction project, and the 'analytical frame' or the observed social phenomenon is the project-based digital collaboration process.

Thomas (2011) noted three types of criteria for select cases: a key case, an outlier case, and a local knowledge case. A key case means to choose a typical or class case of a situation, which is usually an available situation for the researcher, one that can be used as an exemplary case for others. An outlier case means something different from the norm or unique, which motivates the researcher to study the 'extreme' situation (Bryman, 2012). A local knowledge case is where the researcher's special knowledge allows them to be more familiar with the situation. This is recognised as "a ready-made strength" for a researcher to conduct the case study (Thomas, 2011, p. 76). Considering the objectives of the research and its exploratory nature, the researcher seeks to delve into the phenomenon of BIM collaboration within construction projects. Through an in-depth examination of a specific case study, meaningful insights can be gleaned. "Key case" is selected for the study as it offers potentially illuminating perspectives.

4.3 Research Design and Implementation

4.3.1 The design of the embedded case study

Research design is a plan to guide the research process, transitioning from theoretical assumptions to specific methods of data collection and analysis. This decision-making process involves the researcher's worldview assumptions, the nature of the research problems, and the intended audience for the study (Creswell, 2009). Research methods refer to the techniques used for data collection or data analysis (Thomas, 2013). The primary aim of a research design is to ensure that the collected evidence can effectively address the research questions. In the case of a case study process, Yin (2009) distinguished between single- and multiple-case study designs. Furthermore, in terms of the unit of analysis, a case study can include either a single unit or multiple units (Figure 4.1). A single case containing multiple units is referred to as a nested case study (Thomas, 2011) or an embedded case study (Yin, 2009). A construction project, due to its inherent nature, typically involves multiple organisations, each responsible for different areas of expertise, such as designers, engineers, contractors, and subcontractors. Digital collaborations typically occur between two or more parties at different project phases. For instance, a coordination meeting often takes place between the general contractor and the designers without the presence of other stakeholders. Project collaboration aligns with the lifecycle of a construction project, primarily divided into the design phase, the design-construction phase, and the operation phase. Considering the impracticality and difficulty of investigating the lifecycle of an entire construction project within the timescale of a PhD, this research used multiple projects involving four main organisational stakeholders across the entire construction project lifecycle – from design to construction and implementation – to form a comprehensive case. Hence, an embedded single-case study design has been adopted for this research. Specifically, the whole project configuration is considered a large unit of analysis, with each organisational stakeholder identified as individual components of the case study.

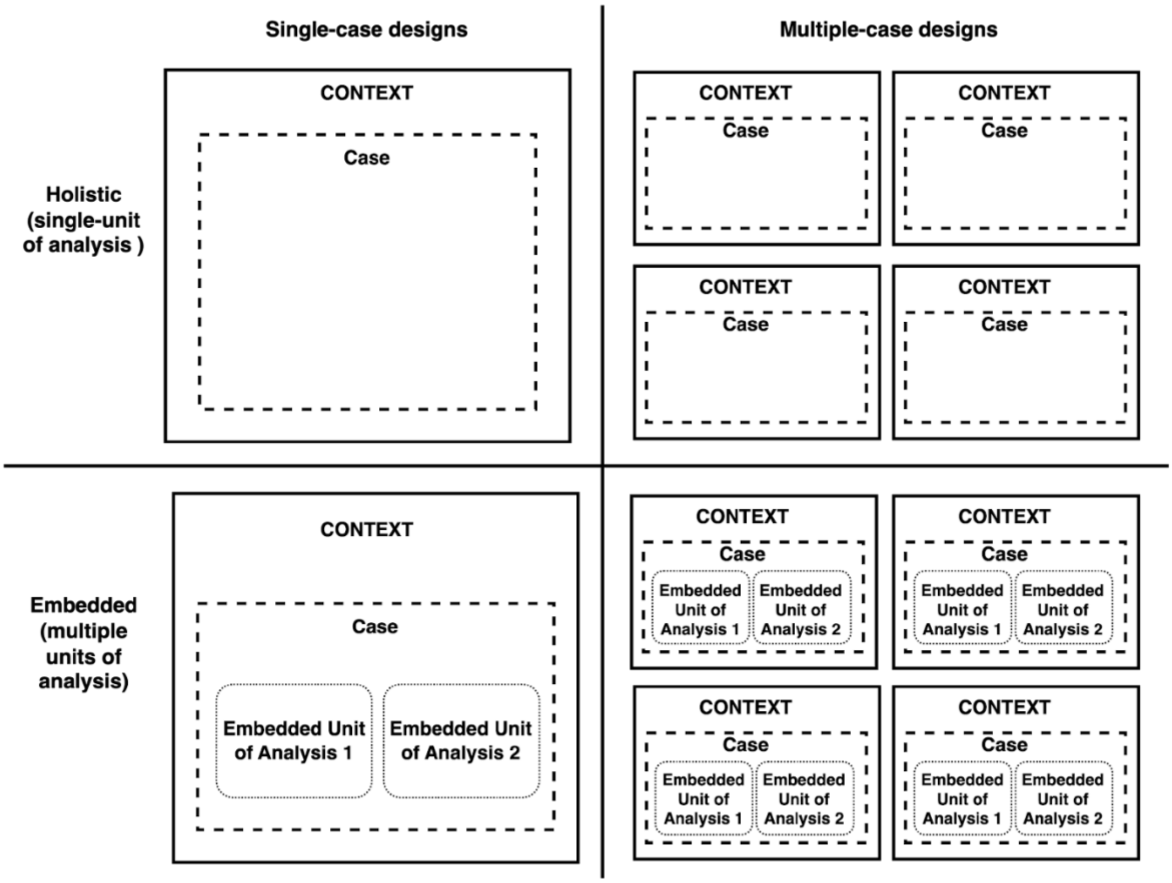

Figure 4.1: The four types of case study design (Yin, 2018)

The designed embedded case study of this research is the BIM-enabled construction project involving four organisational stakeholders as the sub-unit of analysis, including: owner organisations; designing organisation; general contractor organisation; and sub-construction organisation (Figure 4.2).

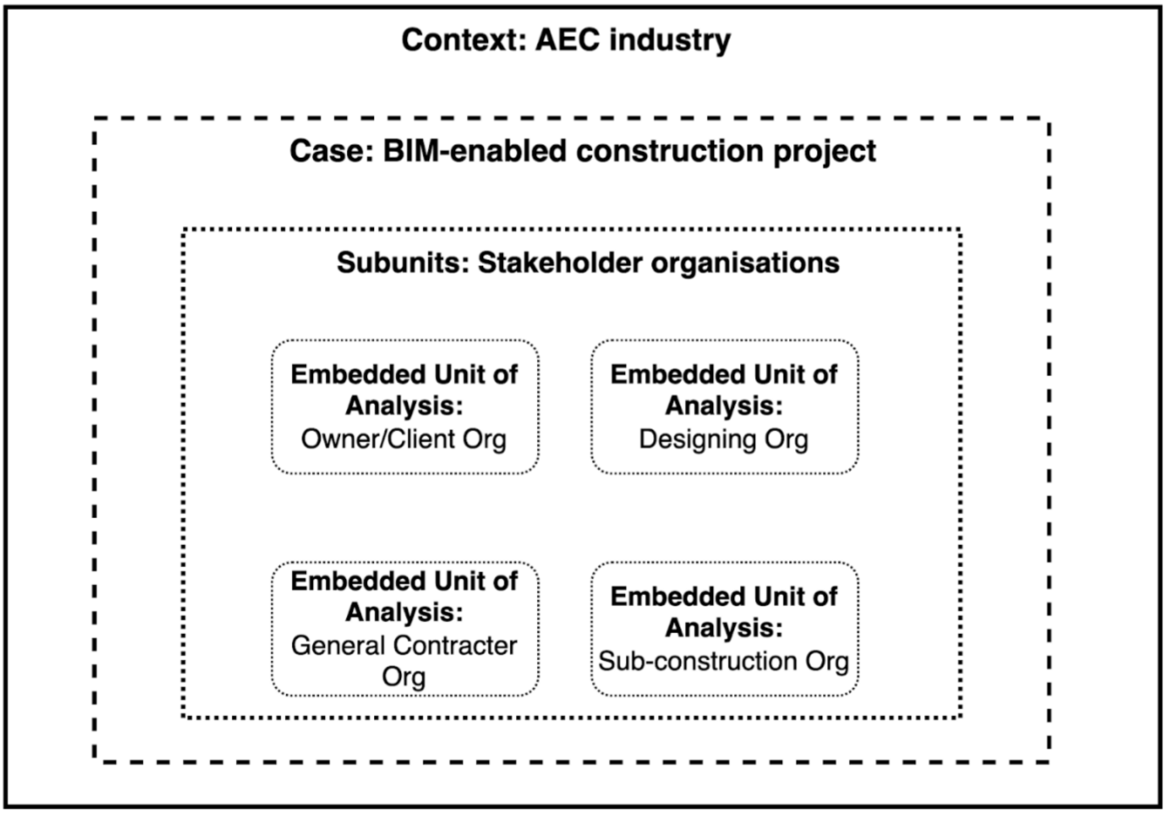

Figure 4.2: The embedded case study of this research—BIM-enabled construction project

4.3.1.1 The selection of the case

Different strategies exist for selecting the most appropriate case in research (Bryman, 2012). Yin (2009) suggests that a revelatory case is suitable for a single-case study, which is considered a class or exemplary case (Thomas, 2011). Therefore, in this study, the case selection is based on features of the candidate case that are revelatory and can help address the research questions. Having an educational background in construction project management and maintaining connections with classmates now working in the AEC industry, the researcher initially contacted these individuals to gather relevant information. This approach facilitated the selection of potential organisational stakeholders to serve as data sources for this embedded case study. As this research focuses on BIM-enabled construction projects, target projects were selected based on contracts indicating the use of BIM-related technology and specific, detailed requirements for BIM process deliverables. Additionally, given the research strategy, this case study was designed as a 'key case' or a revelatory case. In this research, this implies that the involved organisations should have prior experience with BIM-enabled projects for at least three to five years. This criterion ensures that the project is not managed by a novice organisation and can be regarded as a revelatory BIM-enabled project.

This study was conducted in China. It was observed that BIM technology has been actively promoted by AEC institutions and the Chinese government in several major cities including Beijing, Shanghai, Shenzhen, Chengdu, and Guangzhou. Organisations located in these cities could thus serve as revelatory cases, providing rich data for the investigation. Due to the COVID-19 pandemic, however, certain restrictions impacted data collection. According to information from informants and Chinese government policies, to minimise the influence of lockdown measures on the data collection process and quality, cases were selected in Chengdu and Beijing as these cities were less affected by pandemic policies in China during the years 2020 to 2021. As previously mentioned, the sub-units of analysis in this embedded case include organisations based on the main stakeholders involved in different project phases of a BIM-enabled construction project's lifecycle. The appropriate organisations were selected in this research based on the identified criteria.

4.3.2 Data Collection

For a case study, it is imperative to gather evidence from various perspectives to generate an in-depth analysis and understanding of the phenomenon under study. Yin (2018) proposed that a case study requires multiple sources of evidence, including documentation, archival records, interviews, observations, and physical artefacts, each having different comparative strengths and weaknesses. Utilising multiple sources of evidence and establishing a case study database can ensure the validity and reliability of the case study. Therefore, a "polyhedron of intelligibility" should be developed for the case study (Thomas, 2011, p. 4).

Triangulation, crucial for enhancing research quality in a case study approach, involves viewing the phenomena from different perspectives and employing varied methods, thus enabling a comprehensive understanding of the case (Thomas, 2011). The usage of different methods for data collection can provide triangulation (Thomas, 2011). Patton (2015) introduced four types of triangulations: data triangulation; investigator triangulation; theory triangulation; and methodological triangulation. Data triangulation can contribute to the construct validity of the case study (Yin, 2009). For this case, multiple sources have been used tosupport the valid evidence and allow the researcher to depict an overall picture of the case and different facets of the description of the activities in the case based on the obtained details from different sources of data.

Various data collection approaches are used in qualitative research, especially in a case study, such as interviews, observations, focus groups, and documentation:

- **Interviews**: As one of the most common methods for case studies, interviews can collect rich data by obtaining participants' perceptions of the studied phenomenon from their perspectives (Bryman, 2012). This method, flexible in nature, entails diverse techniques to conduct interviews based on research focus, questions, and setting (Yin, 2018). For high-quality interviews, researchers need to build trust with participants and consider ethical aspects to enhance data quality and minimise harm to participants, especially when discussing sensitive topics, such as the organisational management evaluations in this study.
- **Observation**: Commonly used in ethnographic research and increasingly in case studies (Creswell, 2018), observation helps collect data on participants' actual practices rather than their accounts of what they do (Bryman, 2012). The researcher can engage in varying degrees with the participants' work and life depending on research needs and settings. This study focuses on the actual collaborative activities among participants, particularly their interaction with BIM technology or BIM-related tasks. Observation enables the researcher to witness practice-based knowledge work. However, challenges include building trust with participants and gaining access to valuable practices, like coordination meetings. Pandemic-related restrictions exacerbated these difficulties.
- **Focus Groups**: Also known as group interviews, focus groups involve engaging a group of people in discussion around the topics. The interaction among participants in the interview can yield rich information (Creswell, 2018). Conducting focus groups requires researchers to bring together different participants, which can be challenging, especially under lockdown guidelines that discouraged gatherings.
- **Documentation**: Documents are a valuable data source for case studies as they can shed light on different aspects of the studied phenomena (Yin, 2014). In this study, documentation allows the researcher to become familiar with actual work activities, particularly relevant in construction projects which involve a large number of drawings, standards, and reports for collaboration and coordination. Accessing these documents

requires the researchers to obtain permission from informants, especially if the documents contain sensitive information.

In a construction project, collaborative activities often occur in various forms, including formal meetings, informal communication among team members, and extensive usage of project documents for collaboration. Hence, in this research, three data collection methods were adopted: semi-structured interviews; observation; and document analysis. The conceptual framework, based on boundary object theory and activity theory—the main theoretical lenses of this research—was developed during the data collection phase. This provided a more specific and practical perspective for viewing the role of BIM technology in the collaboration process. It also influenced how the interviews were conducted, for example, how follow-up questions related to BIM technology are asked and which insights from the participants would attract interest during data collection. Thus, the conceptual framework serves as a theoretical guide for observing the BIM collaboration process during empirical work. Furthermore, the case study protocol, essential for developing a high-quality case study (Yin, 2018), will be discussed in detail in subsequent sections, detailing the data collection design and procedures for each data collection technique employed in this research.

4.3.2.1 Case description

The first city where the researcher went to was Chengdu to collect data from the general contractor organisation. The second city was Beijing, where the researcher went to access the designing organisation and the sub-construction organisation. Data collection from the owner organisation mainly happened online in the second round of data collection for supplying a complementary perspective. The selected organisations have been described based on their organisations aims and roles in a BIM-enabled construction project. Table 4.1 demonstrates the contextual information of the BIM-enabled construction project as the whole unit of analysis in this case study, and Table 4.2 provides a comparison of the different organisations as the sub-units of analysis.

Table 4.1: The characteristic of different phases over lifecycle of the construction project

Phases	**Objectives/ deliverables**	**Main stakeholders**	**Activities**

Planning	feasibility report	owners	coordination planning
Designing	drawings, 3D models	designing	disciplinary designing, integrating the design
Construction	cost estimation, detailed design drawings, construction plan	contractors and sub-constructors	onsite management and arrangements, construction planning, checking the drawings and reporting detailed designs
Maintenance/Operation	quality of the building	owners	regular checking, maintaining the building

Table 4.2: The different organisations involved in the construction project

Facets	**Owner org**	**Designing org**	**Contractor org**	**Sub-constructor org**
Org business goal	Qualified building	Qualities designing on architecture and structure	Qualified construction following the design	Qualified sub-construction
Work/Tasks	Planning, Demanding	Provide the designs to satisfy the owners' demands and needs. Ensure the feasibility of the design	Put the design into practice. Ensure the quality of the building	Provide further designs to satisfy the owner's use needs. Ensure the compatibility of the detailed design with the main construction/

				Put the detailed design into practice
Roles of project member	Project managers	Architect, civil engineer	Cost estimator, builder	Mechanical, Electrical, Plumbing (MEP)
The engaging phases	Entire process	Designing, sometimes construction, maintenance/operation	Construction, some designing, maintenance/operation	Construction, maintenance/operation

4.3.2.2 Semi-structured Interview approach, design, and procedure

Interview approach and sampling

One of the most important pieces of evidence for a case study is the interview, especially to answer the 'how' question related to exploring the actors' practices and perceptions as in this study (Yin, 2018). There are different types of interview techniques, including structured interviews, unstructured or semi-structured interviews, while the structured interview is commonly used in the quantitative studies (Bryman, 2012). Semi-structured or unstructured interviews can be used in a qualitative case study to conduct in-depth and intensive conversations (Yin, 2018).

In this research, semi-structured interviews were selected as the main source of data collection because of their inherent flexibility and because they allowed the researcher to seek additional explanations for aspects emerging from the initial phase of the research.

With regard to the sampling of potential interviewees, there are different types of sampling approaches for selecting individual participants, such as theoretical sampling; generic purposeful sampling; and snowball sampling (Bryman, 2012), opportunistic sampling (Patton, 2015). This study used a combination of snowball sampling and opportunistic sampling to ensure both representativeness and purposiveness (Bryman, 2012). Snowball sampling was chosen for its utility in identifying relevant participants who are connected with others within the project team (Coleman, 1958). However, it should be noted that this method carries a risk of bias, as the sample is likely to consist of individuals who share similarities (Saunders et al., 2016). To mitigate this issue, opportunistic sampling was employed to guarantee that the participants aligned with the specific needs of the research when unexpected relevant participants arose during fieldwork. In this case, the study necessitated interviewees from various disciplines and roles within the construction project. The recruited interviewees included individuals with different statuses within the same organisations or similar roles across different organisations, representing diverse perspectives (J.Rubin & S.Rubin, 2005) and helping to reduce the elite bias (Myers & Newman, 2007).

Interview questions design

The semi-structured interviews here were designed to elicit participant views and attitudes informed by the findings from the literature review. Therefore, the interviews encompassed various types of questions, with the majority designed as open-ended to secure comprehensive information and in-depth insights from the participants. The semi-structured interview was used in this study to 'know' the participants' perceptions of BIM and the BIM collaboration. This interview questions protocol includes five main sections. The first section includes the initial questions, intermediate questions and ending questions. Each section includes several questions and follow-up questions.

This research studied BIM collaboration by observing knowledge practice and boundaries. Actors have initial boundaries when they have different knowledge backgrounds. The knowledge practice and boundary in the construction project case are situated in my first research question (What are the knowledge boundaries between construction project team members to share knowledge?) and is asked in section 2. That is to ensure the setting of which actor is in, including what they need to know, why they need to know, how they do the knowing, and how the initial boundary is.

Based on the study of Lindberg et al. (2017), the actors have an initial-boundary, and the initial boundary will change with the 'boundary work' in practice that is called a subscription process. In their study, boundary work always happens when the actors communicate with others since they share the same equipment in the case. In contrast, for a construction project, actors use different software and make different digital models for the same project; they find problems and solve them when they make the models that are a knowing process. So the ‘boundary work’ not only occurs when people communicate with each other, it is also embedded in their daily work. Those artefacts made by different disciplinary fields are used to collaborate with each other to mediate knowledge (Yeow et al., 2018). The third section answers the second research question (How do construction project team members collaborate with each other using BIM technology?). Through the information provided by interviewees who have rich AEC industry experience and referred to their practice before adopting BIM technology, the aim of the section here is for the researcher to explore how the actors collaborate with others via BIM to know how the boundary changes are happening.

The fourth section answers the third research question (How do construction team members share knowledge with each other using BIM technology?). According to Yeow et al. (2018, p. 87), “Boundary work develops during a recursive relationship between practice and boundaries: practice drives and constitutes changes in boundaries, while boundaries stabilise and legitimise practice”. So, this section identifies how the practice related to BIM influences the interaction between the knowledge practice and the boundary. In the recursive process, the researcher can know what actions or practise the actor will take or change through using BIM technology when they reconstruct the boundary and what practice has been changed.

To conduct the in-depth interview and ensure consistency between data and questions, the interview design was based on the consideration of two levels of questions: level—verbalised questions to interviewees and level 2—researcher’s line of inquiry, which ensure the simultaneous setting of friendly and understandable questions, whilst maintaining relevancy to the case study (Yin, 2018). Furthermore, the interview guidance was customised based on the characteristics of different organisations for better collecting and seeking the in-depth details due to the organisational feature. Details of the Chinese and English versions of the interview questions can be found in Appendices of 1, 2.

Interview procedure in this study

Audio recording was used during the interview process with the prior permission of the participants. The interview process was planned to take into account the participants’ privacy to attend the research, the power differences between the researchers and interviewees, and the ownership of data (Creswell, 2018). Therefore, the interview was conducted with respect to interviewees’ time, location, and needs for confidentiality of disclosures. Building trust with interviewees and creating a comfortable context for interviewees can reduce the influence of time pressure to give the opinions in the interview (Myers & Newman, 2007). In the interview, researchers' need to be aware of some methodological threat caused by the nature of the interview that the mutual perspectives may unknowingly influence each other between the researchers' line of inquiry and interviewee's responses (Yin, 2018). This research followed the aims of the case study closely, and frequent checking of the interview guidance was applied as a way to minimise this threat during the interview proceedings. Basic information about the interviews used in this study is shown in Table 4.3.

Table 4.3: Basic information regarding the use of interviews in this study

No	Role	Interview format	Anonymised ID
Owner organisation			**OWN**
1	Project manager	Online	OWN1
2	BIM consultant	Online	OWN2
3	Design consultant	Online	OWN3
4	Onsite manager	Online	OWN4
5	Estimator manager	Online	OWN5
Construction organisation			**CON**
6	Project manager	F2F	CON1
7	BIM supporter	Online	CON2
8	Security manager	F2F	CON3
9	Onsite manager	F2F	CON4
10	Technical engineer	Online	CON5
11	Quality manager	F2F	CON6
12	Construction technician	Online	CON7
Sub-construction organisation			**SCON**
13	Project manager	F2F	SCON1
14	MEP engineer	F2F	SCON2
15	BIM technician	Online	SCON3
16	BIM managers	F2F	SCON4
17	Technical engineer	Online	SCON5
18	Onsite manager	F2F	SCON6
19	Construction technician	Online	SCON7

20	Installation engineer	F2F	SCON8
21	Estimator	Online	SCON9
Designing organisation			**DES**
22	Architect designer	F2F	DES1
23	Engineering designer	F2F	DES2
24	BIM managers	F2F	D3
25	BIM designer	Online	D4
26	BIM executive	Online	D5
27	Project assistant	F2F	D6

4.3.2.3 Observation approach, design, and procedure

Observation approach

Given that this research is related to knowledge sharing in digital collaboration, some implicit knowledge is shared in the actors' interactions. Therefore, observation was adopted as complementary to interview data to obtain more comprehensive information for this case study. Through observation, the researcher understands the actors' behaviours by watching and listening directly to their actions (C. Robson, 2002). This mainly involved the observation from formal to casual data collection activities, such as meetings, physical settings, conversations, and interactions (Creswell, 2018; Yin, 2009), and, particularly for this study, the use of BIM technology.

Two types of observation are commonly applied in qualitative research: structured observation; and unstructured observation. Structured observation is used when social activities can be broken down through assumptions of the social world. Unstructured observation is undertaken for researchers to immerse themselves in the situation to understand what is going on (Thomas, 2011). In this research, unstructured observation was deemed more suitable since observation was used to explore how team members collaborate with each other, which is the 'what is going on' question. Therefore, unstructured observation can bring more attention to their interactions. In unstructured observation, the observer is usually a participant to some extent (Thomas, 2011). In addition, regarding the engagement of the research in observing, four types of roles for the researcher have been distinguished in observation, namely, complete participant, complete observer, observer-as-participant, and participant-as-observer (Creswell, 2018; Saunders et al., 2016). In this research, the researcher conducted the observation as a complete observer.

Regarding observation about participants' daily work practices or settings, the observation was carried out considerately in order to avoid evoking the participants' behaviour in a different way (Robson & McCartan, 2016).

Observation design

Robson and McCartan (2016) suggested that researchers commonly engage in descriptive observation and focused observation. To facilitate the observation process, an observational protocol for recording notes is necessary, which can help focus on the content of the observation. Creswell (2018) recommended that recorded notes for observation should include the description of observed facts (e.g., dates, participants' actions, decisions) and the researcher's reflections based on these observations (e.g., the researcher's experiences, learning, hunches).

In this study, the observation focused on several aspects to answer the following questions related to the case study: 1) How do participants communicate using BIM software or models? 2) How do they interact with each other? 3) Do they understand each other's meaning or focus? 4) Is there any conflict between them? 5) Are they satisfied with others' explanations or work? The information recorded in fieldnotes throughout the observation included three aspects (Table 4.4), which were the description of observed notes, the researcher's reflected notes, and contextual information.

Table 4.4: Design of the recording field notes for observations

Aspects recorded in the fieldnote	**Description**
Description of observed notes	The observer will take notes when the observation is proceeding.
Researchers' reflection information	The statements from the observer to ensure that it is understandable and restore the actual observed situation
Experiential information	Those data on the observer's perceptions and feelings as the observer's experience the process being researched.
Contextual information	Those data related to the research setting.

Observation procedure in this study

The implementation of observation throughout the fieldwork was accompanied with other data collection occasions, e.g., the interview (Yin, 2018). Different observations with note taking or audio recording were conducted for the different organisations, depending on the type of permission that they granted. For this study, due to the influence of COVID 19, the observation procedure experienced more difficulties than normal; Only a few observations have been conducted along with the face-to-face interview proceeding, such as observing their physical work setting and informal conversations. However, the observation of the coordination meetings with BIM teams was conducted online with audio recording. The first onsite place where the researcher went was Chengdu City in order to collect data from the general contractor organisation. The observation happened in several scenes, including construction on-site, the meeting room, and the working office. The second onsite place was in Beijing city, where the researcher obtained access to the designing organisation and sub-construction organisation. The table 4.5 shows the summary of the observations that have been done in this study. Figure 4.3 and 4.4 show the coordinating meeting and the workstation in the sub-construction organisation.

Table 4.5: Summary of the observations conduced in this study

Type	**Organisation**	**Description**	**Record format**
Physical workplace	General contractor	Work office, meeting office, construction site	Picture
Coordination meeting	Sub-construction	In Total: 2 hours 30 mins	Audio recording
Colleagues’ conversation	Designing	Involved participants: BIM experts, project managers, BIM managers In Total: 2 hours	Fieldnote
Colleagues’ conversation	Designing	Involved participants: BIM expert, architect designer In Total: 3 hours	Audio recording

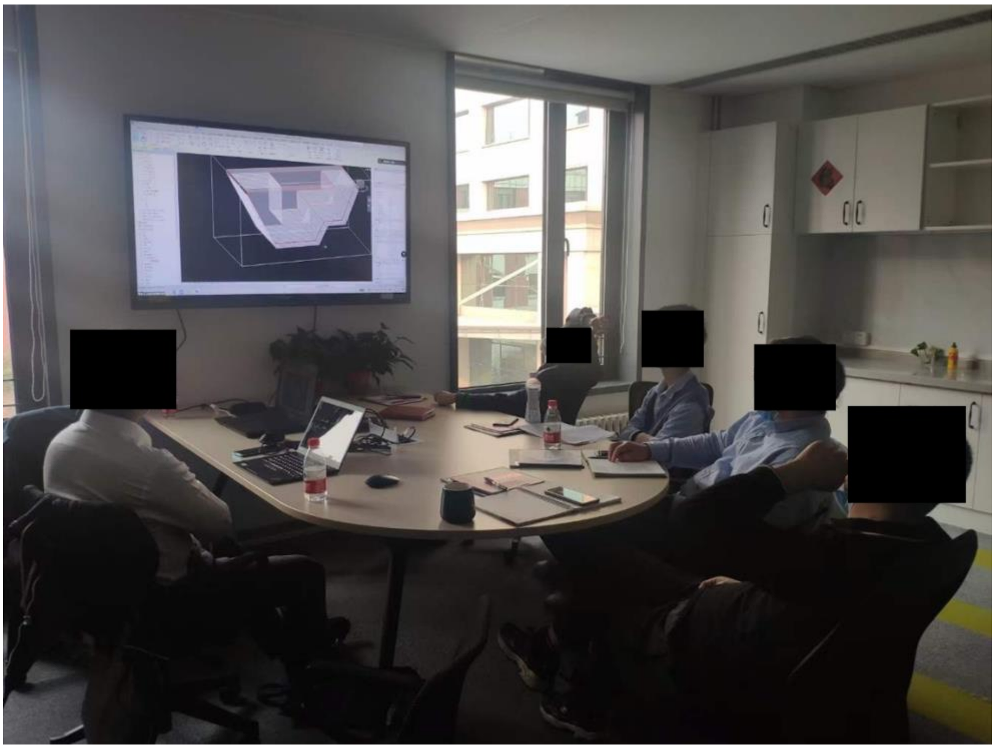

Figure 4.3: the photo of a coordination meeting

Figure 4.4: Work office and work on the BIM model

4.3.2.4 Documentation approach, design, and resources

Documentation approach and source selection

A construction project generally involves significant amounts of materials, such as drawings, digital models, email exchanges and meeting agendas. In the case study, documents can be used to support and corroborate evidence from other sources by verifying the accuracy of interview information, providing more specific details and making inferences for questions or thinking (Yin, 2009). Therefore, documents related to the case of the project were collected as another complementary evidence in this research. To ensure the reliability and validity of the collected documents, Scott (1990) proposed four criteria for assessing the quality of documents in social sciences research: 1) authenticity: if the evidence is genuine and of unquestionable origin; 2) credibility: if the evidence is free from error and distortion; 3) representativeness: if the evidence is typical of its kind, and, if not, is the extent of its untypicality known; and 4) meaning: if the evidence is clear and comprehensible. By following these criteria, the targeted documents in this study came from three sources: 1) those published by the local institutions or state for guiding the industry to complete the BIM-enabled project; 2) those evidencing less error generally and obtainable from official websites, such as the official organisational website; and 3) those mentioned or used by participants, which can show the contextual information, BIM collaboration, or participants/organisational background information (Table 4.6).

Table 4.6: The targeted sources and selection criteria of the documents used in this study

Sources type	**Targeted documents**	**Relevance to this study**
Official documents (state sources)	BIM related Standards/Policy (e.g., Deliverables Standard of Building Design Information Modelling, it depends on which standards are followed in the project)	The guidelines are usually stated in the contract between organisations in the project
Official documents (private sources)	Formal documents for exchanging the model information between project members (e.g., change report, mission form, to record things such as: issues raised at the meeting; the discussion of those issues; views of	These documents are for recording, informing, and/or noticing the adopted actions or activities

	the participants; and actions to be taken (Bryman, 2012, p. 555)	
	Project contract	The document is for the project common goal and required deliverables for each project phase
Participant/Organisation document	Drawings/other objects (digital/non-digital)	These documents are about what individuals complete and plan, such as the drawing, BIM models, clash detection reports

Documentation design and implementation in this study

Bryman (2012) emphasised that researchers needed to consider the meaning of accessing documents in research. Since the documents aim to support the researcher in conducting effective data collection procedures, such as interviews, and in understanding the background and actual conditions of BIM collaboration, the process of collecting documents included two stages during the entire data collection process. In this study, the first stage occurred prior to conducting the interviews and observations and involves accessing public information to familiarise the researcher with the project and the project team. This step focused attention on specific aspects and facilitates better connections between the researcher and participants for subsequent interviews and observations. The second stage occurred during and after fieldwork when the researcher requests relevant documents based on information observed or mentioned in the interviews. For example, in the first stage, the official state document, 'GBT51301-2018 Building Information Modelling Design Delivery Standard' from the Chinese Ministry of Housing and Urban-Rural Development was collected (Figure 4.5). This document helped the researcher become acquainted with current policies and standards governing and guiding BIM collaborative activities and BIM-related deliverables. In the second stage, various documents were collected according to the permissions granted by participants and organisations. Different permissions allowed for the collection of diverse documents, contributing to a more nuanced understanding of the subject under study. For instance, the hierarchical management structure of the designing organisation (Figure 4.6), the service list from the sub-construction organisation (Figure 4.7)

Contents

Figure 4.5: Example of an official state document — 'GBT 51301-2018 Building Information Modelling Design Delivery Standard' from Chinese Ministry of Housing and Urban-Rural Development

Figure 4.6: The hierarchical management structure of the designing organisation

[redacted]

[redacted]有限公司

[redacted]精装 BIM 服务

服务目的：辅助现场管线安装工作并为精装修工作提供点位安装指导、施工指导、复杂节点三维出图及效果展示

1. 工作区域：约 3800 ㎡。
2. 服务方案：

服务项目	分项	服务内容	成果	备注
模型校核	校核原有 BIM 模型	根据最新图纸校核原有 BIM 模型是否满足工作需求，并标出问题，辅助提升原有模型质量。	1.BIM 模型校核报告	
BIM 建模	设备机电专业模型（包含暖通、电气、给排水专业） 精装修表现级建模	依据施工图纸创建各专业模型，模型深度达到 **LOD350**（详情参考《建筑信息模型施工应用标准 GB/T51235-2017》）。 暖通专业：支管（小于 DN50 的管道）及其上的管件、附件、末端； 电气专业：电气点位； 给排水专业：支管（小于 DN50 的管道）及其上的管件、附件、末端；	1. 精装修机电 BIM 模型 2. 表现级精装修模型	
BIM 审图	BIM 审图：暖通专业 BIM 审图 电气专业 BIM 审图 给排水专业 BIM 审图 精装修专业 BIM 审图	通过 BIM 模型，从**空间**和**专业**上进行审图工作，**发现错漏碰缺及空间布局不合理的图纸问题并提出优化意见**，使得问题能在施工前得以解决，有效提高工程质量，减少因图纸问题造成的变更返工及其经济损失。	1. 机电（设备）专业 BIM 审图报告及问题记录 2. 精装修专业 BIM 审图报告及问题记录	
碰撞检测	碰撞检查分析	利用 BIM 技术进行碰撞检测生成碰撞报告，使得碰撞问题在施工之前得以发现。	1. BIM 碰撞检测报告	
BIM 深化	精装修点位深化	根据 BIM 管线综合成果合理布置精装修点位，已达到合理性和美观性要求。	1. BIM 精装修点位模型 2. 各专业精装修点位布置图 3. 复杂精装修节点高精度三维图纸 4. 综合天花图平面示意图	
	吊顶骨架深化	根据点位布置，合理绘制龙骨及吊杆模型	1. 龙骨吊杆 BIM 模型 2. 龙骨吊杆排布平面图	
视觉效果	效果图 360 全景	依据项目及业主方需求，制作漫游动画，展示项目成果，也可用于**三维技术交底**。	1. BIM 效果图 2. 360 全景	
备注	1、以上服务为承接一次机电最终准确模型基础上进行开展工作，如因一次机电模型修改导致以上工作重新排布及增加工作量，需要额外增加费用，具体另议。2、以上服务不包含现场驻场服务及例会服务，如需提供，费用另议。			

[redacted]

Figure 4.7: Example of official document — the service list from the sub-construction organisation

4.3.2.5 Challenges in data collection

Reflection is important for conducting qualitative research. Continuously reflecting on the challenges faced and the solutions devised leads to effective data collection (Bryman, 2012). Additionally, Yin (2018) noted that researchers studying a case study should prepare well before collecting case study data. This preparation includes asking good questions, being a good listener, staying adaptive, having a firm grasp of the issues studied, and conducting the study ethically. During data collection, a journal of the process was kept for the purpose of this research, reflecting on potential questions, concerns, challenges, and solutions.

In this study, as the data collection process was conducted during the COVID-19 pandemic, both the research design and data collection were influenced by COVID-19 and the associated lockdown conditions. During the research design process, the researcher considered data collection methods while acknowledging the potential influence of COVID-19 on the practical situation of fieldwork. The planning of the investigation followed the relevant policies in the main research data collection locations (Chengdu and Beijing). Where the actual pandemic situation might have impacted the researchers and participants' health and safety, physical contact was reduced or even cancelled in line with the most severe policy.

Sichuan province (the location for data collection in this research) also issued the policy 'Notification about Planning Under the COVID-19 Situation' on 1st February 2020, announcing that enterprises could resume business and production (The People's Government of Sichuan Province, 2020). According to information from informants in the targeted organisation in this research prior to the fieldwork, business and social life had largely returned to normal, including the resumption of construction projects. Therefore, the investigation was anticipated to be conducted based on the original plan. However, the research design still accounted for possible changes related to the pandemic situation and adjustments were made during the data collection process. For example, face-to-face interviews have been replaced with audio interviews via online technologies such as WeChat given the participants' preference, and if regular meetings were moved online, the researcher attended these online sessions. This flexibility in the research design allowed for adaptation to the continually evolving situation related to the pandemic.

4.3.3 Data analysis

The analysis of qualitative data requires an awareness of its interrelatedness and interaction with data collection, both of which are influenced by research philosophical assumptions and approaches to theory development (Saunders et al., 2019). Stake (1995) has argued that the analysis and interpretation of evidence in case studies can follow two paths, depending on the research questions and purpose: categorical aggregation; and direct interpretation. The former involves classifying the data analysis in search of collective relationships from multiple perspectives, while the latter seeks to identify differences and similarities among individual stances. Yin (2014, p. 304) maintains that the multi-sourced data collection characteristic of case studies necessitates a data analysis process that "consists of examining, categorising, tabulating, testing, or otherwise recombining evidence". Moreover, Yin (2018) proposed various analytic strategies for analysing case study evidence, including pattern-matching, explanation-building, time-series analysis, logic models, and cross-case synthesis. Given that the present research is inductive in nature, its aim is to construct a holistic understanding of collective patterns of collaborative activities with BIM technology, as derived from participants' practices and perceptions. Therefore, the selected analytical approach in this study should enable the researcher to generate pattern-based analyses in a systematic manner.

Thematic analysis has been selected for this study as a means to identify themes and patterns. This approach can facilitate rich theorising in qualitative research, especially in case studies. Data from observations, semi-structured interviews, and documents will be analysed through thematic analysis. Thematic analysis is a method used "for identifying, analysing, and reporting patterns and themes within data" (Braun & Clarke, 2006, p. 79). Thematic analysis is quite flexible in qualitative research, accommodating various approaches to data analysis (Braun & Clarke, 2006). The conduction of theme analysis is based on considerations such as the size of a theme, the type of analysis (a rich description of an entire data set or a detailed account of a particular theme or themes), the role of theoretical position (inductive or deductive), the level of analysis (semantic and latent levels), and epistemological assumptions (realist and constructionist) (Braun & Clarke, 2006). In this study, the research aim is to explore the factors of BIM collaboration across knowledge boundaries from a social constructivism stance. There are few researchers who have developed a comprehensive and broad framework to explain how BIM collaborative practices influence knowledge practices at boundaries. Hence, there is a lack of a specific conceptual framework to explain such collaborative interactions from multiple views. Therefore, this research adopts an inductive thematic analysis approach, which relies more on data-driven analysis (Braun & Clarke, 2006, 2022). However, this does not imply a complete absence of theoretical basis from the process. For research with an interpretative epistemology, the fundamental principle is to understand a complex whole from preconceptions about the meanings of its parts and their interrelationships (Klein & Myers, 1999). The theory can act as a tool to aid in interpretation and sensemaking (Thomas, 2011). Therefore, theory will be utilised to explain the themes identified from the data.

Computer-aided qualitative data analysis tools, such as NVivo, can enable researchers to make more informed decisions and facilitate the iterative nature of data analysis through efficient management and organisation of qualitative data (Saunders et al., 2019). These provided functionalities of NVivo, such as writing memos/comments, creating codes, or categorising themes and subthemes, searching and exploring data can facilitate qualitative researchers systematically analysing data to aid the continuity of data analysis and methodological rigour (Saunders et al., 2019). This research applied NVivo to assist in the data analysis process. With the established settings of the NVivo package, a suitable analysis paradigm was set up to enable a reflective and reflexive data analysis process. The steps of thematic analysis followed the guide proposed by Braun and Clarke (2006), which includes familiarising with data, initial coding, searching for themes, reviewing themes, defining themes, and producing the report. However, it is worth noting that the actual process of thematic analysis is more iterative (Braun & Clarke, 2022).

4.3.3.1 Data familiarisation

The initial phase of data familiarisation involves the researcher becoming familiar with the context of the dataset through deep immersion. In a practical sense, this process includes transcribing, reading and rereading throughout the dataset (Braun & Clarke, 2022). The familiarisation process offers an opportunity to delve into the data and identify initial patterns or insights that could guide the subsequent phases of thematic analysis (Boyatzis, 1998) including: organising data systematically; transcribing the data; and describing the context of individual participants and organisations. In this study, data familiarisation starts from transcribing the data with a transcript notation system (Bazeley, 2013) (see Figure 4.8)

Feature	Notation
Long pause	(…/…my feeling)
Spoken abbreviations	(Initial Capital)
Uncertainly about the spoken content	(?)
Cut-off speech and speech-sounds	wor-
Emphasis on particular words	**word**
Reported speech	‘ ’
Mispronunciation	(italics)
Identifying information(researcher’s)	「」
the identified speaking person	< >

Figure 4.8 Screenshot of the researcher’s transcript notation system

After transcribing the data using NVivo, the demographic information was subsequently organised and linked to the corresponding participants’ quotes (Bazeley & Jackson, 2013). These data have been organised carefully through classifying the demographic information for each participant, which includes basic details gathered from the interview, such as job role, gender, location, years spent working in the AEC industry, BIM-related work experience, and any AEC-related educational background (See Figure 4.9). This process aids in exploring potential correlations between professional behavioural patterns and participants’ roles or experiences (Creswell, 2018). The demographic information, coupled with details obtained from observational field notes and interview content, facilitates an initial understanding of the dataset marking the crucial first step in thematic analysis (Braun & Clarke, 2006). The features from NVivo have been settled for the further in-depth analysis and journaling, including building cases, memo, project, and mind-map.

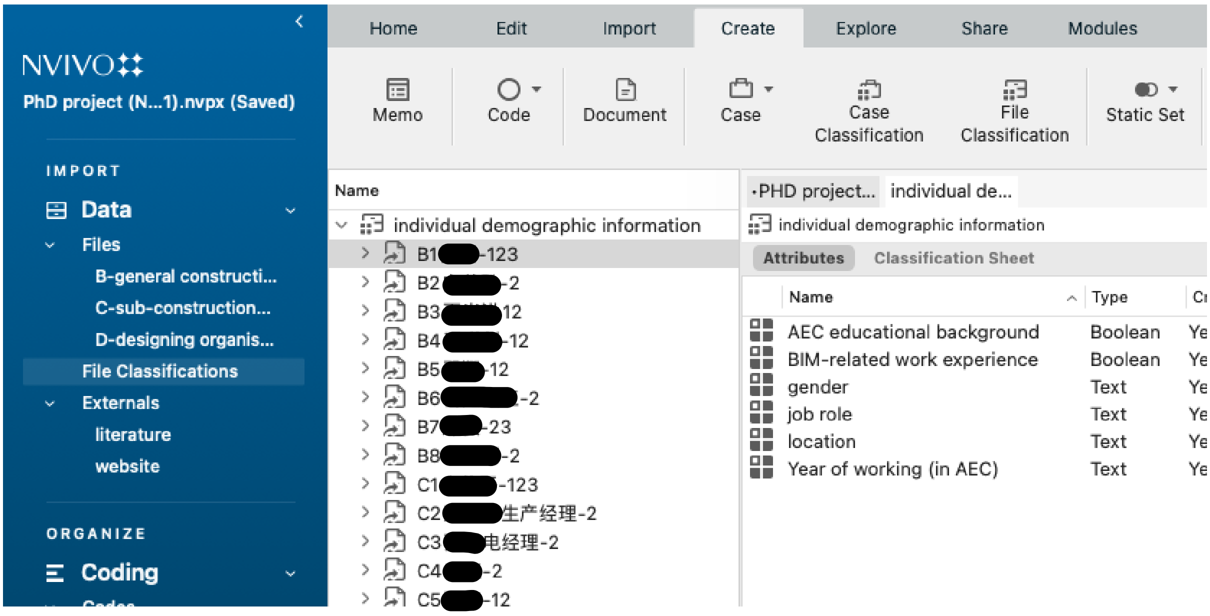

Figure 4.9: Organising the demographic information of participants using NVivo

4.3.3.2 Systematic data coding

This study applied a systematic data coding process. Coding is defined as a process to find the ‘pattern of meaning’ (Braun & Clarke, 2022). Braun and Clark (2022) go on to describe three approaches to code the data in thematic analysis. The first approach is to ensure coding reliability using a structured and fixed codebook suitable for multiple coders to work independently and requiring the measurement of inter-rater reliability and inter-coder agreement. The second is codebook approaches, which involves some type of structured codebook. The third one is the reflexive approach. The boundaries of code can be redrawn when using this approach, and codes can be split into more codes, collapsed with other codes, and even promoted to themes. For the reflexive approach, later themes are developed from clustering similar codes together, and themes should capture shared meaning organised around a central concept or idea. Given that this research aims to explore the ‘how’ question and apply inductive orientation to develop theory from research, this research applies the reflexive approach to code the data (Figure 4.11). The name of code should avoid or remove the derogatory word in the code name and the next coding should be for the consistency of the code labels (i.e., scope the boundary of each code, and add the description on the code). Both descriptive and analytical coding have been developed in the coding process for capturing the semantic meaning and latent meaning from participants (Bazeley, 2013; Boyatzis, 1998; Braun & Clarke, 2022). The definition of codes—when it appears, and the interpretive definition of codes— depends on how it is related to research question, theoretical understanding and research' interests. The arising concerns/questions worth exploring in-depth are those that highlight the potential relevance between the data and the research questions (See Figure 4.10).

The Project memo from a holistic view:

"09/01/2022, 10:59

practice view? what is the practice theories talk about?

the connection between BOT and AT?

18/01/2022, 07:26

What is IS implementation and use focus on? how the data related to IS implementation and use? how to define the RQ in the field? how to relate to digital transformation?

06/02/2022, 17:20
the different collaborative activity let me think about what activity is which "boundary work", why they do that/what they do that for? based on LR, the concept BW is the practice for defending themselves, collabo BW is the practice for building a setting or pattern of collaboration and coordination to achieve the common goals.

09/02/2022, 14:24
How does the boundary can be manifested from single view? how does the practice can show these is a boundary? how does interview describe this practice? --- look from LR

Figure 4.10: Researchers' memo when going through the dataset

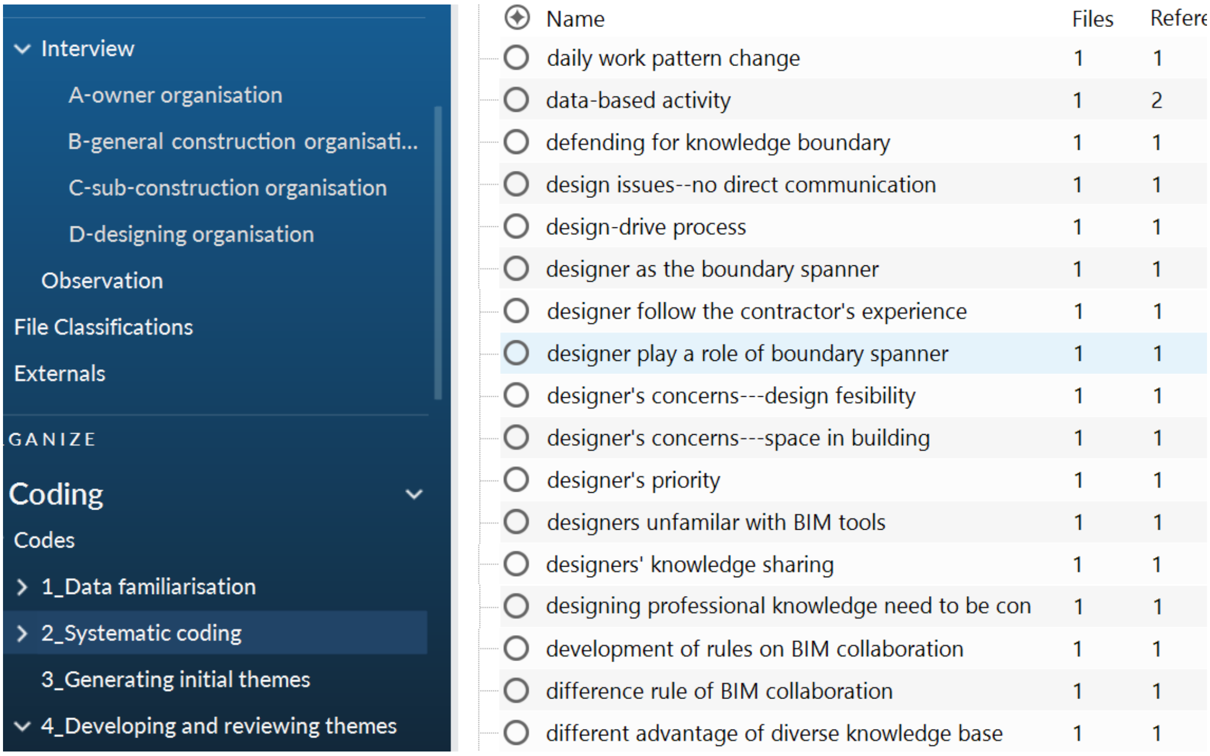

Figure 4.11: The process of systematic coding in NVivo

4.3.3.3 Generating Initial Themes

This step involves the researcher analysing the codes labelled in the last step and sorting them via their interrelations to identify the initial themes (Braun & Clark, 2006). The aim of this step is to generate the candidate themes and relate them to addressing the research questions by telling a particular story about the dataset (Braun & Clark, 2022). A theme should: 1) capture something meaningful; 2) include codes with a coherent central idea; and 3) have a clear boundary (Braun & Clark, 2022). The candidate themes are then listed, and the interlinked codes categorised (Saunders et al., 2019). Sometimes, when multiple codes have been categorised into one theme, these codes are related together to describe one thing at the meta-level, but they may have different meanings, views, insights, or positions (Braun & Clarke, 2013).

In this study, the aims of generating initial themes are based on the research questions to screen the central ideas of BIM technology related collaboration among participants. Participants may have diverse practice and perceptions on BIM technology when interacting with others, and the researcher need to address these challenges between different practices and perceptions. The clustered codes seen as the candidate theme (Figure 4.12) can depict a facet of description of the BIM collaboration and also reflect a certain connection(s) to the entire dataset. Some codes deemed irrelevant to answering the research questions were clustered into a single category for the later review. In this process of generating the candidate themes, the analytic memo was recorded for any promoted awareness of the nature of BIM collaboration across knowledge boundaries from the case study data shown in Figure 3.13.

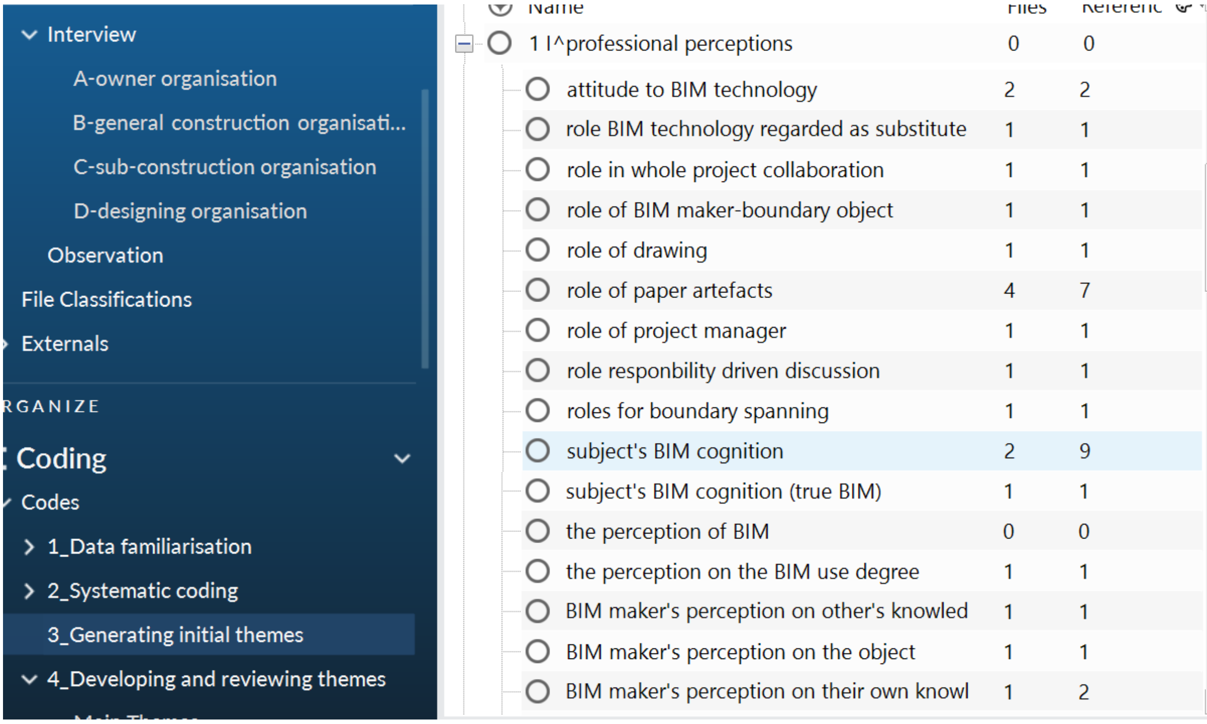

Figure 4.12: initial categorised codes to generate the candidate themes

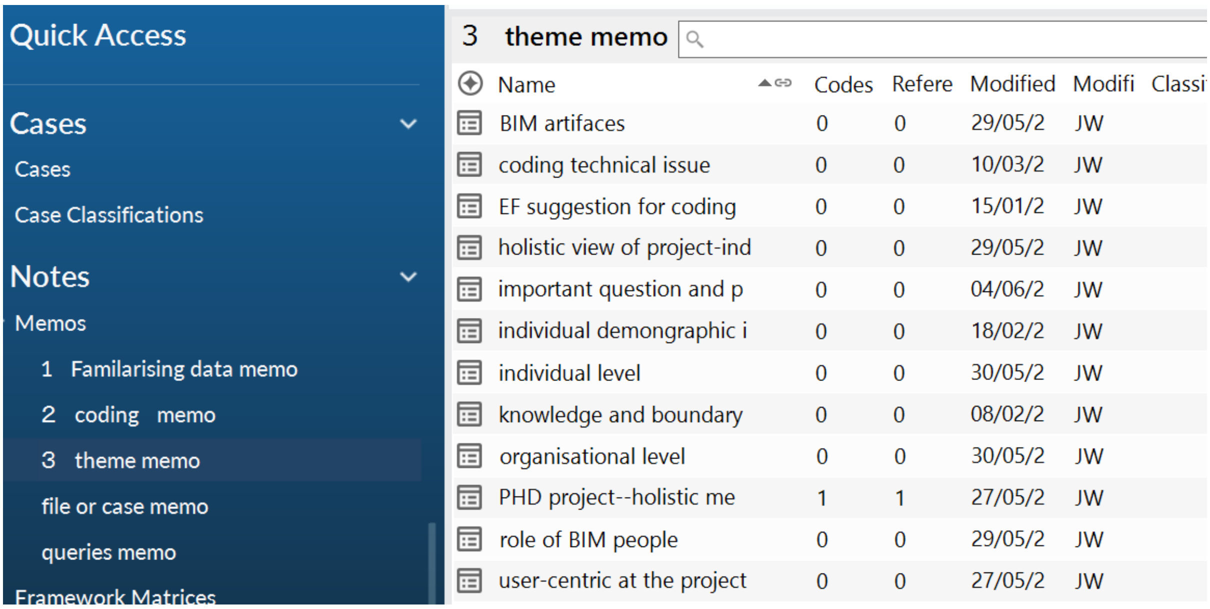

Figure 4.13: the recorded memo during generating the candidate themes

4.3.3.4 Developing and reviewing themes

This stage involves developing and reviewing candidate themes from the categorised codes of the last step. This entails the researcher clarifying the scope of the candidate themes and reviewing data extracts to the entire dataset to ensure coherent codes under the themes (Braun & Clark, 2006). In this process, representative extracts from coded data should be selected for each theme to narratively illustrate all facets of the themes (Saunders et al., 2019). Data extracts can serve two roles in qualitative analysis: to provide illustrative examples, and to offer analytical points to support the researcher's arguments (Braun & Clark, 2013). These roles are based on understanding of semantic meaning or latent meaning of the data in thematic analysis, respectively (Braun & Clark, 2022).

In this study, the development and review of themes involved the use of mind mapping (see Figure 4.14, 4.15, 4.16, 4.17) to clarify the boundaries of each theme during the process of drafting the findings. Relevant data extracts were reviewed and selected for these themes. Unnecessary details, including repetitions or hesitations, were edited out of the selected data extracts. Any incoherent data extracts were removed from the theme and placed into other undefined categories for later review. Some themes were either merged into an overarching theme or separated into several themes. Moreover, care was taken to ensure each theme was developed using extracts from more than one participant, and any repeated extracts found under different themes were replaced to ensure data diversity. Alongside the descriptive analysis of the data, the understanding of the data started to shift towards an interpretative approach, with the aim of developing themes that are analytically related to providing an in-depth explanation for the research questions.

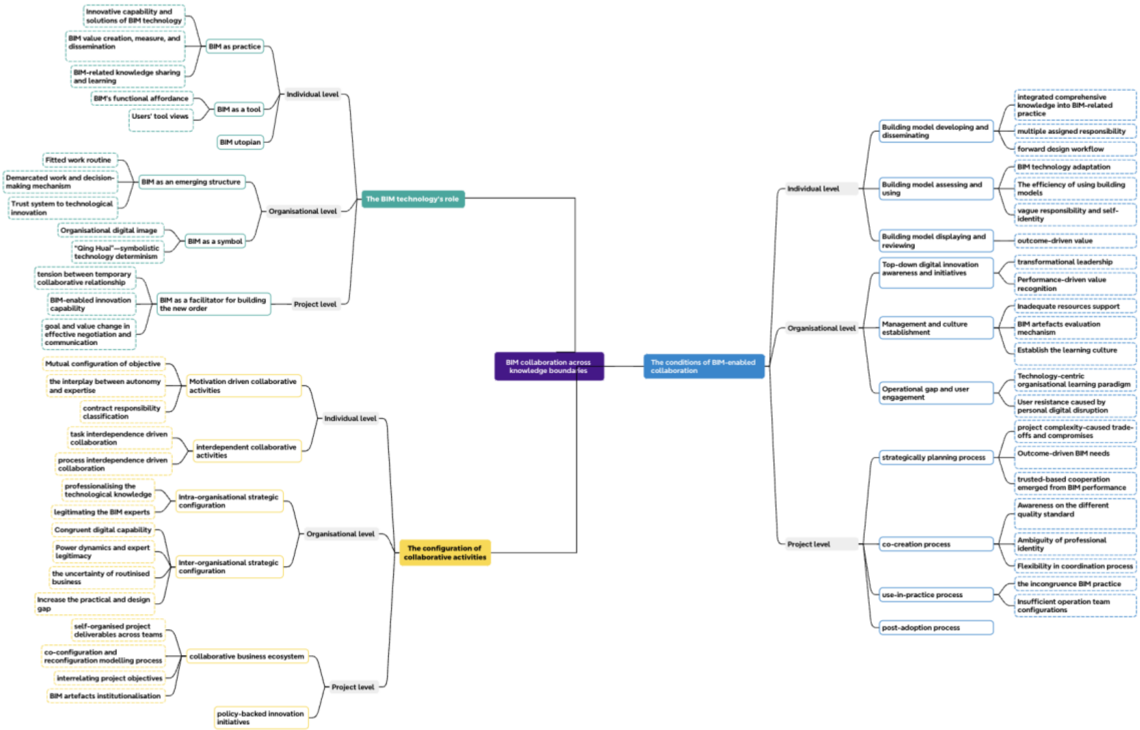

Figure 4.14: Refined thematic map with clear boundaries and central ideas

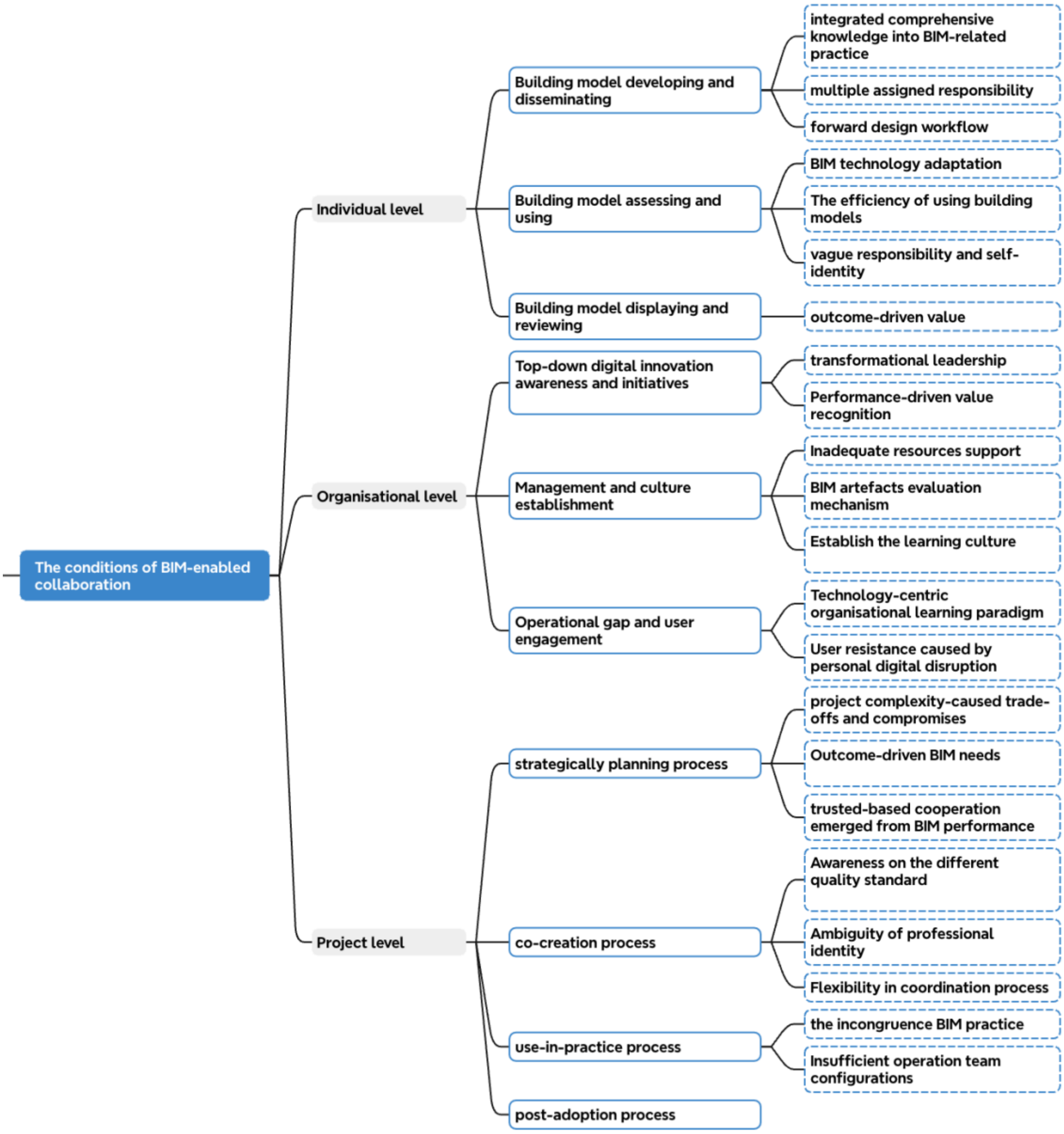

Figure 4.15 Refined thematic map part 1

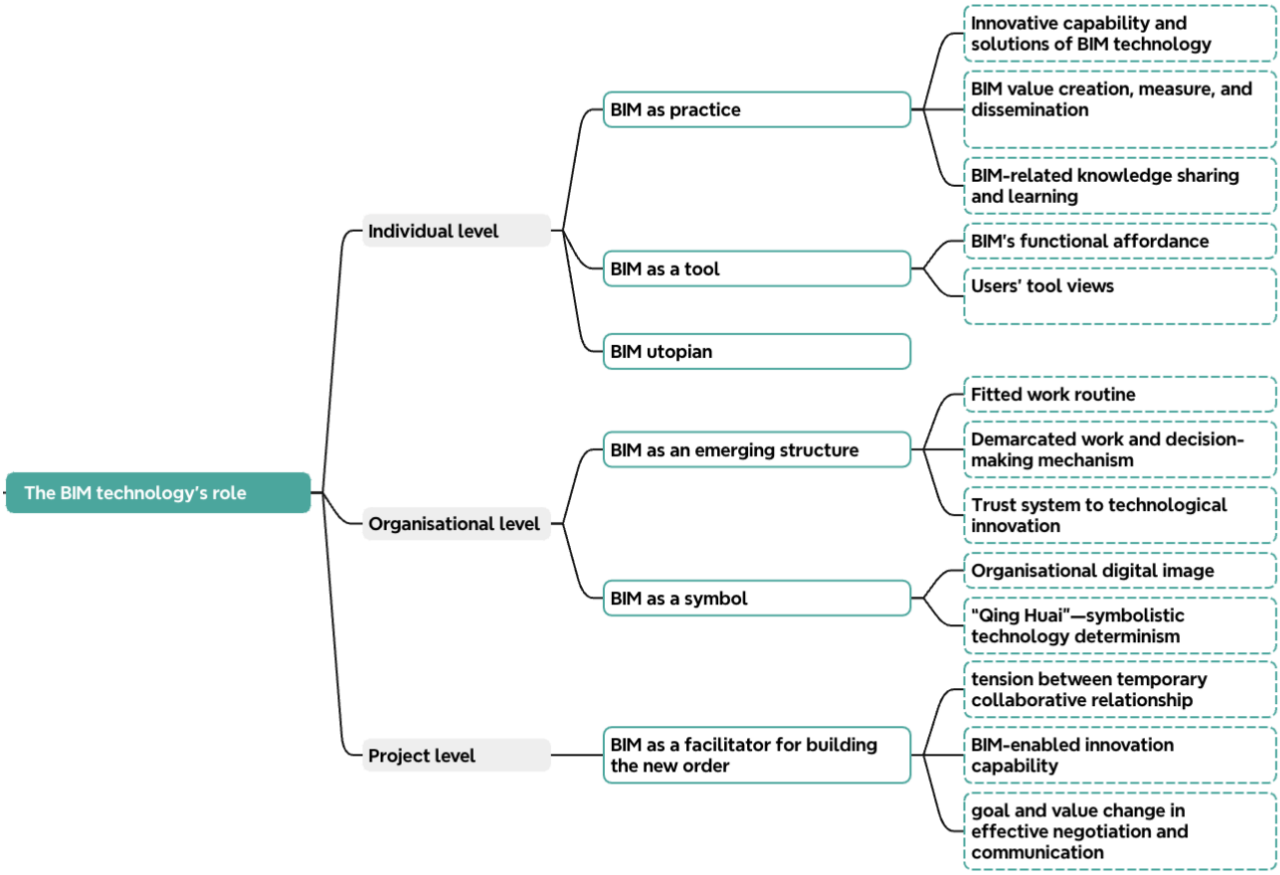

Figure 4.16: Refined thematic map part 2

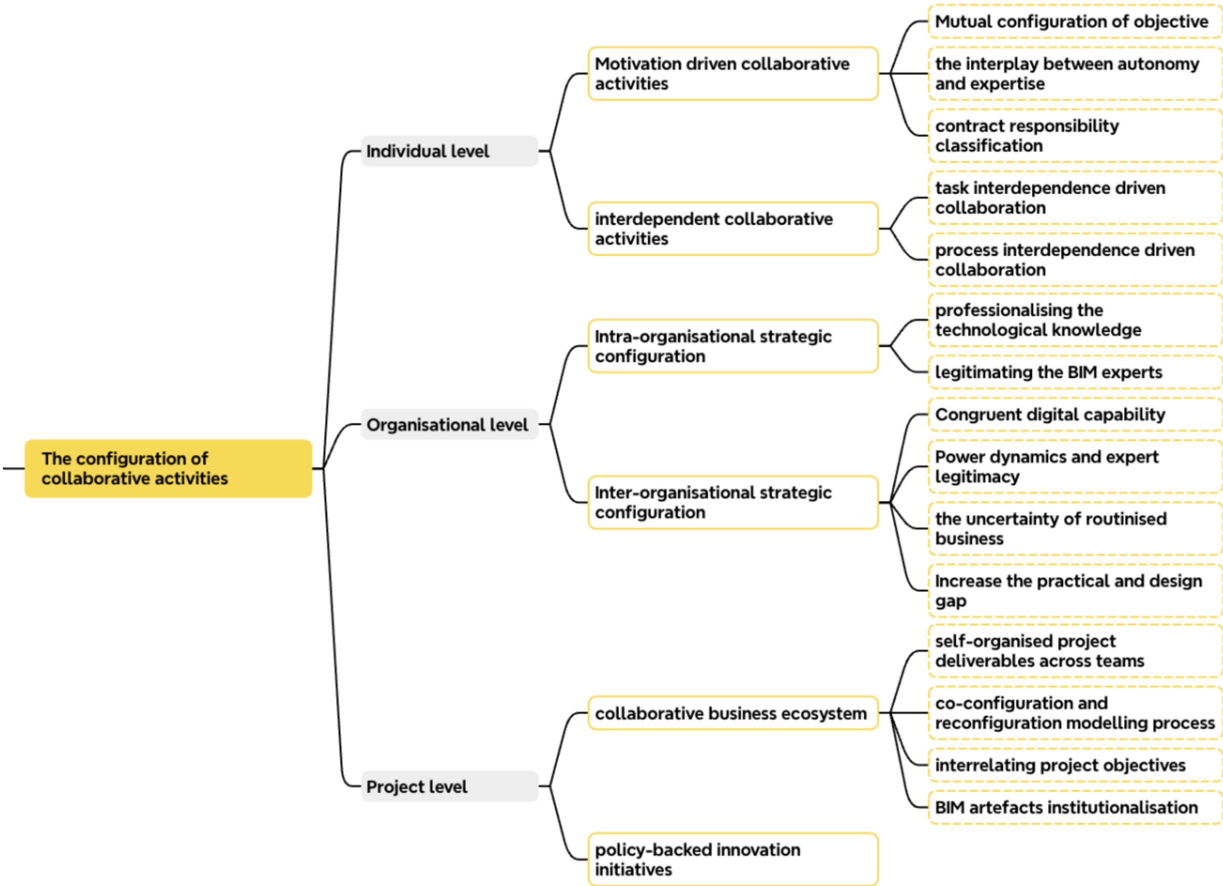

Figure 4.17: Refined thematic map part 3

4.3.3.5 Refining, defining, and naming themes

This step is to further develop the themes by including analytic refinements via writing the findings (Braun & Clark, 2022). Braun and Clark (2022) have indicated that the disciplined writing of theme definitions requires outlining the scope, boundaries, and core concepts. Such refinement also includes going back to the transcribed data to check the data extracts and ensure that its translation preciseness and meaning are representative. In addition, the analytic interpretation of the themes and the relations between different overarching themes will be explained in this step. In this study, the analytic refinement of the themes was conducted when organising and writing the Finding (chapter 5). In the Finding chapter, each theme (along with its definition) was included as a heading and subheading. The selected data for themes were then reviewed to test the clearness and preciseness of the defined boundaries of each theme.

4.3.3.6 Applying the practice/system view to multi-level analysis

The synthesised theoretical perspectives underlay the theoretical assumptions from three dimensions: the changing role of digital technology, the evolving digital practice in collaboration, and the dynamic organisational and project contexts. The research inquiries and explications have been proposed in the following sections. Activity theory emphasises interpreting digital technology-mediated activity from a structural view with a theoretical presumption that the objects are to be reached resulting from the systematic components mediating. At the inter-system level, practice differentiation rising from introducing new technology into activity systems will manifest the contradictions within or between systems. This contradiction may or may not bring changes to the activity system. In digital technology-enabled practice among different organisations, these contradictions arise from digital objects in use gradually becoming transparent and visualising different team members' knowledge practices. The changes are reflected in the modified digital objects and the perceptions of construction. This construction is not only the cause of change. However, it is sometimes an intentional result of redefining digital technology-enabled collaborative processes and relationships within the interaction of different professionals and organisations. When integrating BIM technology into construction project collaboration, it is pivotal to acknowledge its deep-rooted nature within boundary work collective practices. Three elements underscore this process:

- **Individual level:** focus on the Professional's collaborative practice, motivation, and outcome; BIM technology aids knowledge exchange and transformation across distinct boundaries. It bridges varying expertise within a project, minimising knowledge discrepancies and fostering interdisciplinary engagement.
- **Organisational level:** focus on the AEC Organisations' collaborative relations and BIM adoption which induces changes in organisational activity systems. They introduce tensions, congruence, and novel processes, possibly prompting reconfigurations of organisational roles and system dynamics.
- **Project level:** focus on project networked relations: BIM fosters interaction among digitalising organisations, facilitating inter-organisational collaboration and synchronising diverse project participants.

These elements offer a holistic framework to decode the intricacies of BIM-enabled collaboration in construction projects. They allow a deeper dive into how BIM technology influences collaborative practices within and across organisations in boundary work contexts. Therefore, the thematic analysis is based on multiple analytical levels, i.e., individual, organisational, and project levels with different foci. The rationale of the selected three levels of analyses is to focus on multiple sub-units within a single case for providing holistic views on this embedded case study—BIM-enabled cross-boundary collaboration, in which the individual level brings insights based upon the individual's daily practice on BIM technology. The data analysis focuses on the actors' diverse professional roles, and their practice of fulfilling the tasks assigned to them because of their roles, e.g., architect, civil engineer, and cost estimator.

As such, the individual level of analysis examines the relationship between BIM technology and the actors in the case study when engaged in both intra- and inter-organisational collaboration. The organisational level brings insights based upon the overall context of the implementation of BIM technology. The data analysis at this level takes into consideration that each actor belongs to a different organisation, with its own hierarchical organisational structure and organisational culture. Therefore, the organisational level of analysis in this study examines how BIM technology is implemented strategically and operationally within different organisations and the related collaborative partnerships among organisations. Finally, the project level brings insights based on the experience and situated context of the BIM technology used for completing the project goals. Data analysis at the project level focus on the collaboration among actors towards achieving the project goal within set time and resource constraints. Thus, the project level of analysis examines how project-based networks influence the implementation and use of BIM technology across the project lifecycle, within and between organisations.

4.4 Research Ethics

Ethical issues in social science research are a major concern as this can influence whether or not the research can achieve its research goals since it is often related to human objects. Ethical principles should be considered to avoid harming the participants (Bryman, 2012). With regard to the participants, Diener and Crandall (1978) proposed several aspects of concern: if the participants will be harmed in the study; if the participants are informed that they are engaged in the research; if the participants' privacy is in any danger; and if there is deception involved in the investigation process. Following Creswell et.al. (2018), the ethical issues that might occur throughout the research process that were addressed here included:

- **Prior to conducting the study**: before conducting the study, ethical approval was obtained from the university (see Appendix 5). The participants, including the people involved in the interviews and observations, were asked for their permission and informed of the content of the research. For the organisations involved, permission should be acquired from the division managers. The researcher contacted the related informants and obtained some basic information about potential projects. The informants provided the oral permission regarding feasibility of access to the project field after the researcher obtained ethical approval. They also showed willingness to help the researcher contact other firms and projects. From contact with the informants, who are the researcher's previous undergraduate peers, the researcher received oral permission from the organisations and project teams.
- **Beginning the study**: When initially trying to find the potential project and organisations prior to commencing the ethical application, the researcher provided a simple description of the research to the potential informants. For further investigation, the researcher contacted potential participants and managers through the informants (or gatekeeper) to inform them about the research purpose and obtain the trust from the relevant project manager. Meanwhile, the researcher prepared the hard copy and e-version formats of the informed consent and gave it to the participants. At the same time, the informed consent was translated into Chinese to make it easier to understand. The informed consent contained information about this research along with informing participants that they could make decisions freely and voluntarily without pressure.
- **Collecting data**: During the data collection stage, the consent form was distributed to participants before the interview or observation stage to ensure that participants had sufficient time and context to understand the research purpose and make decisions without pressure.
- **Analysing data**: The participants were all assigned fictitious name during data analysis, any identifiable information about individual and organisations have been anonymised and any positive results or negative results from different perspectives were stored and reported.
- **Reporting, sharing, and storing data**: After collecting the data, the raw data was stored in the university data storage, and the files named by code (e.g., 'project A').

> Data access will only be available to the researcher and the two supervisors. The data from the participants has also been stored on another file for analysis; in this file, any identifier information has been anonymised or removed. This is for the researcher to keep track of who said what in case the researcher needs to ensure information accuracy with the participants in future.

In addition, considering the COVID-19 pandemic, the research situation required alteration, and other considerations, aside from ethical issues, needed to be examined. Due to social distancing concerns, the participants might be reluctant to accept a face-to-face interview. Therefore, the interviews were conducted through a video or audio interface. The observations will depend on how people work in practice. Some observations have transformed into online observations if there were virtual meetings among participants.

4.5 Research Quality

4.5.1 Reflection on the role of the researcher

Researchers' subjectivity or bias is hardly avoidable in qualitative research, but it can be viewed as valuable. Capturing researchers' assumptions and values in research helps maintain qualitative sensibility (Braun & Clark, 2022). Braun and Clark (2022) emphasised that researchers need to maintain 'reflexivity' throughout their research. Reflexivity is regarded as "an attitude of attending systematically to the context of knowledge construction, especially to the effect of the researcher, at every step of the research process" (Malterud, 2001, p. 484). It reflects the researchers' perception of their position, bias, or influence in the research process. Therefore, qualitative researchers need to 'position' themselves in their research by understanding their past experiences and how these shape their interpretation of the phenomenon (Creswell, 2018). In this study, the researcher's subjectivity can be identified in several ways. The data collection and analysis are influenced by the researcher's educational background in construction project management. Such influences are reflected in the understanding of research questions, selection of the case, and the interview and coding processes. Maintaining reflexive thinking and journaling helps the researcher interrogate assumptions and perspectives (Braun & Clark, 2022), leading to actions that delve deeper into understanding the rationale behind the phenomenon.

Through reviewing the journaling record in data collection and examining the memo of data analysis, this study is built on the premise that BIM technology can support collaboration, and that potential challenges will be found in the ways of implementing and using BIM technology. Moreover, the perceptions of actors who interact with BIM technology are different and influence others with whom they collaborate. Therefore, the researcher's observations during data collection focus on participants' perceptions of BIM technology, their practice with BIM, and their interactions with others. From a constructivist stance, participants' understanding and interpretation of what they experience in BIM collaboration are related to where they live and work and are shaped through their different perspectives, interactions, and the historical and cultural norms operating in their practice. The researchers' focus on data collection is thus also oriented towards understanding the context of participants' practices and collaboration with BIM technology.

These assumptions and values also influence the data analysis process. The subjectivity of the researcher in data analysis stems from the theoretical lens. Even though this study adopts an inductive approach to generate theory from data, as Braun and Clark (2022) indicated, the theoretical assumptions, philosophical positions, and personal knowledge background inform or shape the data analysis practice. For example, during the data analysis process, although the researcher has educational experience in construction project management, the lack of training and work experience in individual disciplines involved in the construction project, e.g., architectural design, leads the researcher to have a less accurate understanding of participants' meaning of the challenges that designers face when negotiating with construction people. Consequently, this may influence the researcher's evaluation of the meaning of noticed challenges in data analysis.

4.5.2 Quality of research design

The consideration of quality of research design is to balance the understandings between participants, researchers and readers regarding the knowledge coming from real-world practices. There is polyvocal discussion providing insights on the validation and evaluation of qualitative research (Altheide & Johnson, 1994; J. W. Creswell, 2018; Lincoln & Guba, 1985). Some hold the perspective that qualitative research should stick to the parallel standards of validity as in quantitative research, while others establish or reconceptualise the form of validation specifically for qualitative research, such as Lincoln and Guba, (1985). Represented by Lincoln and Guba (1985), the trustworthiness of the research has been described using other forms and terms, or procedures for qualitative research, and this perspective has had a prolonged influence on qualitative research. Based on this fundamental work, some researchers, such as Creswell (2018), have discussed the validation and evaluation process specifically in relation to different research strategies, such as the case study strategy used in this study.

4.5.2.1 Validity

Validity in research pertains to the extent to which the study accurately reflects or measures what it claims to represent or assess (Braun & Clarke, 2016). In other words, it is incumbent upon the researcher to substantiate their methods of observation, identification, and measurement, demonstrating their effectiveness in achieving what the research purports to have accomplished (Bryman, 2012). Compared with internal and external validity, which are related to quantitative research, Lincoln and Guba (1994) have described 'credibility' in qualitative research. This concept emphasises how the findings and interpretations can reflect the actual meanings derived from participants and introduces operational actions in the research design to establish this credibility—such as triangulation. Data triangulation has been applied in this study to facilitate the use of multiple sources to support the evidence. Furthermore, the researcher reports the results to the two supervisors and receives feedback from them, providing audits on the research design and data analysis from external perspectives. In this study's investigation, the researcher has communicated the initial analysis results back to the key respondents, such as the project managers, key BIM experts during the secondary data collection. This process is not only help to validate the initial data analysis from interview, observation and document, but also facilitate to clarify more details in the preliminary findings.

4.5.2.2 Reliability

Reliability is another aspect used to evaluate research quality, which refers to "the possibility of generating the same results when the same measures are administered by different researchers to a different participant group" (Braun & Clark, 2022, p. 389). In qualitative research, repeating a case study rarely occurs, especially in the context of case study research. Regardless, concerns about reliability should be considered in principle and enhanced through the documentation of procedures (Yin, 2018). Similarly, Lincoln and Guba (1985) believe that qualitative researchers should seek the dependability of research, which emphasises establishing a complete record of the research process (Bryman, 2012). For this study, a case study protocol and the development of a case study database are believed to enhance the reliability of a case study (Yin, 2018).

4.5.2.3 Transferability

Another criterion for evaluating qualitative design, especially for a case study, is generalisability. However, it is hard to generalise the results to the wider population since it is difficult to replicate qualitative research, especially in the case of a case study (Yin, 2018). The transferability of the research has been used as an evaluative criterion. Transferability is seen as the responsibility of the researchers to provide sufficient empirical evidence for further research to make a judgement about the contextual similarity (Lincoln & Guba, 1985). Thick description can be employed to enhance the research's transferability (Lincoln & Guba, 1994). Braun and Clark (2013) mentioned that the description should contain the research context, participants, and circumstances in detail, enabling other researchers to evaluate the settings that may be transferable from the research results. As shown in this chapter, the researcher in this study provides a rich description of the case study, ranging from professional practice to different organisational characteristics, thereby enhancing the transferability of this research.

4.6 Chapter Summary

This chapter presented the methodology adopted for the purposes of this study. Interpretivism and social constructivism as the philosophical assumptions in this study provides the stance of methodological design and consideration. The inductive approach to develop the theory impacts the reasoning orientation in this study and the relation between data and theory. The qualitative embedded case study is believed appropriate for studying BIM collaboration across multiple organisations and disciplines involved in construction projects.

For the research design and implementation in this study, following the case study design, data was collected from multiple sources with a focus on the interview data as the primary data source in the data analysis phase. The reflexive thematic analysis process based on Braun and Clark was applied in order to analyse the qualitative data and the interaction between data and the researcher's subjectivity in the analysis process. The last section considered how to ensure the quality of the research in a qualitative study.

5 Findings Chapter

5.1 Introduction

Before presenting the findings, it is important to clarify and review the main research question of this study: 'How does collaboration occur across knowledge boundaries in the BIM-enabled construction project?' This question is addressed through three sub-questions: 1) How are collaborative activities across knowledge boundaries organised in the construction project? 2) How is BIM technology implemented and used to enable these collaborative activities? 3) How does the arrangement of collaborative activities shape BIM implementation and use over time? Established on the theoretical understanding of digital collaboration, knowledge boundary, and BIM adoption in the AEC industry from the literature review, and steed the stage for the Discussion chapter. The identified findings respond to each sub-question by mapping into three analysis dimensions respectively: a) the configuration of collaborative activities, b) the role of BIM technology, and c) the contextual conditions of BIM-enabled collaboration (Table 5.1).

Table 5.1: The three analysed dimensions mapped to the research sub-questions

RQ: How does collaboration occur across knowledge boundaries in the BIM-enabled construction project?	
Analysis dimensions	Research sub-questions
D1. The configuration of collaborative activities	1 How are collaborative activities across knowledge boundaries organised in a construction project?
D2. The BIM technology's role	2 How is BIM technology implemented and used in enabling these collaborative activities?
D3. The contextual conditions of BIM-enabled collaboration	3 How does the arrangement of collaborative activity shape BIM implementation and use over time?

In order to present the thematic analysis of the embedded case study from sub-unit to the single case in a narrative form, the rest of the chapter is organised into the three levels of analysis – individual, organisational, and project – with the section headings labelled accordingly. Within each section, the themes associated with each analysed dimension (D1, D2, D3) are presented and discussed, as presented in Table 5.2. The following sections elaborate on the findings of BIM-enabled cross-boundary collaboration and present the thematic analysis process including themes and codes.

Table 5.2: Themes of the study findings from multi-level thematic analysis

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Analysis Dimensions</td></tr>
<tr><td>D1</td><td>D2</td><td>D3</td></tr>
<tr><td rowspan="11">Levels of Analysis</td><td rowspan="4">Individual</td><td>Intrinsic motivation</td><td>BIM as a practice</td><td>Building model developing and circulating</td></tr>
<tr><td rowspan="2">Extrinsic interdependent actions</td><td rowspan="2">BIM as a tool</td><td>Building model assessing and using</td></tr>
<tr><td>Building model displaying and reviewing</td></tr>
<tr style="display:none"></tr>
<tr><td rowspan="2">Organisational</td><td>Intra-organisational strategic configuration</td><td>BIM as an emerging structure</td><td>Top-down digital innovation awareness and initiatives</td></tr>
<tr><td>Inter-organisational strategic configuration</td><td>BIM as a symbol</td><td>Management and culture establishment</td></tr>
<tr><td rowspan="4">Project</td><td rowspan="2">Collaborative business ecosystem</td><td rowspan="4">BIM as a facilitator</td><td>Shared collaborative vision</td></tr>
<tr><td>Shared artefacts creation process</td></tr>
<tr><td rowspan="2">Policy-backed innovation initiatives</td><td>Shared technological perception</td></tr>
<tr><td>Shared outcome precognitions</td></tr>
</table>

5.2 Configuration of Collaborative Activities

This section presents the findings on BIM-enabled cross-boundary collaboration at the individual, organisational and project levels. As mentioned in the introduction, the individual level is concerned with exploring the BIM-enabled cross-boundary collaboration among different professionals when using BIM technology in their practice to fulfil tasks. This section shows that collaborative activities are associated based on the different professionals' intrinsic motivation for collaboration and the interdependent actions as extrinsic factors affecting the collaborative activities (Table 5.3).

For the organisational level. Data were collected from four main stakeholders identified in the construction project: the owner organisation, designing organisation, construction organisation, and sub-construction organisation. Participants reflected on their intra- and inter-organisational BIM-related strategies, BIM-enabled collaboration, and their experiences with the implementation and adoption of BIM technology within their organisations. This analysis primarily focused on participants' perceptions of how BIM technology is strategically and operationally implemented within diverse organisational structures and cultures. Findings reveal that different organisational digital innovation strategies transform their BIM technology capabilities, affecting intra-organisational business processes and inter-organisational collaborative relations. By examining the impact of organisational BIM strategies on digital innovation practice, this section demonstrates how organisational strategic responses to BIM technology facilitate digital innovation and the perceived organisational structural and cultural changes within actors' BIM-enabled collaboration. The configuration of collaborative activities within and between organisations is regarded as innovation oriented.

In terms of the project level analysis, which examines collaborative activities and the use of BIM technology within the context of short-term project goals. Unlike the organisational level of analysis, the project level emphasises the dynamic relationships among actors who collaborate to achieve a shared project goal within the constraints of limited time and resources, while operating within their different organisational contexts. This presents project-based collaborative activities as subject to institutionalisation through the collaborative business ecosystem and policy-based initiatives.

Table 5.3: Professional, organisational and project collaborative activities

Level of analysis	Theme	Code
Individual level	Intrinsic motivation	Goal Alignment Motivation
		Expertise-Driven Autonomy Motivation
		Contractual Accountability Motivation
	Extrinsic interdependent actions	Task interdependence
		Process interdependence
Organisational level	Intra-organisational strategic configuration	Professionalising technological knowledge
		Legitimating BIM specialists
	Inter-organisational strategic configuration	Congruent digital capabilities
		Power dynamics and expert legitimacy
		Uncertainty of routinised business
Project level	Collaborative business ecosystem	Artefact-enabled collaboration network
		Artefact-driven adaptive collaboration lifecycle
		BIM-facilitated artefact institutionalisation
	Policy-backed innovation initiatives	Policy-backed innovation initiatives

5.2.1 Individual level

This subsection presents evidence of how and why professionals engage in collaborative practices and interact with others. Based on actors' reflections on their professional roles and collaborative practices, these relationships among actors may be manifested in collaborative motivation and co-creation-based work relations. Through thematic analysis of the individual-level data, two central themes that drive these interactions have been identified: ‘intrinsic motivation’ and ‘extrinsic interdependent actions’. These themes highlight the underlying factors that shape the collaborative activities among different professional actors, who bring diverse work objectives and concerns to their collaborative relationships.

5.2.1.1 Intrinsic motivation

Intrinsic motivation emerges as a key theme suggesting that professionals are driven by their desire to interact with others to achieve their work objectives or fulfil their duties. According to participants, the introduction of BIM technology in collaborative activities presents professionals with ambiguous work demands, necessitating the acquisition of new knowledge to effectively perform their roles. This challenge generates a genuine motivation to collaborate with others. Intrinsic motivation plays a crucial role in shaping collaborative practices among professionals, revealing the internal drivers that foster such practices. This theme constitutes with three forms of motivation, which have been coded as: (1) goal alignment motivation, (2) expertise-driven autonomy motivation, and (3) contractual accountability motivation.

Goal Alignment Motivation

The study findings suggest that professionals are more motivated to align their goals when they collaborate, fostering a shared understanding of their goals. Interviewed actors reported that they often mutually set goals and expectations of outcomes through collaborative efforts. These professionals communicate the rationale behind their decisions and actions, taking into account the potential consequences of their work.

This type of collaborative practice often occurs in initial meetings with stakeholders when establishing a collaborative relationship. For instance, actors who are knowledgeable about BIM technology will prioritise introducing its capabilities to others. Given the varying levels of familiarity with BIM technology among project team members due to diverse professional backgrounds, BIM models serve as a means of communication to foster mutual understanding by showcasing the potential outcomes of incorporating BIM technology in the modelling process. Negotiating work goals and expectations related to BIM during coordination meetings are believed to help prevent potential conflicts and contradictions in advance. This is achieved by engaging in outcome-driven discussions, where actors present their capabilities and limitations. As shown in the following statements from an actor from the design organisation about how to align the goals in collaborative meeting:

> *"At the beginning of the project, there will be a kick-off meeting [between design organisation and the owner organisation]. At this stage, all of us will be familiar with and understand [each other]. In fact, it is convenient for later work because we are familiar with it in advance, and there will be*

a tacit understanding between us…What kind of height can it reach after we finish it, then we will give some optimisation suggestions, and then based on this problem and based on our suggestions, we will get various parties to discuss, which may be based on our suggestions. to fix it, or they have more suggestions. We basically provide such an outcome." (DES1)

In addition, individuals proactively identify their own objectives, driven by different agendas such as adhering to their role's principles and knowledge domain, achieving outcomes more effectively and efficiently, or following the plan to complete their assigned tasks. When new factors, such as the introduction of BIM technology, interfere with their original objectives, professionals reconfigure their goals as part of their collaborative activities.

For example, when BIM technology is integrated into the work routines of MEP engineers, the development of BIM models introduces more detail, which in turn affects their original work scope. In response, actors need to clarify their work scope, including BIM-related tasks, to ensure that their efforts align with collaborators' expectations. Otherwise, they may default to their traditional roles—modelling details without BIM technology—which may not meet the expectations of their colleagues. Consequently, the work scope is reconfigured through interaction during collaborative activities, allowing professionals to adapt to the changing demands of their collaborators. The negotiation about BIM work scope is as mentioned by a participant from the sub-construction organisation:

"The first is to confirm the workload, which means that sometimes they [Party A] may show a partial room, right? You have to set the workload with them. What are you focusing on in the show? Which direction? Confirm first. The second is to confirm the time. How much time can you give me? I can achieve it only when I bring something. Let me first say how long it will take for me to achieve this [BIM] work. Can you allow it? Then there are your requirements, your ideas, what you want to make it look like, and who it is for. Right? For example, if you want to show it to professionals, it may mean that we are relatively complicated in the final export, right? The information behind this [BIM] model will bring you everything. " (SCON5)

Expertise-Driven Autonomy Motivation

'Expertise-driven autonomy motivation' refers to the inherent drive of actors to make independent decisions about their work, based on their comprehensive understanding of others' needs, rather than being influenced by the hierarchical positions of collaborators. Actors with greater professional expertise tend to have a stronger desire for decision-making autonomy. Participants in this study noted that an increase in BIM-related expertise highlights the interplay between autonomy and expertise in collaborative activities, revealing the power dynamics between BIM specialists and other stakeholders. For example, adopting BIM technology grants actors with greater potential for decision-making autonomy through improved technological knowledge.

Furthermore, the study found that BIM specialists could gain a more comprehensive understanding of emerging problems by integrating models from different disciplines, allowing them to develop a more holistic view of model quality. Traditionally, architects have had significant autonomy in making changes when conflicts arise, and still tend to make more decisions during co-design. This finding suggests that BIM specialists may gain increased autonomy due to their more comprehensive insights and role in the collaboration, leading to ability to make decisions. As a result, a zero-sum game regarding autonomy between BIM specialists and higher-status decision-makers is identified within the interactive practices amongst actors from different organisations. As a project manager from the sub-construction organisation mentioned:

> *"[Specific decision-making] still mainly depends on [traditional] designers. Maybe because it is mainly the drawings that they designed, so the control of automatic rights may be like this, such as how to change what things, maybe in this regard." (SCON4)*

Actors within construction organisations expressed concerns about their lack of autonomy, particularly when facing problems during the implementation of blueprints. Although they are the actual users of the building model during the construction phase, they heavily rely on the design organisation for optimisation decisions. They suggest that to gain more autonomy, they need to balance the costs and needs of different actors. Simultaneously, they highlight the necessity for efficient communication regarding actual on-site problems encountered in construction and the feasibility of design ideas during the construction process. Both participants from sub-construction and design organisations confirmed the concerns about autonomy:

> *"There are numerous complex issues related to pipelines, and professionals from various specialities believe that the openings may be more suitable for their own pipelines. They often want to make adjustments or change the position to address these problems. Since their specialised factories have their own sources of income, including construction costs, they all aim to reduce operating expenses and place their pipelines in a more advantageous position." (SCON4)*

> *"Anyway, it is almost equivalent to relying more on the designers, not saying that they have as much control over the autonomy as the design side. Maybe this is the case, because it is mainly the blueprints designed by them, for example, how to change things, maybe for example in this regard." (DES3)*

Contractual Accountability Motivation

Contractual accountability motivation is based on the idea of motivation stemming from professionals' desire to understand their contractual responsibilities by communicating and negotiating with others to identify the accountability of meeting the expectations outlined in their contracts. In the AEC industry, contracts specify the project goals and the expectations of each involved organisation in terms of these goals. With the adoption of BIM technology, professional roles and work have changed, making it crucial for professionals to clarify their contractual responsibilities to guide their BIM-related practices. In a construction project, the demarcation of contract-based responsibility is always important throughout the entire project lifecycle. Actors emphasise the importance of demarcating work responsibility based on the contract, as it serves as the most legitimate guidance for dividing risk and profit. Identifying the responsible party in a contract is a significant concern when making decisions, driving collaborative negotiation and communication among different professionals. Additionally, clients should be involved in collaborative activities, which should be authorised by the clients based on the contract. This is confirmed by one participant from the sub-construction organisation:

"It is necessary to send a letter to Party A, and he will go to the design side because the design is his design. When he looks for it, we design it. Our contract relationship is only with Party A, and everything is based on the contract. If he authorises, we can Communicate directly with the design, but the post must be [by] Party A." (SCON1)

5.2.1.2 Extrinsic interdependent actions

This theme captures the extrinsic interdependent actions of collaborative activities at individual levels, highlighting the mutual reliance among professionals and the interconnected nature of their tasks and processes. This theme emphasises the significance of interdependent actions as a key driver for collaborative activities. The findings identified two primary types of interdependent actions from the actors' perspectives: task interdependence and process interdependence. Task interdependence refers to the extent to which professionals' tasks are connected and reliant on each other's inputs, while process interdependence pertains to the interconnectedness of the workflows and procedures undertaken by various professionals.

Task interdependence

Task interdependence refers to the performance of a specific task that influences the performance of subsequent tasks, or how the output of one task might affect the input of another task. The findings indicate that participants collaborate to clarify whether the demands and requirements of one task have been satisfied or not for other stakeholders, especially for actors who are working on tasks related to others. Collaborative interactions constantly give rise to demands due to task interdependence, such as the demand for building models.

For instance, the BIM model designer might directly impact the work of the MEP engineer when the model is used directly by the MEP engineer in a report meeting. Extra work may arise due to a lack of communication or understanding of each other's requirements and constraints. BIM model designers might adopt strategies such as regular meetings, effective communication channels, and obtaining clearly defined expectations on task output from their collaborators to manage extra effort. By doing so, they can better coordinate their efforts and achieve more efficient work. One participant from the sub-construction organisation mentioned their work output – model information will influence on their collaborator's task:

"Sometimes I need to communicate with Party A about how to achieve what they want. This is a bit like planning… just look at their requirements

and ideas, see what they want to make it into, and who is it for? Right? For example, if you want to show it to professionals, it may mean that we are relatively complicated in the final export, right? The [various] information behind this building model will take you there… For example, if this thing is made for Party A, they are the people [users] who buy houses in the sales office, or they are displayed to other people related to the government, so there is no need to fill in the model information. If it is easy to operate. The launch time is short, the file size is small, and it is easy to operate." (SCON5)

Challenges can arise due to task interdependence. Participants mentioned that sometimes actual problems may not fit the established routines from BIM processes and the related task interdependence, causing actors to deviate from the procedures entailed in formal BIM procedures. This can lead to informal collaboration, which is not based on adopting BIM technology, but rather on traditional processes. For example, actors may engage in informal collaboration when they identify that their priority is to address the actual problems of the project rather than follow the designed norm or practice. Alternatively, they might find that the new BIM technology does not provide the most efficient approach to addressing their issues, so they tend to pursue the approach they are most familiar with before dealing with their current problems. Consequently, they fall back on their conventional practices, but this can impact the further BIM-related work of other professionals. One interviewee from the construction organisation validates this reason:

"It is also possible to use BIM directly for painting, and it is also possible to convert 3D into 2D, but the way we work now is that because this [BIM] technology is not very well applied now, which means that we may traditionally use 2D because now it is generally two-dimensional, and then you go to convert it to 3D." (CON5)

In BIM-related work, task interdependence significantly increases the complexity of the changes in work practices compared to traditional methods. For example, when there is a change in design, the BIM model needs to be updated accordingly. However, this implies that BIM-related professionals need to undertake additional work resulting from this change than the conventional methods. As BIM specialist from the construction organisation mentioned, during the co-creation process, the work leads to financial issues because changes in the models can potentially lead to increased costs and effort:

> *"In fact, any changes now have to involve the amount. They agreed to change, and he gave you the quote because he agreed to pay, and he didn't say they gave you new money, but if there was a change, we said that our construction unit came over and the project was under construction. It's not about doing charity. If you think you know it, if you ask me to do something, you have to give me money. It's the same. So if you ask me to do everything, you have to say that you want to reform and change. You just give me something, and I say to you." (CON7)*

Process interdependence

Process interdependence refers to multiple processes with different aims that are intertwined together. These interdependent processes drive professionals to collaborate with each other while pursuing different goals. However, they also intend to establish consensus for achieving these process goals through collaboration. The findings suggest that there are two types of process interdependence: the design process vs. the construction process, and the BIM implementation process vs. the build model co-creation process. Both types of interdependence drive collaborative activities, seeking points of convergence to achieve different goals. Additionally, various tensions exist within these intertwined processes, influencing the way professionals configure their collaborative activities.

The interdependence between design processes and construction processes requires professionals to collaborate and exchange knowledge and expertise while adopting BIM technology to integrate different information. These intertwined processes also highlight the connections between the design and construction processes, emphasising the significance of diverse professionals' knowledge contributing to the same goals. For example, according to one participant from the construction organisation, this interdependence entails actors examining the model for any problems by drawing on their practical experience, knowledge, and expertise, and engaging designers in the feedback process to incorporate this knowledge into the creation of the building models:

> *"Because we can avoid some construction problems in advance through modelling. For example, in the process of our current construction, when*

we reach a certain node, there will be drawings that do not match our site situation. If there are deviations, if we can notice them [in the models], we will find out such problems in advance, and then avoid them in advance, so that we will not be so passive that we have already constructed to that place, and suddenly find that the construction cannot go ahead, then we will feed back the problem to the technical section, and then to the design organisations, and then the design organisations will make corresponding design changes for this problem, and then return it [the changed designing drawing] to us." (CON3)

BIM implementation processes and building model co-creation processes interdependently drive professionals to collaborate in adopting BIM technology to complete building models. The building model creation process aims to create precise and instrumental building models by designers (e.g., architect designers and engineering designers). The BIM implementation process aims to encourage professionals adopt BIM technology into their work and adapt to new practices while utilising the advantages of BIM technology. Project managers reflect that when they modify building models, they tend to use BIM models to explain their 2D drawings, making it easier for their clients to understand their work by communication and increasing BIM technology acceptance in collaboration. However, challenges also exist in the intertwined processes of building model co-creation when collaborators have diverse digital capabilities. For example, as mentioned by a manager from design organisation, using digital models requires Party A to know how to operate BIM software and understand its features to showcase its details whereas a lack of BIM capabilities makes building model co-creation more complex for professionals:

"When our BIM technology intervenes, we will also have some training sessions, including the party A in some projects who have never even seen this BIM software, or they can't even open the model. In this kind of situation, we will also give them some training, to tell them how to use it, to install the software for them, and then to briefly explain the basic software operations, to give them training, so that they can open the model we made to view, to see some information, such as to see some components. We all have these [interactions]." (DES1)

5.2.2 Organisational level

At the organisational level, cross-boundary collaborative activities are influenced by an organisation's digital innovation strategy. This strategy shapes how digital technologies, including BIM, are embedded in actors' practices and interactions. The findings reveal that organisations strategically configure collaborative activities to incorporate BIM-related knowledge into their business and management processes through various digital innovation strategies. Based on participants' reflections on their organisational activities, they believe that the success of BIM performance in collaborative activities is highly dependent on the consequences of intra- and inter-organisational innovation strategies.

5.2.2.1. Intra-organisational strategic configuration

Participant interviews revealed that intra-organisational strategies for BIM implementation primarily focus on BIM-related knowledge and expertise. The participants emphasised the importance of technological knowledge and the increased legitimacy of BIM technology, as well as the related professional actors within organisations. The organisational strategic configuration of collaborative activities targets structural change by enhancing competitive advantage and developing capabilities in terms of using BIM technology internally. These intra-organisational strategies have been identified as crucial for organisations to incorporate BIM technology into their business models and bolster their digital capabilities.

Professionalising technological knowledge

BIM knowledge is considered an individual discipline within an organisation. The findings indicate that organisations tend to establish a distinct structure in their original division of labour, treating BIM knowledge as a specific discipline. Consequently, BIM practice within the organisation is carried out by a specialist BIM team, complete with its own community of practice and norms. For instance, the design organisation appeared to create a clear identity for their BIM team, distinguishing them from traditional designers, even though their task involves creating 3D design models for the building. Nevertheless, a participant from the BIM teams in the design organisation believe they possess BIM knowledge and provide support for traditional designers:

> *"Because we do not belong to design at present, BIM is now classified as a [separate] item. For example, there is building structure electromechanical on the design side. Now many of them also include BIM modelling.*

Building structure, water, heating, electricity, and BIM, [BIM] is equivalent to a professional. It is equivalent to saying that for a project, it is in a project team, and then there are all majors, and then BIM is now one of the majors." (DES3)

However, some participants seem unprepared to appreciate the complexity of BIM technology, even though the BIM model is considered to provide a more visualised building model for those with less professional construction knowledge. However, such highly visualised building models also present more transparent and accessible information for actors, which may not be relevant to some actors' practice. When the irrelevant information becomes overwhelming, at times, actors who lack related knowledge report experiencing 'heavy' and implicit demands to access the information from the BIM model, leading them to endorse their current way of practice, as mentioned by one from the sub-construction organisation:

"Just because its algorithm is different, all these sanitary wares expressed in CAD are very simple. Yes, but he will have every detail in Revit. In this case, the drawings you type on the plane will have more details, and sometimes it will interfere with the drawings. When the staff looks at the drawings, he may be blinded when he sees something. I feel this is a very complicated one, but I see so many details above, is there something else? [Sometimes] their construction on their side will also have something similar to a lightweight model, that is, if you can't understand something in the drawings, I can go to the lightweight model." (SCON5)

Legitimating BIM specialists

Legitimating BIM specialists refers to the way which organisations acknowledge and empower BIM specialists as key contributors to BIM-related decision-making, practices, and collaboration. This involves granting BIM specialists greater autonomy and influence within the organisation and recognising their expertise as essential for effective BIM implementation, fostering innovation, and ensuring successful cross-boundary collaboration. Utilising BIM in collaborative practice requires the cooperation of all parties involved. Some actors, such as decision-makers, may not know how to operate BIM technology or create BIM models. Consequently, the decision-making process might depend on the proposals or suggestions from BIM specialists. These experts have greater ownership over practices related to BIM technology and are likely to trust their own opinions. For example, the owner organisation, as the primary decision-making party across collaborating organisations, may also require an exclusive team with BIM expertise as their consultants, and thus, would tend to grant them more autonomy. This observation highlights the importance of legitimating the role of BIM specialists in the context of BIM-enabled collaboration, as mentioned by one from the design organisation:

> *"Party A hired a BIM consultant, in this form, for example, I am a Party A. For example, I think that the design organisation has a problem, or their attitude is wrong, the quality of the drawings is too poor, I am not at ease with his drawings. Then I will ask a BIM consultant and a BIM team to check their drawings, check their quality, just check and forget if it is right. right. Then give some opinions, of course, this method is basically completely responsible for Party A, which is completely responsible for Party A." (DES1)*

However, some BIM specialists expressed concerns that their perceived lack of legitimacy within the organisation could potentially reduce efficiency in BIM-enabled collaborative activities. When BIM specialists feel that their expertise and input are not sufficiently recognised or valued, it may hinder their ability to effectively contribute to decision-making processes and collaboration, as a BIM specialist from the design organisation mentioned:

> *"Basically, our BIM team has the final say with the design team, and they [the client-party A] only provide one idea. Yes, this can actually improve our efficiency, but what we are most afraid of is the kind of half-baked, they understand a little, but they don't understand everything, and then give you instructions blindly, but they are Party A. . . Sometimes this will greatly affect your efficiency, and they will change frequently." (DES1)*

5.2.2.2 Inter-organisational strategic configuration

This theme examines how organisational collaborative partnerships are embedded in cross-organisational collaborative activities. The findings indicate that innovation strategy-oriented configuration drives changes and dynamics in collaborative relationships between organisations due to differing digital innovation strategy initiatives. As a result, their capabilities become more distinct. When organisations implement various innovation strategies in their BIM-supported business, the altered collaborative relationships are reflected in congruent digital capabilities, power dynamics and expert legitimacy, and uncertainty of routinised business.

Congruent digital capabilities

The digital transformation process within an organisation can enhance its digital capabilities, addressing the knowledge difference between BIM-enabled practice and other professional practices. This is particularly evident in the more pronounced asymmetry of BIM technology-related project knowledge between organisations. The actors reveal that organisational digital capabilities might influence communication and negotiation between organisations, especially concerning co-created plans between the design company and the construction company. One of the managers in the construction company considered BIM-related knowledge as organisational capability, which is used for negotiation with the design company:

> *"As for our construction party, if we are not strong enough, it will be difficult to do it, because the drawings are used to guide the construction. [If] your drawings have problems, what should we do when we come to construction? [But if] we are particularly capable, to put it bluntly, we [will] give a multiple-choice question, and we will go through your drawings to deepen [design], and we will come up with a better [plan]. Tell us what the problems with your drawings are, we will give you solutions, [plan] 123, (let) you adjust, after you sign and approve, we will do it [according to the plan]." (SCON1)*

The asymmetry of BIM-related knowledge is also reflected in the differences in the significance assigned to BIM technology or BIM value in project decision-making. According to the participants, particularly BIM technicians, those responsible for coordinating various groups in the project may rely more on their extensive previous project experience and underestimate the relative role of BIM in decision-making, even though these coordinators may not possess adequate BIM knowledge. For those experienced coordinators, BIM represents just one of many modelling tools. Although technicians can integrate information and report potential problems using BIM technology, this advantage is not considered more significant than their own experience and judgement. The contradiction between knowledge gained by extensive experience and knowledge obtained through new technologies is directly reflected in the struggle between experienced coordinators and BIM technicians, as one participant from sub-construction organisation mentioned:

"Our Party A [the general construction] thinks that their current construction experience has been done for so many years, and the experience is actually very rich, so they think that BIM is just a tool, just as a tool to show to the clients. Then they just gave [us] a few months for us to model. After the model is completed, what procedure should be followed [just follow the procedure]…but when the general contractor needs to deliver the results, or production and construction, just when there are difficulties in this aspect, then they wants to base on past experience… there is such a lack, which then may need to be caused [the problem of program change], then this problem is information asymmetry, [they] feel that according to their own experience can also be done, [but in fact it can't be done], then this [at that time] will be more troublesome."(SCON4)

Power dynamics and expert legitimacy

The customary power dynamic between owners and contractors is disrupted when BIM technology-related knowledge is needed in practice. Decision-makers are familiar with conventional ways of thinking and their outcomes. However, when BIM artefacts are created during the project, requirements need to be re-clarified, and the differences in knowledge levels between employees and managers, as well as between owners and contractors regarding BIM technology, become explicit. Actors who hold less power in the relationship (i.e., employees or contractors) require more autonomy for decision-making, and the existing power relations cannot satisfy this need. Actors who hold more power in the relationship (i.e., managers or owners) often lack credibility in terms of professional knowledge and expertise, as mentioned by one from the design organisation:

"Party A is laissez-faire, they don't care about anything, they don't understand, and they don't want to understand, and now most of Party A, in fact, most of Party A in our design industry, they have some teams and some subordinates Most of the people are actually transferred from the design organisation. . . Basically, our BIM team and the design team have the final say, and they [Party A] only provide an idea. This can actually improve our efficiency, but what we are most afraid of is the half-toned kind. They [Party A] understand a little, but not all, and then give you

instructions blindly, but they are Party A again. . . Sometimes this will greatly affect your efficiency, and they will change frequently." (DES1)

When decision-makers lack relevant knowledge or expertise, their decision-making can significantly impact other tasks, potentially leading to an imbalance in upstream and downstream power relations. According to the participants, the dominant partner, Party A, if engaged in a single contract, may hold excessive decision-making power. The absence of adequate expertise and capability, coupled with decision-making authority, may result in situations where incorrect decisions are made. In other words, when actors with genuinely relevant knowledge and more effective experience are overshadowed by this power relationship and lose the opportunity to participate in decision-making, it increases the possibility of incorrect decisions, which in turn increases the number of tasks and costs of collaboration, as validated by one from the sub-construction organisation:

"In fact, this is mainly a management issue, and it mainly depends on the ability of Party A. For example, in this hotel project, Party A's ability is very poor, and there is often a lack of information [between us]. Because for Party A, there is our primary electromechanical party, a hardcover party, some general contractors, and other small subcontractors, such as consultants, and some manufacturers, so this is very important for Party A." (SCON7)

The clients' ability to manage technological innovation within the team is also crucial for excellent collaboration based on BIM technology. Poor team management can sometimes impede communication. However, this ability or knowledge of clients may also be regarded as a potential risk for BIM specialists, since the mismatch between knowledge and power means that when clients have not acquired sufficient BIM knowledge but maintain high control over the project team, they can hinder the capability of the BIM team to support collaboration.

Uncertainty of routinised business

Business routines among organisations in a construction project are relatively stable and embedded in the project artefacts (e.g., drawings). However, with BIM technology integrated into business processes, traditional rules and norms are challenged when managing new BIM artefacts, such as quality standards for building information deliverables across organisations. Typically, organisations in the project structure their behaviour based on their contracts with one another. Some BIM-related project experience, however, is non-transferable between actors from different organisations, which increases uncertainty in the project outcomes, as mentioned by one from the design organisation:

> *"We also divide BIM in the design phase and BIM in the construction phase, but the division is not so clear now, and the division was clearer in the past. In the past, the design stage was the design stage, and the construction stage was the construction stage. After the construction was clarified, we could ignore it. Of course, we still had to deal with problems, which means that most of them were ignored. But if we are doing the construction stage, [we] really need to [communicate] more frequently with the construction side. Because they also sometimes have this kind of results, we [among others] report the results to [ask] questions or something, that is, we need to mark out the special positions, and show the construction side to see." (DES3)*

Under the current provisions of contracts and industry standards, deliverables from each organisation at each construction stage are known and relatively fixed. This includes drawings which are considered important deliverables since they represent the building design and the requirements of Party A. Moreover, drawings also constitute the requirements for the code of conduct for all parties under their industry regulations (for example, the primary electromechanical design needs to consider reserving sufficient space for the layout of the subsequent secondary electromechanical). When BIM technology becomes part of this process, expectations might change; for instance, the construction organisation might expect more accurate architectural models from the design organisation. However, if the client expects deliverables from each organisation in a conventional manner, they may unconsciously hinder the use of BIM technology to efficiently produce this architectural information and knowledge in the project.

5.2.3 Project level

This subsection focuses on the configuration of collaborative activities within project-based collaborations among actors in the construction industry. These collaborations are typically built upon industry-based guidelines that regulate project deliverables at different stages. Project-based collaborations provide a short-term and intensive interaction context among actors, with the use of BIM technology both within and between organisations. Based on participants' accounts of their different construction project experiences, it is evident that project-based collaborative activities within the AEC industry are naturally constrained by the systematic tensions caused by distinct organisational capabilities, goals, and routines. Institutionalised collaborative activities are guided by industrial standards, norms, or contracts. The following subsections Illustrate this structural feature of project-based collaborative activities by identifying the collaborative business ecosystem forming the network for the collaborative activities surrounding the project goals. They also examine the role of industrial policies in guiding the innovation initiatives embedded in the project-based collaboration. Overall, this subsection provides insights into the factors that influence the configuration of collaborative activities within project-based collaborations in the construction industry.

5.2.3.1 Collaborative business ecosystem

Project-based collaboration enables organisations to work as a network towards a shared project goal, entailing systematic interdependence. The findings reveal that project-based collaboration can be seen as a collaborative business ecosystem that connects various collaborative activities, which include both the inner tensions among actors representing different stakeholders and data intercorrelation. This ecosystem fosters a culture of trust, cooperation, and mutual benefit, where participants share resources, knowledge, and expertise to achieve common goals. In the construction industry, the ecosystem connects multiple actors, such as architects, engineers, contractors, and subcontractors, who have different skills, experiences, and interests. The inner tensions among actors, such as conflicts of interest and power struggles, can arise within this ecosystem. However, effective collaboration supported by technologies such as BIM can help overcome these tensions and foster successful outcomes. Data intercorrelation also plays a crucial role in shaping the collaborative activities within the ecosystem. By sharing and integrating data, participants can make informed decisions and coordinate their activities effectively. Overall, the elaboration provides a comprehensive understanding of the concept of a collaborative business ecosystem and its relevance to project-based collaborations in the construction industry.

Artefact-enabled collaboration network

The findings reveal that project teams heavily rely on project artefacts to facilitate collaboration between various organisations and disciplines. Project artefacts, which represent information created by actors from different organisations and disciplines, can be material (e.g., blueprints) or digital (e.g., CAD models or BIM models). They are employed in various scenarios throughout project collaboration. The participants indicated that adopting BIM technology enhanced their professional knowledge, as BIM technology-related expertise became integrated into their disciplinary practice. As construction projects depend significantly on artefacts for collaboration, BIM artefacts provide a more visually comprehensive representation of information, thus revealing the potential limitations of a single perspective from just one discipline or organisation. These artefacts make the disciplinary differences more transparent and facilitate communication across teams within the network. As the MEP engineers from the sub-construction organisation mentioned:

> *"We can avoid 80% of the problems in this kind of in-depth design. For example, pipelines connecting our systems to the electricity supply pass through certain structures and move, resulting in shear forces. Professionals in these structural fields all need to communicate. Should the electromechanical engineer reserve a hole? In our BIM model, it is easy to identify which areas have obstructions, and these issues are exposed in advance. As a result, the construction site is less likely to become disorganised during construction, and conflicts among team members can be minimised." (SCON7)*

Artefact-driven adaptive collaboration lifecycle

The application of BIM-related processes to cross-boundary collaboration in a project is co-configured and re-configured during different stages of the project lifecycle, involving a multitude of activities. Projects vary in type, size, and scope, and the configuration of the BIM-related process need to be tailored to the characteristics of each project. The BIM-related process evolves alongside the project lifecycle. Although basic requirements for BIM use in the project are determined at the project planning stage, the actual implementation of BIM is influenced by the organisation's BIM capability and situated collaborative practices, requiring individuals and are temporally linked to the project lifecycles. The participants from the owner organisation elaborated their consideration regarding the entire project lifecycle:

> *"When we communicated with the design organisation at the early stage of the design, [we] did not need them to have to produce the BIM model, because it was not necessary, and this was not the final drawing we needed. Then don't waste time doing it. When it comes to the secondary*

electromechanical group, their secondary electromechanical personnel will sort out all the drawings, summarise them, and then produce BIM drawings" (OWN1)

BIM-facilitated artefact institutionalisation

Institutionalised rules are regarded as the benchmark to evaluate the quality of artefacts that also shape actors' behaviour during project-based collaboration within a collaborative network. The AEC industry has generated institutionalised rules which are commonly acknowledged by the various organisations and disciplines participating. This leads to an implicit consensus among actors about the quality benchmark of the artefacts, such as design drawings and construction drawings, at the project level configuration of collaborative activities. When BIM technology is used to generate artefacts, there is not always an industry-standard benchmark, so this 'implicit consensus' needs to be developed by the organisation itself. In other words, organisations create their own BIM-related standards that cater to their specific collaborative ecosystem. In this context, the conventional industry standards are viewed as the existing benchmarks, while the organisational standards are seen as new and informal benchmarks that evolve and adapt within the collaborative business ecosystem. This is validated by one participant from the contractor organisation:

"In terms of construction technology now, basically there are some [guidance] atlases in the entire industry… [Then] the company has some of its own things, but the entire industry is the whole industry. For example, if you have an atlas for your craft, it generally refers to what atlas, and then basically according to the national specifications [there are], what are the drawings, [then] on the basis of this, you will have higher requirements, It's all like that. Therefore, each company I mentioned may have different standards, but in fact, it is basically based on some standard atlases of the country." (CON5)

Furthermore, BIM technology is often regarded as an instructive approach to address the lack of standardised quality and guidance in conventional operations. For contractor or sub-construction organisations, BIM models can provide more detail and increase the likelihood of identifying unreasonable and unfeasible design issues. However, this substantive advantage relies on the actors from construction organisations' practice of using BIM models, meaning they may need to remodel the designs from the design organisations themselves, further integrating BIM into their collaborative processes and contributing to the establishment of BIM-related standards and practices. A participant from the sub-construction organisation indicated:

> *"…we do the BIM for construction, we will reorganise the model, and then re-organise all the piping systems, and then there will be some pipeline intersections and unreasonable places [found], we will propose and give optimisation. Then, if the actual construction person holds our drawings, many on-site problems will be avoided." (SCON7)*

5.2.3.2 Policy-backed innovation initiatives

According to the study participants, the construction industry is a mature traditional industry with relatively stable craftsmanship and management methods that promote stability and predictability in risk, time, and cost control of construction projects. However, the introduction of BIM technologies, while potentially innovative, also increases instability, particularly when organisations face high financial and time costs, leading to weakened motivation for innovation. Nevertheless, the industry's overall development requires numerous projects to continuously experiment and introduce innovation. Therefore, the direction of project development needs to be highly dependent on the guidance and promotion of policies. An interviewee from the owner organisation showed their opinions regarding on the BIM-related policies:

> *"This is a group of BIM systems in one project. A project of 500,000 yuan is really not something that ordinary projects can handle. . . For example, government departments have made progress in this area, which has something to do with BIM in the past two years, because I think many of them are produced by them. Policies determine what kind of digital transformation the construction industry needs. . . It depends on what the development need of the government is." (OWN2)*

From the perspective of one participant from the design organisation, these initiatives primarily focus on project deliverables. The adoption of BIM technology necessitates clear instructions and rules to inform the creation of deliverables throughout the project lifecycle:

> *"In some cities, the government has begun to force you to use BIM. As I told you just now, to apply for a project planning certificate, you need to*

bring the BIM model along with the drawings and report the work regulation certificate. No work can be done until the work permit is reached. All projects like these must have BIM. In some places, it is equivalent to, in other words, the government is forcing you to do BIM." (DES1)

5.3 The role of BIM technology

The results of the thematic analysis can be found in Table 5.4. The following subsections provide a detailed explanation of the themes and codes resulting from the thematic analysis on the role of BIM technology. At the individual level, BIM technology is found to play both a practice and tool role depending on actors' diverse interactions and perceptions of BIM technology. At organisational level, BIM technology plays both structural and symbolic roles for organisations, enabling them to implement new business processes and display their digital capabilities. At project level, when BIM technology is involved in the construction project, it can facilitate transformative change for each related project team, with potential long-term consequences.

Table 5.4: The role of BIM technology for professions, organisations, and project teams

Level of analysis	**Theme**	**Code**
Individual level	BIM as practice	BIM-enabled innovation and problem-solving
		BIM value creation and dissemination
		BIM knowledge sharing and learning practices
	BIM as tool	BIM perceived as a tool
		BIM used as a tool
Organisational level	BIM as an emerging structure	Adapted work routine
		Demarcated work and decision-making mechanism
		Collective trust in technological innovation
	BIM as symbol	Organisational digital image
		"Qing Huai"
Project level	BIM as a facilitator	Navigating collaborative dynamics

		Innovation enablement
	Policy-backed innovation initiatives	Policy-backed innovation initiatives

5.3.1 Individual level

The role of BIM technology at the individual level is reflected in professionals' perceptions of how they incorporate BIM technology into their tasks, their interactions with others using BIM technology, and the influence that BIM technology plays in their daily professional practices. Actors' reflections highlight two perspectives regarding the role of BIM technology: BIM as a practice, and BIM as a tool. These perspectives relate to the dynamics of actors' interactions with BIM tools and artefacts. On the one hand, BIM technology as a practice is used by professionals to complete their tasks and interact with others for collaboration, employing BIM tools (e.g., BIM software) and BIM artefacts (e.g., BIM models). On the other hand, actors also share their perceptions of the role of BIM technology as a tool that enables coordination by illustrating the observed consequences of adopting BIM technology in their work.

5.3.1.1 BIM as a practice

BIM as practice refers to the ways in which professionals actively engage with BIM technology, such as creating and updating BIM models, using BIM software for analysis and coordination, and collaborating with team members through digital platforms. By integrating BIM into their work processes, actors view the technology as transformative, changing their work routines and becoming embedded in their daily tasks. This perspective also acknowledges the influence of mutual interactions among professionals on the use of BIM. Reflecting on the role of BIM, actors recognise its impact on their BIM-enabled practice and the underlying rationale for their actions. The BIM-embedded practices include BIM-enabled innovation and problem-solving, BIM value creation and dissemination, and BIM knowledge sharing and learning practices.

BIM-enabled Innovation and Problem-solving

BIM technology has the potential to enhance innovation and the problem-solving capabilities of professionals in the construction industry. By adopting BIM as a practice of innovation, contractors can use BIM to bring their innovative technical ideas to life on the actual construction site. BIM enables actors to integrate their knowledge with BIM solutions and find optimal solutions for their tasks. This is exemplified by the BIM detailing process, which provides opportunities for identifying potentially different understandings and conflicts between designers and contractors during the construction phase. This situation has been mentioned by one from the own organisation.

> *"First, he [a technician from the contractor organisation] took the design organisation's drawing to find out the problem in the BIM model deepening stage, like which piece was missing a valve…. The model can be found now to help the designer find the problem. He [the technician from the contractor organisation] knows the construction process." (OWN1)*

However, while BIM can reduce gaps between the actual construction and the designers' understanding of it, BIM modelling in practice still has limitations in predicting on-site construction situations and potential modifications. For instance, if minor building issues arise, designers may decide not to modify the BIM models, as it is too complex and not worth the effort. Meanwhile, contractors may opt to loosely reference the models during the actual construction process. This decision, however, can lead to inconsistencies between the building models used in practice and those designed, ultimately increasing both designers' and contractors' distrust of the BIM model's flexibility in the actual construction processes. As indicated by one from the contractor organisation:

> *"This model adjustment is a comprehensive thing. On the [construction] site, I might tell them [the builders] to follow this model, but there are some parts of the site where the structure is different, or there are some differences [with the actual construction situations], and they can't make it. In many situations, it was impossible for us to adjust the model then, and it didn't make much sense to adjust the model. At that time, I [told them] that we could do it directly. . ." (CON7)*

BIM Value Creation and Dissemination

Creating, and disseminating the actual value of BIM technology is an important aspect of BIM-related practice among professionals collaborating on construction projects. The creation of building information using BIM technology is the first step towards value creation. Disseminating the value of BIM artefacts to others is also important for actors to create shared acceptance and awareness of its value for efficient work practice.

However, due to the varying levels of understanding of BIM-related work and the emerging BIM value within the construction project, actors may show differing levels of acceptance and awareness of the integration of BIM technology into work practices, especially before the BIM-related work is specified. Most actors who take up BIM-related work expressed their preference for demonstrating the value and benefits of BIM work in advance to constitute shared acceptance and awareness of BIM value.

Some actors who plan how BIM will be applied to the project usually consider and discuss the role of BIM and whether the workload of BIM modelling merits the time and effort required. In these cases, BIM specialists and project managers will negotiate to specify more accurate tasks related to BIM, ensuring that BIM-related work creates real value for the project and is disseminated to other stakeholders. One project manager from the owner organisation presented their understanding on the BIM value in practice:

> *"Because, for example, the secondary electromechanical diagram, XXX drew the secondary electromechanical CAD drawings. She felt that there was no problem in theory. I'll start to implement it. [Therefore] It is not worth anymore for them to do BIM [models] for me. If we meet any problem, we can just negotiate and mediate with each other."(OWN2)*

The dissemination of BIM value to others varies depending on the experience and the knowledge base of the involved actors. BIM specialists consider the visibility and permeability of BIM value as crucial for the collaboration among professionals. To enhance its visibility, they share successful BIM-related experiences and highlight potential benefits of BIM technology to their collaborators. The significance of BIM value disseminated in practice has been suggested by an interviewee from the contractor organisation:

> *"In terms of benefits, because we satisfy their construction [company], they will definitely be more willing to accept some of our opinions or suggestions... [but for Party A] Simply put, let the people of Party A Know, the money is spent... They need to know, although they don't understand, they need to see [the value of BIM]." (CON1)*

BIM Knowledge Sharing and Learning Practices

Actors also mentioned learning about BIM as part of their collaborative practice. Due to the diversity of project experiences and knowledge domains, learning from others is common among actors, especially for interprofessional collaborations. When one of the contractor organisations reflecting on their BIM engagement and learning practices, the 'learning' practice includes not only learning the BIM-supported modelling process or technical knowledge brought about by new digital technologies, but also learning from other projects or expertise in the collaborative process, such as the typical content of a 'waterproofing layer'. This knowledge may be familiar to on-site technicians, but it may be vague for inexperienced estimators to assess from plan drawings. By integrating BIM technology into their work and interactions, BIM-related knowledge-sharing and learning practices can reskill and upskill actors in different knowledge areas, not just BIM-related technical knowledge:

> *"Our [different departments] study [BIM content] is the same. The main reason is that many BIM applications [software] now exist. We have to learn each software, and everyone must master it. The main reason is that we may want to achieve the goal in the future. That is, each of our departments can use BIM applications to make our job a little easier... For example, if we build this model now, it is actually in the modelling process because we also have to look at the drawings. Then we can understand [building information] very clearly, for example, what is the structure of this building?... and then… [This BIM learning process] is quite helpful for this piece." (CON4)*

In addition, participants also collaborate to share knowledge. Regardless of their role, most participants can identify the role of BIM technology in collaborative practice, which prompts them to share their experiences or recognition of BIM or to learn from others. The specific knowledge sharing with BIM-enabled practice has been mentioned by another participant from the contractor organisation:

> *"I can learn some from some of their chats. For example, some simple ones, such as some "mirrors", I can directly find a more convenient mirror in half, and these [skills] are still learned. Yes, and then they mentioned some new words at that time [during the chat], if I didn't know it, I would*

ask, and then they would teach me to do these [operations]. . . These are gradually learned from their chat." (CON3)

5.3.1.2 BIM as a tool

BIM as a tool refers to actors using BIM technology with the expectation of achieving their substantial objectives through collaboration. This expectation is founded on the technological possibilities that can bring about efficient collaboration. Participants were found to embrace a BIM technology-in-use perspective that emphasises the consequences or influence of using BIM technology regarding the actor's intention, the expectation of using BIM, and the evaluation of BIM technology use. By focusing on the actors' demonstration of their work practices with BIM technology and their reflections on how BIM technology does or does not work, two perspectives were identified: BIM perceived as a tool and BIM used as a tool.

BIM perceived as a tool

BIM perceived as a tool refers to the way actors view BIM technology as a means to achieve their collaboration objectives. From this perspective, actors perceive BIM technology as a useful tool for their work, which can facilitate their collaboration by providing features and functionalities that are aligned with their project goals. For example, BIM's increased visualisation capability was viewed as a valuable tool for sharing information and knowledge easily among actors from different disciplines in the project. Thus, the perceived functionality of BIM aligns with actors' actional goals, and actors proactively engage with BIM technology to achieve their collaboration objectives. One participant from the owner organisation in the study tended to view BIM technology as particularly suitable for complex projects with complicated structures and high-spec designs, where the features of BIM technology were seen to be aligned with the project's requirements:

" …BIM…it is suitable for such buildings with complex scenes, complex structures, and relatively high elevation requirements." (OWN2)

Actors' perceptions of the project's complexity reflect the high requirements of building data accuracy and details and BIM models are believed to functionally achieve detailed representation through its visualisation, as mentioned by one participant from the owner organisation.

"On the BIM [model], a screw, a hanger, and a tripod are all displayed in a complete manner, so we can see in three dimensions what these things look like and what kind of problems they can solve." (OWN2)

In the context of BIM perceived as an advanced tool, actors, especially project managers involved the construction and construction personnel, utilise BIM software to enhance the visualisation of complex pipeline designs in the detailed design process of electromechanical pipelines. This facilitates decision-making by providing a clear understanding of the building model through the generation of a 3D model, which visualises the arrangements. One project manager from the sub-construction organisation reflected how and what he perceived BIM models can support the work:

"BIM is mainly about hardcover [it can play a role], it is a display function, and the specific size must [need] be controlled by traditional detailed design [two-dimensional drawings]. Then in terms of pipeline electromechanical, the early stage [BIM aspect] is well coordinated with primary electromechanical, which mainly affects some hidden things in my elevation, [but BIM] does not involve other functions [on the design]." (SCON1)

Actors' perceptions of BIM as a useful tool are shaped by their experiences and may vary based on their familiarity with the technology and their specific needs in the project. By combining BIM technology with their existing experience, actors gain the possibility and confidence to explore and implement innovative solutions. When reflecting on their past work experiences, participants have demonstrated a tendency to seek out better solutions, and BIM provides a new technology that can facilitate this process. For example, the accuracy of BIM models is a characteristic that actors perceive as a useful tool for achieving their objectives in collaboration. As mentioned by one from the contractor organisation:

"Now we are still in the initial stage, that is to use Revit [a kind of BIM software] to model, and then we want to achieve the goal [need] through the application of the whole BIM [technology], and then make our materials purchase this piece, has a slightly more precise prediction, such as how many formworks and concrete are needed for this house, [BIM] mainly [can] make this prediction, and then reduce the waste of our materials." (CON4)

However, BIM is not always perceived as a useful tool due to its constrains for some cases. For example, actors also perceived that the graphic visualisation function of BIM modelling software can make specific numerical information unclear, especially elevation information, which is typically displayed in a more standardised way in two-dimensional drawings. The overload of image information in the BIM 3D model is perceived as weakening the numerical information, leading to a less consistent understanding of the information, which may affect the decision-making process. These perceived constraints lead actors to use the BIM model only in the most suitable situations rather than forcing it into expected use cases. This can be confirmed by a practitioner from the contractor organisation:

> *"In terms of construction, at least in our current understanding, two-dimensional drawings are indispensable. Yyou can also achieve three-dimensional annotation, but it may be more troublesome or more challenging to implement.." (CON5)*

According to practitioners, a 2D drawing is a better choice than 3D models since its instant operability allows them to understand and share information immediately. Practitioners normally make notes on the drawings but cannot achieve this when using the digital models. This practice helps them to organise information when working on the subsequent floors of the building. This occurs because during the project's timeframe project collaborators may need to go back and check their decisions made during the previous stage to anticipate potential problems at the next stage. In this case, physical drawings can satisfy this process rather than BIM tools.

BIM used as a tool

The user's tool view of BIM technology illustrates how actors deliberately and strategically employ BIM as a tool for their work and collaboration, based on their subjective understanding of the technology. Practitioners may choose to use BIM to support their own practice and tailor their usage for specific needs. The findings reveal different views among various actors, demonstrated by their reasons for choosing the tool and the functions they assign to it.

For example, according to a participant from the owner organisation, they acknowledge that the initial drawings created were not the final ones needed for the project, suggesting that creating BIM models with such great detail at this stage may not have been necessary. Designing BIM work is regarded as a wasted effort when they are already familiar with the drawings. Instead of using BIM to create the initial design models, they prefer to utilise BIM by clarifying all details with its accuracy feature to verify that the initial drawings can meet their needs more efficiently:

> *"This is not necessary because the drawings he made are not the final drawings we need. Then there is no need to waste time. When it comes to the secondary electromechanical unit, we finished sorting, summarising, and then producing BIM drawings, and then it was time to create BIM models because, at that time, it was to use BIM to prove whether his mechanical and electrical drawings were correct or not and whether they were implementable or not, it was like this way of working." (OWN1)*

The way of using BIM as a tool is believed to relate to the decisions from high-status actors in the project, such as project managers, they make decisions on how to use BIM tools. For example, sometimes, the project managers emphasise their rich experience and advocate BIM as a similar modelling tool to their conventional modelling tool (CAD). By trivialising the role of BIM and BIM professionals' knowledge, they treat the use of BIM as a technical ability rather than an enhanced capability to uncover potential hidden issues (e.g., confusion caused by complex pipelines). As a result, people who make significant decisions might be unaware of how the BIM specialists will complete their tasks. This leads to the proposal of unreasonable demands or unrealistic requirements by decision-makers based on their previous experience rather than embracing new knowledge. The participants from construction organisation confirms this:

> *"They think that it means that their current construction experience has been done for so many years, and the experience is actually very rich, so they think that the closing is just a tool, just as a tool to show to the leaders, then it is But that means it's not so worrying about this one, right? Then he just said that, for example, he would give you a few months to model. After the model is completed, what procedure should you follow? Not sure if it is used or not." (SCON4)*

In this case, as described by another practitioner from the sub-construction organisation, the actual efficiency of the BIM model has not been prioritised. Instead, the focus is on whether the leader perceives that BIM has been used in the process, rather than its genuine contribution to the project. This approach may lead to BIM models that do not fully meet the needs of the construction team, as they should. This discrepancy between expectations and perceptions of

BIM technology results from using BIM as a tool to demonstrate technical competence rather than harnessing its full potential for collaborative and practical applications in the project:

> *"There is a thing in BIM to make an animation tour. To be honest, I only need to make a tour of this project and show it to the leader. There are 3D animations running in it, so I can give the leader a sense (that we are using BIM). In fact, it is foolish and failing to truly implement BIM."(SCON5)*

5.3.2. Organisational level

This subsection explores the role of BIM technology at an organisational level, focusing on its impact on organisational structure and as a symbol during the digital transformation process. It investigates how actors perceive the collective value and influence of BIM technology on organisational business and management. The findings suggest that BIM technology use may affect organisational structure when integrated into organisational routines. Furthermore, while it is not always directly linked to business performance, BIM technology can symbolically serve as a driver of competitive advantage. This phenomenon is related to the organisation's image and "Qing Huai", a form of technology determinism-driven leadership associated with digital transformation.

5.3.2.1 BIM as an emerging structure

When BIM technology is integrated into organisational collaborations within construction projects, structural changes occur as it transforms actors' conventional practices in intra- and inter-organisational activities. Participants from various organisations involved in the project reported that the integrative nature of BIM technology allows for immersive exchange of building data and information, redefining their work practices and relationships. Moreover, the structural properties of BIM technology's integrative capabilities facilitate the transfer of cultural changes regarding trust in technological innovation within intra-organisational and inter-organisational collaborations. The structural aspects of BIM technology in organisational collaboration can be categorised into three dimensions: adapted work routines, demarcated work and decision-making mechanisms, and collective trust in technological innovation.

Adapted work routine

From the interviews from the contractor organisation, it was found that the implementation and use of BIM within organisations and projects creates new work routines and ways of organising for most project team members. With BIM incorporated into the collaboration process, there frequently seems to be a transformation taking place, especially for individuals and organisations with the project. Changes are frequently occurring in a construction project, e.g., change of requirements from the owners, change of solutions due to more information gathered to solve a technical problem. BIM can play a role as a bridge between innovative approaches and conventional approaches to assist the collaboration. One participant from the sub-organisation illustrated the approach they adopted for their current work routine:

"We will also use some [BIM-related] platform technologies, such as transferring business models to the shared platform. This kind of thing that everyone can watch together when they are in a meeting... It is a cloud platform... You can go to the platform when you are in a meeting. And It is also very convenient when you are coordinating work and managing." (SCON4)

Most predictive modelling tasks need to be done during the pre-construction stage so as to avoid more unexpected changes occurring later as mentioned by one from the sub-construction organisation:

"We can avoid 80% of the problems in this in-depth design." (SCON7)

Demarcated work and decision-making mechanism

Project team members need to decide which tasks are related to the BIM work. BIM technology increases the need for building information accuracy and data precision, which means more design work needs to be done. This situation leads to the re-deployment of work among different disciplines and ambiguity in the division of labour in intra- and inter-organisational collaborations. Thus, BIM effectively reconstructs the division of labour at the beginning of the project. Participants from both contractor and design organisations reported that this seems to have more influence on the decision-maker organisation, i.e., the owner organisation in the construction project:

"In the bidding process, it is directly in the accounting workloads, and it has been divided into their respective functions." (OWN2)

However, even though BIM technology can contribute to closer inter-organisational collaboration through the ambiguity it introduces into work tasks, there are also contradictions and constraints related to the outputs of their work (e.g., BIM models constrained by different regulatory standards/requirements for deliverables of different organisations in the industry), as confirmed by one from design organisation:

> *"We have this standard now, but because design and construction are different. The purpose is different…Therefore, if the standards differ, this cannot be handed over. This is the biggest contradiction, which is called a data outage." (DES2)*

Collective trust in technological innovation

Collective trust in technological innovation refers to the trust that organisations place in technological advancements like BIM technology, which fosters collaboration within the industry. Some professionals in the AEC industry have been reluctant to change their conventional practices to avoid the high costs of technological innovation. According to participants from sub-construction organisations, improved project performance due to BIM technology conveys and establishes confidence for organisations in applying BIM technology, and increases their collective willingness to collaborate within the industry using BIM technology in the future at organisational level. As mentioned by one BIM specialist from a sub-construction organisation, this is how collective trust has been established:

> *"After we cooperated with these projects, our construction unit is quite satisfied because we can really help them. A lot of things have avoided a lot of repeated dismantling and modification in the later stage and the negotiation of all parties. Basically, they took the [BIM] model, and then raised the material and covered it up, and they didn't have to worry about anything." (SCON7)*

5.3.2.2 BIM as a symbol

The following elaboration is appropriate for the "theme "BIM as symbol": Across the interviews, there was a general consensus that adopting BIM technology symbolises an organisation's commitment to innovation, especially in the context of inter-organisational collaboration processes. As a result, developing BIM capabilities is seen as essential for increasing competitive advantage, both in the construction project bidding process and for enhancing an organisation's long-term digital image. For some top managers in this study, using BIM technology represents high quality and performance in the project. This perceived value has also been identified as a spontaneous motivator, along with personal sentiment, for integrating BIM technology into organisations or projects – a concept referred to by the actors themselves as BIM – "Qing Huai".

Organisational digital image

Organisational digital image emphasises the perception of BIM technology as an indicator of an organisation's commitment to innovation and professionalism. It suggests that incorporating BIM technology can enhance an organisation's reputation and increase its chances of being recognised for excellence in the industry. The use of BIM implies an improvement in the organisation's image, which demonstrates organisational capability and competence. BIM sometimes symbolises technological innovation in organisational and project collaborations, primarily from the owner organisation's perspective, especially for large and advanced firms. From the perspective of top management, BIM is regarded as capable of achieving better quality for different disciplines in the project, as mentioned by one from the owner organisation:

"For example, if companies want to apply for an award, they will consider using BIM."(OWN2)

Moreover, BIM use is regarded as a kind of competitive advantage for projects. The adoption of BIM technology can attract potential clients and partners who value technological advancements and seek organisations that prioritise digital transformation. By incorporating BIM into their operations, organisations can present themselves as leaders in their field and appeal to a broader range of stakeholders, as one interviewee from the contractor organisation said:

"That is to say, through the application of BIM, it may be of great help to our whole project, that is, the core competitiveness in bidding." (CON4)

BIM specialists' previous rich and successful BIM-related experience can also be regarded as a symbol of their capability that increases trust in and knowledge of BIM technology from other actors, such as BIM users or BIM observers. Industry awards are also regarded as important for legitimating technological performance and improving the organisation's innovative image and competitive advantage. This is confined by one BIM specialist from the designer organisation:

"Basically, we will use a successful project in the past to give them a simple example, which is more intuitive." (DES1)

“Qing Huai”

“Qing Huai” is a Chinese word, represents a personal sentiment or emotional attachment that individuals, particularly those in leadership positions, have towards the adoption and implementation of BIM technology within their organisations or projects. These leaders view BIM technology as a symbol of innovation and professionalism and maintain a positive attitude towards its adoption, believing that it will yield good results. "Qing Huai" can be seen as a form of technological determinism, wherein the leader decides to incorporate BIM technology into their business processes, who actually promote the implementation of BIM technology, even if they lack sufficient evidence to support this decision. They strongly believe that BIM technology can bring about significant change and innovation potential for their organisation and its employees. This personal connection might influence their decisions and promote the adoption of BIM technology as a symbol of innovation and professionalism, even if the results may not always align with their ideal or expected outcomes, as mentioned by one employee from the owner organisation:

> *“Because our vice president in charge of leadership is from the design organisation, he has this feeling of “Qing Huai”, he thinks [BIM] is more professional and perfect, anyway, it will be easier for the later construction, but it is not the case.” (OWN2)*

5.3.3 Project level

The exploration of BIM technology at the project level focuses on its role in project-based collaborative networks. Participants’ related experience of project-based collaboration emphasises the influence of BIM technology on project goals, life cycle, and deliverables. Sometimes, BIM technology use is only nominal in the project. The potential for transformative outcomes shapes BIM implementation and use, leading to the generation of transformative impact and its consequences.

At the project level, the goal is joint collaboration across the entire project team. However, to some extent, project teams have different objectives. To achieve consensus, they need to build a shared joint community of practice to ultimately establish a common direction. BIM-enabled transformative change may have a long-term influence on the organisation’s entire digital transformation. To explore this influence, it is necessary to identify the types of transformative change that have occurred, such as changes related to BIM technology use, which could involve

BIM specialists, BIM practices, and/or BIM tools/artefacts. Furthermore, transformative change implies that BIM technology would have had an impact on actors' perception of conventional collaboration, including collaborative practice/patterns, identities, culture, or more structural aspects.

4.3.3.1 BIM as a facilitator

At the project level, the use of BIM technology results in a more efficient path for different actors to achieve their project goal. BIM facilitates a new organisation of work among actors from various project teams, challenging conventional collaborative patterns between organisations due to the introduction of BIM-related practices and artefacts. BIM technology-enabled projects provide opportunities for diverse organisations and stakeholders to interact, increasing exposure to distinct BIM visions and strategies. The turbulence experienced within the project-based network encourages practitioners to re-examine project-based collaborative relationships that rely on conventional collaborative practices.

Additionally, BIM technology lowers the threshold for innovation in projects, even though it may conceal deeper underlying issues. The resulting performance improvements due to BIM are believed to significantly influence key decision-makers' perceptions of BIM technology. This subsection explores the facilitator role of BIM technology in project-based collaboration through three aspects: navigating collaborative dynamics, and innovation enablement.

Navigating collaborative dynamics

Navigating collaborate dynamics captures the tension between temporary collaborative relationships, highlighting how BIM fosters the flexibility in navigating these dynamic interactions. Changeable, temporary collaborative relationships among individuals, groups, and organisations involved in project collaborations imply the uncertainty of cross-boundary practice. According to participants, the stability of the collaborative practice is built upon steady and systematic collaborative structures developed long-term in the AEC industry. These structures are built on disciplinary knowledge and industry standards, forming the collaborative relations and basic of cooperation. Participants emphasised the significance of the 'common sense' existing in the industry standards that enables them to know 'what to do' for each other:

"The main, each very clear document, that is to say, there is some general industry consensus, about how to do it, there will be some [consensus] in this regard." (CON1)

While the multiplicity stakeholders' engagement of the BIM technology fosters the flexibility of the partnership. The nature of temporary project collaborative relationships is also reflected in the responsibility of the roles of BIM-related deliverables from different project stages. For example, a participant from the design organisation mentioned about the change on their partnerships with others in the project lifecycle:

"We also divide the closing of the design phase and the closing of the construction phase, but the distinction is not so clear now [after introducing BIM technology], and it was clearer before. In the past, the design stage was the design stage, and the construction stage was the construction stage. After the construction is revealed, we can ignore it. Of course, if there are problems, we still have to worry about it, that is to say, most of them do not need to be done." (DES3).

Innovation Enablement

BIM technology plays a significant role in lowering innovation thresholds and facilitating innovation capabilities. Participants' reflections demonstrate how BIM encourages the adoption of new ideas and practices in projects. BIM artefacts enable the visualisation of building information, assisting practitioners in identifying practical issues that may not be explicitly represented in conventional drawings. If a BIM-enabled modelling process can help identify potential problems that might arise in practice, changes can be made proactively, thus addressing the problems in advance. One participant from the design organisation indicated that prediction is crucial to decision-making in construction projects, and BIM technology effectively supports this process:

"The main thing is to look at the [potential] problems… if I use BIM to draw them, they will look at this and find there might be some problem with it…because all the pipelines are put together, they are not so intuitive, [with BIM model] they can see with their own eyes what this thing looks like when it is placed there, and the specific sense of space." (DES4).

While BIM technology increases the possibility of linking different models through built-in modelling logic, allowing building information to be updated more promptly and enabling designers' ideas to be iterated accurately and swiftly, it also raises challenges for on-site practitioners who are the actual model users. They may have fewer hints and clues about the changes that have occurred and might be uncertain about whether operational changes are required when the model design changes, such as the need to alter materials. As mentioned by a participant from the sub-construction organisation, this built-in modelling logic is perceived to increase the invisibility of potential problems:

> *"In fact, this is a software problem, or a software optimisation problem. There may be some built-in logic and algorithms inside, and it may have some problems when it is used. Cause these problems are invisible, you know?" (SCON5)*

5.4 Contextual conditions of the BIM-enabled collaboration

The results of the thematic analysis can be found in Table 5.5. The following subsections provide a detailed explanation of the themes and codes resulting from the thematic analysis. Finally, the contextual conditions for individual-level BIM-enabled collaboration are artefact-oriented, which carry a relational structure for organising actors working together. It refers to the arrangement of BIM-enabled collaboration naturally following the artefact development process (such as create, use, and review) among different professionals. At the organisational level, the hierarchical management and contextual conditions of BIM-enabled collaboration at the organisational level characterise digital innovation in the organisations. At project level, the changing perceptions of BIM-enabled collaboration are regarded as temporally related to four main processes embedded in the different project stages: shared collaborative vision, shared artefacts creation process, shared technological perceptions, and shared precognitions.

Table 5.5: Professional, organisational and project context of BIM collaboration

Level of analysis	**Theme**	**Code**
Individual level	Building model developing and circulating	BIM-related integrated knowledge application
		Multi-faceted assigned responsibility

		Advanced cognition of design workflow
	Building model assessing and using	BIM technology adaptation
		BIM capability
		Outcome-driven value
Organisational level	Digital innovation leadership formation	Transformational Leadership
		Performance-driven value recognition
	Management and culture establishment	Inadequate resources support
		BIM artefacts evaluation mechanism
		Establish the learning culture
	Operational Integration and User Engagement	Technology-centric organisational learning paradigm
		User resistance
Project level	Shared collaborative vision in planning stage	Complexity-driven trade-offs and compromises
		Reliable BIM team performance
	Shared collaborative value and norm in designing stages	Quality standard awareness
		Professional identity clarity
		Coordination process adaptability
	Shared technology capabilities in construction stage	BIM practice alignment
		BIM team integration and support
	Shared optimism for future BIM impact in Operation and Maintenance Stage	Positive attitude and expectation

5.4.1 Individual level

The contextual conditions of BIM-enabled collaboration at the individual level play a crucial role in shaping the overall success of BIM-enabled collaboration. These conditions focus on the abilities, skills, knowledge, and communication capabilities of individual professionals as they contribute to various phases of building modelling, including development, assessment, and presentation.

This subsection presents the relationship between the collaborative activities and the use of BIM technology at the individual level, which is identified in different phases of the artefact's development process. With the use of BIM technology becoming part of the conventional building information modelling process, the quality of the artefacts involved in the modelling process through the interaction of actors can affect the professional practices with BIM technology.

The use of BIM technology, embedded in actors' different practices, is associated with three phases of the building modelling process: 1) building model developing and circulating, 2) building model assessing and using, and 3) building model displaying and reviewing. Within the different phases of the building modelling process, the participants in this study link the development of BIM artefacts to their expertise/ability and assigned responsibility.

5.4.1.1 Building model developing and circulating

The development and circulation of BIM artefacts are undertaken by various professionals, known in this study as BIM specialists. These specialists possess advanced knowledge of BIM technology and dedicate their time to learning and creating innovative building information artefacts. Their role is multifaceted, involving the sharing of BIM knowledge by completing assigned tasks and interacting with others to transfer their BIM work, including innovative building model artefacts. BIM specialists are also responsible for presenting and promoting the value of innovative artefacts created using BIM technology. They communicate with people from multiple disciplines and organisations within the project and embrace a wide range of knowledge domains.

These individual professional attributes relate to the individual-level contextual conditions of BIM-enabled collaboration, as they emphasise the aspects that contribute to the effective use of BIM technology during the building model development and circulation process. These attributes underscore specific aspects of an individual's professional capabilities, responsibilities, and cognitions on the building modelling process, which together shape the collaboration and BIM implementation outcomes. The following elements have been highlighted: BIM-related integrated knowledge application, multi-faceted assigned responsibilities, and advanced cognitions of design workflow.

BIM-related integrated knowledge application

Integrating knowledge comprehensively is crucial for successfully embedding BIM technology into existing building modelling practices. BIM specialists, as described by the participants, are more likely to demonstrate this capability compared to other professionals. They believe it is essential to possess not only BIM-related knowledge but also cross-disciplinary knowledge, encompassing architecture, engineering, and construction. This is because their work requires them to integrate information and data from different disciplines and perform clash detection within BIM models. Additionally, they may need to take over tasks from various disciplines, necessitating effective communication and negotiation with actors from different fields. For example, as mentioned by one BIM specialist from the design organisation, their comprehensive knowledge enables them to identify problems, conflicts, and negotiate solutions with others. The act of revising the building model provides an opportunity for BIM specialists to identity any problems and conflicts from a different viewpoint for other designers:

> *"We help them find problems, and then coordinate with them after we find the problems. Then [discuss] between each design to see how it can be changed, and then this requirement can be met." (DES4)*

When BIM specialists integrate the knowledge and interests of different actors to solve problems, the ability to combine various knowledge domains (e.g., construction, design) may lead to providing technological solutions for achieving objectives more effectively. This contextual factor becomes more pronounced when implementing BIM technology in collaborative practice. The successful application of BIM-related integrated knowledge by BIM specialists in BIM-based work may contribute to the collaboration by offering innovative solutions to resolve conflicts among actors.

Multi-faceted assigned responsibilities

Multi-faceted assigned responsibilities refer to the fact that BIM specialists, who develop and circulate building models, often take on multiple responsibilities within their organisations or projects. Generally, organisations aim to demonstrate competence through innovation, and as a result, may promote the use of BIM in their projects as evidence of innovation. Consequently, BIM specialists take on the responsibility of applying BIM in the project. In this process, they are responsible for sharing and transferring their expertise to others involved in the project. Although not formally designated as trainers, they informally act as individuals responsible for transformative learning within their organisations during the project. However, organisations often lack specific demands, requirements, or guidance to support such roles, making it challenging for BIM specialists to operate and manage effectively, as indicated another participant from the contractor organisation:

> *"... He [BIM specialists] also trains us for free, sometimes he is a little annoying to the leader, and the leader will put him under pressure, so I ask him how we are doing, because he is also about the same age as everyone, and he is impossible to push to restrain us [to learn]." (CON2)*

A BIM specialist from the sub-construction organisation indicated that their role is versatile and not fixed. Due to their wide-ranging knowledge and work content, they also navigate between different professionals and stakeholders to achieve different objectives using BIM approaches:

> *"It's not limited to the projects I'm doing now. In fact, in daily life, my positioning here is actually relatively strong in mobilisation and mobility. Start with the modelling of civil engineering and electrical, and then adjust the pipeline integration, right? I will definitely do all of these, and then include some hardcover projects, which are usually mine. Then there will be effect display, animation, and roaming after the hardcover. I will also do these things that Party A will watch." (SCON5)*

BIM specialists also indicate that they play a role in translating the information from building models to others. This translation is sometimes undertaken to connect others' existing knowledge with the BIM models, so as to enhance the understanding of the presented information and data from the BIM models. This further highlights the versatile and adaptive nature of their roles as they collaborate with different professionals and stakeholders. As mentioned by one from the contractor organisation.

Advanced cognition of design workflow

The advanced cognition of design workflow highlights the professional understanding of 'forward design' among BIM specialists. Forward design refers to a design process that incorporates BIM technology from the very beginning of a project, ensuring all aspects of design and construction are integrated and optimised throughout the entire process. This approach helps minimise conflicts, reduce errors, and improve collaboration among various project stakeholders.

In contrast, ‘non-forward design’ refers to a process where designers first prepare design drawings of the project, and then BIM staff use BIM software to convert the contents of the drawings into 3D models. Instead of using the early BIM-engaged design to support construction in the “forward design” process, this approach relies heavily on designer conventional 2D drawings and late turned 3D models to represent the design and facilitate construction process. Therefore, it is believed to lack the integrated and collaborative features offered by BIM, potentially resulting in a less efficient design process and limited ability to identify and resolve conflicts or errors early in the project lifecycle.

From the perspective of BIM specialists, most stakeholders strongly advocate for “forward design” but often overlook the fact that the design process is iterative by nature. An unrealistic perception of BIM technology, as achieving the desired outcome in a single attempt, is seen as hindering the integration of BIM technology with the design process. BIM specialists understand that forward design should serve the design workflow, and a moderate integration with BIM technology can achieve the intended purpose. This is confirmed by one from the design organisation:

> *“Whether you are forward or non-forward, what do you want to achieve? Just do things with a purpose. My goal is to improve the quality of the design, right? Save design cost and save construction cost. Then save the design cycle. All the construction cycles are my time and money. I can only achieve my goal. No matter what method I use, all roads lead to Rome, right? Your forward design is equivalent to taking a detour, turning around, and finally arriving in Rome. But actually, you didn't say this in a good way, right? We still want a direct connection between the two points.” (DES2)*

Specifically, according to BIM specialists from the owner organisation, the real ‘forward design’ should functionally facilitate on-site construction rather than merely adhere to a theoretical definition. The modelling process with BIM technology is not solely concerned with replacing the conventional design process to guide construction but integrating it with the construction process and situation to effectively utilise BIM technology, as mentioned by one from owner organisation:

"It can't be as simple as turning over the model, they [BIM personnel] must be stationed. I ask them to be fully present. . . . . . The matter of turning over the model (in my opinion) belongs to his drawing (BIM model) and often fails to land. [Our current way of using BIM] can be actually regarded as forward design." (OWN1)

5.4.1.2 Building model assessing and using

Building model assessment and use is a crucial theme at the individual level, as it relates to the phase of evaluating and utilising BIM models with BIM technology integrated into this process. This phase is primarily carried out by practitioners, such as resource managers or cost estimators, who do not directly use BIM tools to create building models (e.g., 3D models). But their work is influenced by BIM artefacts, and they usually use building models as a database. The impact of using BIM technology may be reflected in their decision-making for tasks (e.g., planning on-site arrangements) and in improving their work efficiency (e.g., calculating costs). The quality of the BIM artefacts (e.g., BIM 3D models) will have a subsequent impact on their work and efficiency. Therefore, they need to both assess the BIM artefacts through interaction with actors who create them to ensure their knowledge is updated, and know how to adapt their practice based on the BIM artefacts. This phase involves professionals' acceptance and practice of BIM artefacts, which in turn influences the performance of BIM-enabled collaboration. Several factors have been identified from the building model assessment and use phase that reflect professionals' acceptance and practice of BIM technology: BIM technology adaptation and BIM capability.

BIM technology adaptation

BIM technology adaptation refers to actors modifying their conventional practices to incorporate the use of BIM technology or BIM artefacts in their work. Most BIM users interviewed in this study base their approach to integrating BIM technology on their previous project experiences. Typically, their practice is focused on achieving outcomes, using BIM technology to support problem-solving. In other words, users employ BIM technology to identify issues or provide solutions to reach their objectives. They are likely to adapt their conventional practices by using BIM technology, cooperating with collaborators for efficient problem-solving, as mentioned by one from the sub-construction organisation:

"Now that BIM [technology] has been added into practice, BIM needs to guide the construction…. But when it comes to construction, it will be reversed. It is equivalent to your BIM engineer explaining to me, communicating with the production manager, and the production manager communicating with the workers in that direction." (SCON1)

BIM capability

BIM capability refers to a user's ability to combine different knowledge domains effectively while using BIM technology for greater benefits. The findings show distinct performance levels when users integrate various knowledge domains while using BIM technology during the building model assessment and usage phases. Most users proficient in disciplinary knowledge can use BIM to address building model issues by integrating their technical abilities with BIM functionality. According a participant from the contractor organisation, this integration between disciplinary knowledge and technical BIM use can enhance collaboration effectiveness:

"Like before, it means to do it with blueprints, and various majors meet with each other [communicate], that is, to solve problems after they arise. Now after the BIM model is modelled, we first synthesise all professional models in advance before we can give an optimal solution." (CON7)

Some BIM users place great importance on integrating BIM technology with their project knowledge through various methods. Relying on BIM specialists' explanations of BIM functionality can help users with project knowledge to incorporate the benefits of BIM technology into their decision-making process. As mentioned by one from the sub-construction organisation:

"Because he is also an industry person, he hired a [BIM] consultant. You must tell him what you did during the process, and then let him have a basis. Although he provided the drawing, we came to refine it. To land, we are operators. So when it comes to which step, what is your progress, and what do you want to do, you have to report to him. In the process of reporting to him, as long as you have a plan, he will know how to supervise you." (SCON1)

5.4.1.3 Building model presentation and reviewing

Building model presentation and review are crucial aspects of BIM-enabled collaboration, as they demonstrate the role of the building model as an essential intermediate project output. This process helps evaluate the practical value and performance of BIM technology implementation. Participants identified this work as primarily involving decision-makers, such as clients or top management in organisations, who respond to the presented building models and assess BIM technology performance. As their practice is not directly related to using BIM tools, these actors have a limited understanding of the capabilities of BIM technology. They rely on building model presentation and review to evaluate BIM technology performance, despite their unfamiliarity with the innovative artefacts being created and the potential changes to original practices.

Outcome-driven value

Outcome-driven value refers to the value that BIM technology can contribute to the project's outcome. Participants in this study who served as BIM observers emphasised the importance of BIM technology in delivering value to the project by focusing on the quality of BIM-enabled models. Most of these observers lack BIM technical knowledge and skills, and their perceptions of BIM technology are mainly influenced by others' uses of the technology (e.g., BIM models by BIM specialists). On the one hand, this may empower BIM specialists to express their thoughts on the implementation and use of BIM technology, encouraging them to focus on providing substantive value to project performance through BIM technology, as suggested by one from the sub-construction organisation:

> *"He [the manager] doesn't care, but I have to manage myself. This belongs to my work, but I want to show him …I must let it reflect its value, so that Party A can rest assured that our side is more scientific, and let them know how to make these Technology serves the real project, we create value, no matter what means we use, the ultimate goal is to create value, yes, what can BIM create? Guide the construction and let them save money during the construction stage. They spent 200,000 yuan on BIM, and they can save at least 400,000 yuan in this [use] process, otherwise it is meaningless."*
> *(SCON1)*

On the other hand, this compels BIM users and specialists to concentrate more on the appearance of BIM technology-enabled models, which may lead to the pursuit of superficial and impractical value in adopting BIM technology. For example, the participants from design organisation indicated that they may emphasise the importance of representing the value of BIM models to party A. However, the actual effectiveness of BIM technology may be overlooked during the presentation and review of the BIM technology-enabled model:

> *"To put it simply, let Party A know, that is to say, they gave the money, and then let them see this model is very posh." (CON1)*

> *"When I communicated with them, it was not compulsory that we had to show them the model, but they only looked at the outline, they only looked at the partial... Mainly because they were working on the site, starting with construction, basically there is enough experience." (CON7)*

5.4.2 Organisational level

The contextual conditions in this section demonstrate the organisational factors that shape BIM-enabled collaboration. These conditions focus on the organisation's digital innovation management, culture, and strategic initiatives that support and drive the adoption and use of BIM technology throughout the organisation.

The organisation's digital innovation process influences the adoption of BIM technology to solve business problems within and between organisations. This digital innovation process in the organisation is top-down and progresses through different stages. Various characteristics of these organisational digital innovation stages reveal the diverse influences on BIM implementation and adoption, as drawn from participants' views of their organisational strategies at different hierarchical levels (e.g., managers and employees). The ongoing digital innovation process is depicted in three stages of change within the organisation from top to bottom: digital innovation leadership formation, management and culture establishment, and operational integration and user engagement.

5.4.2.1 Digital innovation leadership formation

Digital innovation leadership formation refers to the significant awareness of innovative capability that top management demonstrates within project organisations. This theme is identified through an analysis of participants' perceptions of long-term strategic development direction set by top management and the actual actions adopted by them. Digital innovation initiatives are also devolved from top management to employees through two pathways: transformational leadership and performance-driven value proposition.

Transformational leadership

Participants mentioned management innovation as a significant contextual factor for their BIM-enabled collaboration. The leadership is highlighted for effectively promoting BIM adoption into projects. Management innovation is demonstrated mainly in the development of BIM innovation teams and the establishment of BIM artefact review mechanisms and standards:

> *"The top management of the company and the leaders of our projects must pay attention to and emphasise this thing [the use of BIM], which means that everyone should pay attention to it from the cognitive level. Yes, the leadership definitely need s support in this regard." (CON5)*

> *"... In such a situation, it may sometimes be better to let the leader arrange this matter, that is, the person who does this [to arrange] is a leader. If they can arrange it, it will be better. They [leaders] have credibility, and they [colleagues] feel that the tasks arranged by the leader need to be done. But for me, we are at the same level, and then maybe their original requirements are not strict, and then the efficiency of completing this thing will be very low, and it will not be completed in the end." (CON5)*

However, from participants, the slow adoption of BIM in current construction industry is seen be subject to the perspectives of project managers on how to use BIM technology into project and the substantive limitation of the traditional construction industry, as mentioned by one from the contractor organisation:

> *"Many people in the traditional construction industry do not accept new things, so the status of BIM is not so high. In fact, it [BIM] can fully meet the needs of site management, but many project managers basically just use it as a model. wasteful." (CON1)*

Performance-driven value proposition

The recognition of the value of BIM is key to the strategic adoption of BIM transformation by upper management. Respondents indicated that the perception of BIM's value mainly comes from managers' views on its performance in previous projects. When different organisations have different roles in a project, the performance of BIM has different meanings for each organisation. These role differences determine how organisations measure the strengths and weaknesses of BIM in projects. The pre-simulation provided by the BIM model offers more accurate information for the construction stage, as mentioned by one from owner organisation:

> *"The leader should have seen it in some project, and they thought it was good, otherwise the leader would not have suggested that I want me to take the Id in BIM... Anyway, after all, they know the difference between doing BIM and not doing it, so you can go to the site to take a look Mechanical and electrical pipeline, you can know that the BIM -enabled [on-site construction structure] is really beautiful, and this [pipeline] is very good. When I went to see the site where BIM had never been used, it was just how the workers wanted to do it, and it was really messed up." (OWN1)*

For Party A or the construction party, BIM technology allows projects to utilise more accurate information, reducing the likelihood of rework during construction and providing a clearer understanding of the project quality at the construction site. For designers, it is unrealistic to expect the BIM model to be fully pre-simulated. Some flexibility is needed at the design stage for potential changes during the construction phase. Overemphasising the model's accuracy in the design stage can actually result in an increased workload without benefiting the project itself:

> *"In fact, the leaders are also aware of it. When it comes to forward design flow, these people are people who have never done BIM-related project. If you have been working for five or six years, talk to my old colleagues. When you talk about this kind of design, we all know what's going on., why can't everyone understand, but what is going on? So you have never done it, the leader has never done it, we have to design normally, and after you have done it, we will come out without forward design." (DES2)*

5.4.2.2 Management and culture establishment

The innovation fostered in collaboration processes and practices within and between organisations, driven by BIM technology, has led to the transformation of management and the establishment of an organisational learning culture. Based on participants' arguments and critical views of their current organisational practices and strategies, specific aspects of management and culture establishment are reflected in insufficient resource support, BIM artefact assessment mechanisms, and a technology-centric approach to organisational learning.

Inadequate resources support

Different actors from various organisations indicated that applying BIM technology to projects requires substantial resources for support. They claim they did not receive adequate support for organisational innovation, such as time exclusively allocated for learning and training. When BIM specialists, who are specifically responsible for innovation, are assigned to support BIM in projects alongside other project members who actually complete the work or task, this creates a conflict between work responsibility and technological innovation. Furthermore, it was found that insufficient quality of BIM models and high costs in the preliminary stage make it difficult to follow a holistic, organisational, long-term innovation process, especially in project-based collaboration. This is reflected in hasty, in-project BIM training processes within the contractor organisations:

> *"In fact, to be honest, the company asked us to learn in the project, but did not give us [study] time alone… we have our own things to do during the day." (CON3)*

It has been shown that digital transformation within an organisation requires high-level management to establish awareness of technological innovation and to make corresponding transformations in the organisation's internal resource allocation and knowledge management to effectively implement digital transformation. Most participants from different organisations have reported that the construction industry is currently making high-profile proposals for various companies to introduce BIM technology and realise digital transformation. Senior executives have also begun to attach importance to establishing and promoting BIM technology in their company's organisational learning. However, there is a lack of awareness of the current organisational capabilities and the allocation of knowledge resources within the organisation, which leads to the introduction of BIM technology remaining only at the upper-level promotional stage. At the same time, the middle-level management of the organisation has not established a corresponding transformation mechanism:

> *"…first of all, I am not a professional, and it is already very good that I can understand this. [Then] the leader means that you have to learn' I said I can't learn, [and the leader said] I don't care about you, I said this is*

something that the property management should learn, and this should not be what I want to learn….” (OWN1)

BIM artefacts evaluation mechanism

Currently in the construction industry, the management and review of collaborative processes involving BIM is not standardised. BIM artefacts are different from the architectural information contained in two-dimensional conventional construction drawings. The construction information in two-dimensional drawings has a relatively complete evaluation mechanism and review process. However, for BIM modelling, since the entire construction industry has not yet formed a complete specification and guidance, in most cases, the review of BIM artefacts depends on the initial establishment of the BIM artefacts within an enterprise. The review mechanism, most of the existing review process and internal requirements of the enterprise remain part of this negotiation process within the enterprise or between enterprises and lack a structured review mechanism for the corresponding BIM artefacts and the standardisation of the BIM process:

“Because we have two mechanisms, the first is the internal mechanism. Before our drawings or models come out, the internal mechanism must be reviewed on my part. Only if I have a successful review, the layout can be sent out only after the review is passed. This is the internal mechanism. For the second external mechanism, generally, there will be a BIM person in charge of the project, that is, the BIM communicator [from the owner organisations], who communicates with [our] BIM team, and they [BIM communicators] will also review and assess.” (SCON4)

Establish the learning culture

Decision-makers within the organisation are aware of the importance of BIM technology for the organisation’s long-term development and have shown a certain degree of promotion strategy and direction. Both participants at the management level and employees reflected a relatively positive vision of the BIM technology innovation culture within the organisation through their review and description of the status and perception of organisational BIM promotion. This comes mainly from established assumptions among actors that BIM technology affects their work practices and changes organisational roles, as mentioned by one from the contractor organisation:

"In our case, BIM technology is mainly used in the construction stage and is used less... The company has not emphasised that you should do it. For example, everyone is advocating it now. Just try to do it, and then what we are doing now, our next step is to build a team now, and then slowly prepare to learn something, and then try to learn from it. This is the state of learning to do by practising and then learning while doing." (CON5)

5.4.2.3. Operational Integration and User Engagement

The impact of BIM-related innovation initiatives and their performance within organisations is dependent on user engagement, reflecting a gap between the practicality of BIM innovation initiatives and actual use by users during implementation. According to the actors' feedback on their participation in the BIM promotion measures within the organisation and their feelings about these measures based on their own work needs, it was found that most of the BIM innovation measures within the organisation did not meet the actual needs of users. Relevant skills training and the establishment of BIM process awareness are still at the technical guidance level and lack measurement of actual user needs. There is a gap in initiatives that connect the needs of the user's work practices, relevant work experience, and the disruptive changes BIM technology brings. Operational management have not brought users an effective transition from conventional practice to the digital innovation-driven change. The following findings reveal the main aspects of this gap.

Technology-centric organisational learning paradigm

Organisational digital innovation strategy is a technology-centric training/ learning strategy rather than a user-centric strategy. The findings show that organisations pay more attention to whether actors know how to operate the BIM technology than whether their learning can be applied to their real work practice. According to two participants form the contractor organisation, due to different needs/practices of BIM technology heavily relying on discipline, the learning/training may not fit the employees' needs so that actors only learn the generic knowledge /practice about BIM technology, such as building the 3D roof through Revit (a BIM software) and may not situate this in local practice. This knowledge can then play a role in the collaboration process:

"Our company has also organised and trained before, but mainly for the technical department of technicians, and then organised BIM training, and

then there are not many people involved... The training is definitely something that can be learned, but I didn't participate at that time, because we belonged to the material [department], and it was mainly promoted for the technical department, and the promotion was too narrow." (CON4)

"Because this technology [BIM] is a new thing for some people, that is, we need to organise and carry out learning, so that everyone can learn this thing. Because everyone has to know how to use it, then there will be no barriers to communication. If some people understand it but some don't, then it will definitely not work well when using it." (CON5)

User resistance

User resistance refers to the reluctance of BIM users within organisations, particularly experienced participants, to adopt digital innovation strategies. Specifically, they are often more inclined to rely on their extensive project experience and believe that this experience can be equated with the advantages of technological changes. However, most users are not entirely unwilling to accept the influence of BIM technology in their work practices. The digital technology transformation makes them realise that their traditional skills may need updating, which involves a considerable learning cost, meaning that they need to devote more time and effort trying. For example, as indicated by one from the sub-construction organisation, the lack of substantive organisational support for innovation increases the difficulties for these experienced employees to accept BIM technology:

"They themselves have relatively rich construction experience, and he thinks that I have such rich experience, and it is not necessary for me to rely on your BIM... They think they have done it for so many years I have a project and have a lot of experience, but I am not willing to learn new things, I just don't know how to innovate, and I don't want to spend effort to innovate." (SCON6)

5.4.3 Project level

Project-based collaboration plays a crucial role in the use and implementation of BIM technology. Each project comprises various stages, with collaborative activities being carried out in accordance with lifecycle management. The implementation and use of BIM in project-based collaboration are contingent upon the objectives and requirements of individual project stages. In contrast with the deployment of BIM technology and its associated business models at the organisational level, BIM implementation and utilisation at the project level are embedded within lifecycle-based project management. This process encompasses the entirety of the BIM process, including establishing BIM objectives, creating BIM artefacts, using BIM artefacts and tools into practice, and evaluating the subsequent impact of BIM on project operations and maintenance.

In this study, participants have distinct goals and practices concerning BIM collaboration during different project stages. As they participate in multiple collaborative processes across various project stages, their perspectives may continually evolve based on the project stage objectives and collaborative relationships. The collaboration process in this research is divided into project planning, project designing, project construction, and project operation/maintenance stages, focusing on the contextual conditions that impact the effectiveness of BIM-enabled collaboration within each project stage.

5.4.3.1 Shared collaborative vision in planning stage

The shared collaborative vision emerges from participants' reflections during the initial stage of the project, which is considered the strategic planning stage. According to the participants, this theme presents their perspectives on the crucial elements necessary for establishing a shared collaborative vision in BIM-enabled collaboration at the construction project planning stage. These elements include addressing project complexity-driven trade-offs and compromises and ensuring reliable BIM team performance. This theme underscores the important elements of aligning stakeholders' goals, expectations, and efforts to foster a cohesive and effective BIM collaborative environment in the project planning stage.

Complexity-driven trade-offs and compromises

Complexity-driven trade-offs and compromises play a crucial role in establishing the shared collaborative vision during the project planning stage, particularly for BIM-enabled projects. In construction projects, project costs and time constraints are determined at the initial stage across various stakeholders. In BIM-enabled projects, the higher cost of technology implementation increases the considerations for decision-makers (e.g., project managers, clients) to negotiate and make decisions that align with the project's characteristics to optimise resources, depending on the degree of complexity involved in the project. Examples of such complexity include building complexity (in terms of design and operability), organisational complexity (involving resources, capabilities, and interests), and stakeholder complexity (with diverse requirements and expectations).

These decisions establish a consensus on how to apply BIM to the project to maximise its benefits while minimising costs in relation to project complexity. As varying degrees of BIM usage entail different time, effort, and cost implications for the project, the most crucial and necessary BIM applications are discussed and determined. More complex projects offer more ways to utilise BIM, but trade-offs and compromises need be made to create a shared collaborative vision that saves both time and cost. The consideration from the owner organisation is mentioned by one interviewee:

> *"For example, the developers pay more attention to BIM, but they also adjust measures according to the local conditions of the project. It does not mean that all projects are not suitable for BIM, because the cost of BIM is quite high." (OWN2)*

In discussions regarding the decision to use BIM in a project, the purpose of employing BIM is often linked to and focused on the overall project objectives. This connection provides a potential shared interest among stakeholders, and a collaborative vision can be formed through the trade-offs of stakeholders' requirements. As mentioned by one from the sub-construction organisation:

> *"In fact, no matter how BIM is done, it is for the implementation of construction, whether it is displayed, including how its process is done, and whoever makes it. Its purpose is to make [the project process] more reasonable and economical when the time comes. Make no mistake." (SCON1)*

Reliable BIM team performance

Reliable BIM team performance captures participants' perspectives on the importance of trust and agreed collaborative relationships among stakeholders when planning a project. In the decision-making stage, especially when planning the application of BIM processes, assessing the level of trust in the BIM team's capabilities is considered critical. According to the interviewees, this trust is primarily based on the BIM team's previous performance, which can foster the collective understanding and expectations regarding the application of BIM technology throughout the project lifecycle. The project manager or decision-maker makes a judgement based on the BIM team's successful experiences. This assessment affects the degree to which the decision-maker relies on the BIM team during the project implementation stage. An experienced interviewee from a BIM team in the sub-construction organisation mentioned that when a client has greater trust in their BIM capabilities, they are more willing to cooperate with them and establish stable, long-term collaborative relationships:

> *"For instance, when initially collaborating with a new client [Party A], they generally may not know how to use the tool or be aware of its capabilities. Their understanding is often limited at first. However, after working together on a project, we gradually develop a working relationship. Once we've completed a project together, they typically gain trust in our capabilities, and if they have any future projects, they will undoubtedly approach us for collaboration." (SCON7)*

5.4.3.2 Shared collaborative values and norm in designing stage

Shared collaborative values and norms in project designing stages refer to the collaborative culture that exists among multiple stakeholders during the co-creation of artefacts in the design process. This collaborative culture is seen as an important collective value and belief, involving different disciplines working together to develop building models when BIM technology is involved. As a more integrated method for artefacts co-creation, the BIM process raises the need for a unified collective understanding of how to promote the co-creation process in project designing stages. Based on participants' reflections, several values and norms affecting BIM implementation and use in design collaboration have been identified during this process, including quality standard awareness, professional identity clarity, and coordination process adaptability. The actors involved in the shared artefacts creation process at this stage are mainly professional designers and clients.

Quality standard awareness

Quality standard awareness highlights the actors' ability to recognise different quality standards of BIM artefacts, which contributes to building a shared collaborative norm in the project design stage. In the model co-creation process, actors apply different quality standards in the construction of artefacts. Actors generally have different opinions on what constitutes high or low quality with respect to the artefacts. Initially, BIM artefacts lacked institutionalised standards in the industry, leading to no common reference for evaluating their quality and resulting in diverse expectations and awareness of the composition of the final BIM artefact. This diversity, whether within or external to the team, generally occurs due to different disciplinary knowledge sources or previous perceptions of conventional project objectives. For example, BIM users/observers may expect details to be embedded in CAD drawings and have the same expectations of BIM artefacts, even though the two tools model different details and present the models in distinct ways.

Professional identity clarity

Professional identity clarity highlights the need for a clear understanding of the roles of BIM professionals in the designing stage of a project. By exploring the design process and the related BIM outputs from participants, it was found that ambiguity related to professional identity appears to impact the collaborative relationship after the project introduces BIM technology use. This ambiguity mainly arises due to changes in actors' work tasks following the introduction of the technology to the project and shifts in their professional abilities after acquiring BIM knowledge. As actors gain more BIM knowledge, the range of tasks they can accomplish expands beyond their initial capabilities. Concurrently, since BIM has not reorganised or increased related work tasks within the project, team members continue to self-organise through social means such as negotiation and communication. This dynamic results in actors expressing their professional characteristics and value recognition, making it difficult to precisely identify changes. For instance, BIM specialists in the design organisation are often considered as a single group within the project team's organisation. The absence of a clear role description creates confusion about their responsibilities and tasks, sometimes necessitating additional work to supplement the efforts of other groups:

> *"… After all, the design side has not been familiar with these [BIM] in recent years, so [we] will have a separate department. Like the one you see now…For example, the design process is something in the process of their drawing, because we are not professional designers, so we want to know more about them…" (DES3)*

Coordination process adaptability

Coordination process adaptability is defined as actors maintaining flexibility while coordinating with designers concerning errors on artefacts. According to the study participants, the coordination process involves potential change, conflicts, others' interests and concerns, and limitations. When the project team has a clear perception of others' practices and understanding in the coordination process, they show more tolerance for others' mistakes and also move towards negotiating to create a shared outcome. This adaptability is essential for effectively addressing issues and fostering collaboration in the design stages of a project. As mentioned by one from the contractor organisation:

> *"What can be solved in private should be solved first, it is not a big problem. In fact, the big problems have been dealt with, and these small problems can basically be solved on the spot... In fact, the design organisation will issue a new version of the drawings according to our opinions. [But] if such a record is left, it is actually not very good for them." (CON1)*

5.4.3.3 Shared technology capabilities in construction stage

Shared technology capabilities have been identified in the construction phase of the project lifecycle, which reveal the significance of the collectively held, encompassed, and developed technology capabilities for BIM-enabled construction stage, including the ability to use BIM tools, the combined technology knowledge, and the capability to develop and manage technology. These capabilities may be key factors that influence the effectiveness of BIM technology in enabling project construction collaboration. BIM tools and processes involved in this phase are used to improve the utility of building models, facilitate informed decisions, detect and predict potential construction issues, and track the progress of on-site construction, among other functions. Factors identified at this stage, which shape BIM implementation and use, include the incongruence of BIM practices and insufficient operation configurations. According to the participants, these factors might primarily affect the efficiency of BIM use, meaning that BIM artefacts may not achieve the expected performance outcomes and could even cause tensions between project stakeholders.

BIM practice alignment

The findings demonstrate that there is an incongruence in BIM practice. Participants highlight the importance of effective communication and synchronisation among project teams when updating BIM models and drawings. Inconsistencies between versions of drawings and BIM models can lead to confusion, redundancy, and wasted time during the project construction stage. Actors emphasise the need for proper alignment of BIM practices. For example, one participant from the design organisation implies that aligned BIM practice can improve the efficiency and usefulness of BIM in the project construction stage:

> *"The first aspect is the problem of uploading and delivering. Sometimes it may be that the design side said that they updated a version of the drawing, and then they didn't know what to do, and it was not communicated. As a result, my BIM model was the model of the previous version of the drawing. Just this version is inconsistent with this model. For example, if we find a problem, we have actually fixed it, and it is not [the same] problem at all. That is equivalent to saying that the work we [current] BIM is doing is useless and wastes time." (DES1)*

The study also reflects the divergent outcomes between design and construction within the project. Participants mention that while the initial BIM models provided by the design organisations may look visually appealing, they are often too rough and not detailed enough for electromechanical construction purposes. As a result, the construction team has to reorganise the models, adjust pipeline systems, and optimise intersections and other unreasonable aspects. It emphasises the need for better alignment between design BIM practices and construction BIM practices. When BIM models are accurately developed and refined, it can lead to smoother on-site execution and help avoid issues such as design omissions or pipeline discrepancies. Aligning BIM practices between design and construction will ensure that models are both useful and practical, ultimately improving efficiency and reducing the potential for errors during construction, as indicated by one interviewee from the sub-construction organisation:

> *"…this model is too rough for us [in terms of electromechanical design]. In fact, to put it bluntly, the BIM of the design organisation, those things look good, but they are actually useless, and then we do the construction BIM, we reorganise the model, reorganise all the pipeline systems, and propose*

some pipeline intersections and unreasonable places for optimisation… Then wait for real construction workers to speak with our drawings, and many on-site problems can be avoided.” (SCON7)

For the design organisation, Party A's concerns may affect their control over the creation of the BIM model and the maintenance of consistency between drawings. As a result, their BIM-enabled design may depend on whether the construction party has sufficient ability to use BIM models and drawings effectively:

“In fact, it still depends on the purpose and what they want BIM to do. This is relatively routine if you want to check for errors, omissions, and vacancies and [meet] the clear height requirements. If you need to do this, then the quality [requirements] of the model is that the drawing and the model must be consistent. That is, the drawing is the same as the model because it needs to be passed to the construction process later. However, the previous construction party did not use the designed model. Sometimes they may have different specifications and standards, and they may not be able to use them smoothly. But now, many of them are basically passed directly to the past and can be used.” (DES3)

BIM team integration and support

Project teams are organised such that there is a specific BIM team to support BIM-based project work. These BIM groups may be from their organisation or other companies and can provide professional support to create/use BIM models and even help them learn to use BIM technology. However, participants believe that the configuration of the BIM team significantly affects their BIM-related collaborative work. As proposed by participants from both contractor and sub-construction organisations:

“Now our company does have a BIM team and a R&D team working on this piece of work, but in terms of its promotion, it has not been implemented in every project, that's it.” (CON4)

“Now because of many domestic standards, everyone's recognition of BIM has basically become popular. Everyone thinks that it is necessary, but many people are not very good at using it. They don't know how to use

BIM, so we are also When telling Party A how to look at it, how good we think it is, and the advantages of BIM, we are slowly instilling this understanding in them. Like the earliest Party A who came into contact with us, they said at the first project that BIM is useful, and we can do it ourselves. They didn't understand us very much, but after a project, they slowly began to understand that this is still more useful, and they just know our value from the beginning." (SCON7)

5.4.3.4 Shared optimism for future BIM impact in Operation and Maintenance Stage

Shared optimism for future BIM impact in the operation and maintenance stage focuses on the operation and maintenance phase of the construction project lifecycle. For most projects, this may involve the use of BIM data to improve operation and maintenance activities on the building, and to enhance communication with related staff. The effect is satisfactory based on the BIM model. People have a very positive attitude and clear expectations regarding the future role of BIM in this stage. This positive attitude cultivates a potential environment for the implementation and use of BIM in project.

Positive attitude and expectation

For the project operation and maintenance stage, actors demonstrate a positive attitude and expectations regarding the use of BIM data to improve operation and maintenance activities for the building, as well as communication with related staff. Although it is suggested that minimal BIM practice has been involved in the operation and maintenance stage thus far, stakeholders hold a similar belief for future projects – that BIM technology will play a significant role in the operation and maintenance stage, as indicated by one from the sub-construction organisation:

"In terms of operation, we are mainly in the early stage of closing, based on the modelling of the closing, and then carry out the layout of my construction site. This part is used a lot, and there is a tower crane coverage, and then I told you just now. The material mentioned may be an effect that we want to achieve with BIM at the initial stage at this stage, and it is like this. It hasn't been applied yet, and everyone is still in the process of learning..." (CON4)

5.5 Chapter Summary

This section presents findings related to BIM-enabled cross-boundary collaboration in the situated context of actors' experiences in a construction project, focusing on completing shared project goals with BIM-related practices and processes. Construction project-based collaboration is viewed as highly institutionalised due to its embeddedness in the business ecosystem and policy-oriented innovation of the AEC industry. Collaborative activities are configured within the construction project based on project teams' deliverables and industry regulations. BIM technology is regarded as a facilitator of new norms and collaborative relationships between project teams aiming to achieve shared project goals throughout the construction project lifecycle. The main findings associated with each analysed dimension (D1, D2, D3) and at each level of analysis (individual, organisational, project) are explained below:

- *Configuration of collaborative activities (D1):* This dimension presents the collaborative practices in a BIM-engaged construction project, highlighting configurations from different knowledge backgrounds. At the *individual level*, it suggests intertwined professional relations among actors during their collaborative activities. At the *organisational level*, it demonstrates strategically planned BIM implementation collaborative activities within and between organisations. Finally, the institutionalised nature of project-based collaboration is illustrated at the *project level*.
- *Role of BIM technology (D2):* This dimension shows that the role of BIM technology in practice is multifaceted and evolves to enable collaborative practices at different levels. At the *individual level*, actors perceive BIM technology as a practice or a tool. The *organisation level* views BIM technology as an emerging structure and symbol that is manifested in organisational strategies and management. At the *project level*, BIM technology has been enrolled as a facilitator for transformative change.
- *Contextual conditions of BIM-enabled collaboration (D3):* This dimension demonstrates temporal changes in the conditions and dynamics of the relationship between collaborative activities and the use of BIM technology. At the *individual level*, digital artefacts orient collective relations and structure BIM implementation and use patterns among actors. At the *organisational level*, strategic digital innovation processes drive BIM implementation and long-term use from the top down. At the *project level*, the nature of the project lifecycle process leads to complexity in different lifecycle stages, affecting the congruence between building information and data

standards between stages and consequently influencing the implementation and use of BIM in projects.

These findings provide a holistic insight into BIM-enabled cross-boundary collaboration from individual, organisational, and project levels of analysis. By exploring the configuration of collaborative activity, the role of BIM technology, and the contextual conditions of BIM-enabled collaboration in-depth, this research sheds light on the key factors affecting digital collaboration, the dynamic relationships between BIM technology and different stakeholders, and the complex context of BIM collaboration. It contributes a profound understanding of digital technology adoption in the context of the AEC industry. In the following chapter, the Discussion chapter, the findings will be further analysed and interpreted, and the implications of the findings in light of the existing literature will be explored.

6 Discussion Chapter

6.1 Introduction

This chapter provides an in-depth discussion of the research findings, integrating a multi-level thematic analysis across the individual, organisational, and project levels to illustrate BIM-enabled collaboration within the context of construction projects. It also contextualises these findings, discussing their convergences and divergences with existing research. The discussion further assesses how these findings contribute to the wider body of relevant literature, both theoretically and in terms of practical implications.

The synthesised theoretical framework, as presented in the literature review chapter (Figure 5.1), is designed to explore the dynamics between digital technology-enabled boundary work and the digitally organising context. As digital technology emerges, is implemented, and used in organising collaborative work, it assumes different roles within its context, producing varied implications for boundary work. This theoretical framework accentuates the need to investigate how, under certain circumstances, digital technologies enable boundary work and how this process exerts transformative influences on its organising context.

Building on the theoretical framework, the Findings chapter delineates the structure of collaborative activities, the roles of BIM technology, and the contextual conditions at various levels (individual, organisational, and project levels). The aim of this study is to elucidate the process of collaboration across knowledge boundaries in BIM-enabled construction projects.

In response to these sub-questions, the Findings chapter underscores the diverse factors propelling collaborative activities, the multifaceted role of BIM technology, and the dynamic contextual conditions at different analytical levels. The configuration of collaborative activities facilitated by BIM technology integrates both the internal driving force of interdependent work paths and motivations among professionals, and the external driving force of organisational digital innovation strategies and project institutionalised collaboration. These forces trigger various types of boundary work (Langley et al., 2019). BIM technology is characterised by its variability and multifaceted roles across individuals, organisations, and projects. As digital technology evolves within boundary work, it assumes different roles and produces diverse transformative effects. Further, this study uncovers the boundary conditions within the BIM collaboration context, demonstrating the interactivity and permeability of different knowledge boundaries. Due to multiple contexts contributing to the dynamics and complexity of BIM-enabled collaboration (Papadonikolaki et al., 2022), several recurring features of the contextual conditions are manifest in the activity systems and characteristics of different boundaries. In summary, the evolution of digital technology-enabled boundary work is co-configured by the dynamic mechanisms of multiple activity systems.

This chapter is organised into five sections to discuss the findings. Section 6.2 explicates the practice view of boundary theory and system view of activity theory in data analysis. Section 6.3 interprets the study's findings about the configuration of collaborative activities – namely the multiplicity of factors driving collaborative activities. Section 6.4 explores the evolution of the role of BIM technology in professional collaboration within organisational and project contexts. Section 6.5 delves into the dynamics of collaborative conditions across distinct levels, specifically, the individual, organisational, and project levels. The final section summarises the chapter.

6.2 Reflection on the relative utility of the Activity Theory and Boundary Theory

The pluralistic views from boundary theory and activity theory led to the data analysis from the professional practice of collaboration with BIM and its complex organisational and project context. Drawing from the practice view and the system view, the findings show the analysis from individual, organisational and project levels in terms of different aspects (i.e., collaborative activity, role of BIM technology, and context) of the digital collaboration phenomenon. Based on the elaboration in Chapter 3 - Theoretical Foundations, the practice view of boundary theory led to the analytical focus applied to the interactive digital collaboration practice. The system view led to the analytical focus on the structural and relational dimensions of digital collaboration, as shown in Figure 6.1. In terms of multiple levels involved in the project-based BIM collaboration, the findings show the configuration of collaboration activity, role of digital technology and contextual conditions of digital collaboration at different levels.

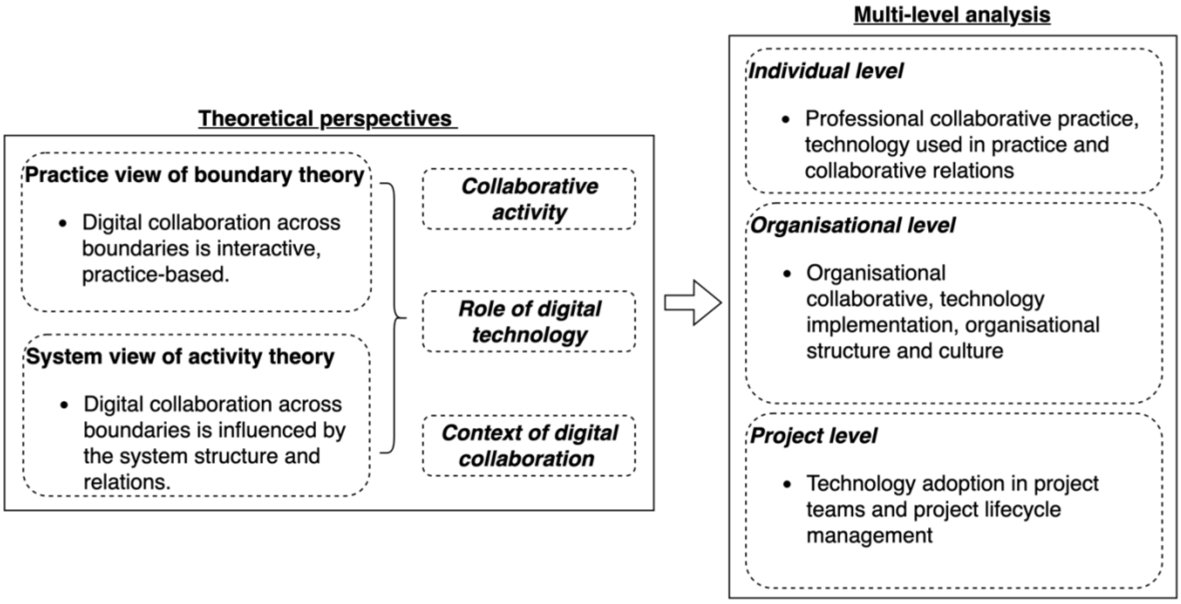

Figure 6.1: Reflection on the relative utility of the Activity Theory and Boundary Theory

From the practice view, collaborative activity can be manifested by intra-professional individual and collective practice to achieve their goals and inter-professional cross-boundary practice motivated by collaborative purposes. In terms of the role of BIM technology, the practice view of boundary theory sheds light on the used-in-practice role of BIM technology in collaborative activities. Besides, the role of digital technology is also entwined with the dynamics of the organisational and project technological goals in practice, manifested in the object-oriented collaborative interaction within organisations and project teams.

From the system view, professional collaborative relations show how collaborative activities are organised; the implementation of technology framed by the organisational structure and culture indicates the influence of the organisational system on digital collaboration. The project network highlights that lifecycle management-based organising provides temporal conditions for BIM collaboration across boundaries.

6.3 Synthesised Theoretical Framework of Digital Collaboration across Boundaries

Drawing on the empirical analysis and the theoretical foundations of digital technology-engaged collaborative activity, this section elaborates on the findings derived from core concepts of boundary and activity theories, providing a synthesised theoretical framework of digital collaboration across boundaries. The phenomenon of digital collaboration across knowledge boundaries is seen as intricate due to the evolving influence of digital technology in collaboration, a process without a straightforward trajectory. The collaborative practice's dynamic nature is inherent, likely influencing structural configurations. Elaborating further, BIM technology's role is examined through both theoretical lenses.

This theorising echo recent studies suggesting that digital technology persistently impacts social activities and alters structural conditions, as elaborated in the literature review chapter, a theoretical presumption underpinning this study. As shown in Figure 6.2, this framework contributes to comprehending digital technology-enabled boundary work, dynamics associated with digital technology-as-boundary objects, and the digital collaboration context. On the one hand, the practice view, stemming from boundary theory, conceptualises the cross-boundary practice and boundary work aspects. On the other hand, the system view from activity theory theorises the collaborative activities' context and the activity system's status. Moreover, from a practice perspective, BIM can transform into a boundary object during cross-boundary activities. From a system perspective, BIM is seen as a digitising catalyst within AEC organisations, fostering project-based collaboration. Digital technology, when acting as a boundary object, can fortify the system's deep structure via boundary work (Thompson et al., 2019). Thus, the amalgamated theoretical perspectives illuminate the dynamic interplay between digitally enabled practices and evolving digitised organisational systems. Interacting activity systems evolve over time (Karanasios, 2018), but these systems' intricate networks and interactions warrant further examination. Such interactions are integral to knowledge practices, especially those spanning boundaries, and can reshape boundary statuses and relationships.

As illustrated in Figure 6.2, when integrating digital technology, i.e. BIM technology, into construction project collaboration, it's pivotal to acknowledge its deep-rooted nature within boundary work collective practices. This process is underscored by three elements:

- Individual knowledge boundary: digital technology aiding knowledge transfer and transformation across distinct boundaries. It bridges varying expertise within a project, minimising knowledge discrepancies and fostering interdisciplinary engagement.

- Organisational System Impact: digital technology's adoption induces changes within organisational activity systems. It introduces tensions, congruence, and novel processes, possibly prompting reconfigurations of organisational roles and system dynamics.
- Transformative Object in Project Network: digital objects foster interaction among digitalising organisations, facilitating inter-organisational collaboration, and synchronising diverse project participants.

Collectively, these elements articulate a holistic framework to decode the intricacies of BIM-facilitated collaboration in construction. They allow a deeper dive into how digital technology influences collaborative practices, both within and across organisations, in boundary work contexts.

Figure 6.2: The integrated conceptual framework of digital collaboration across boundaries

Informed by the principles of boundary work, this research aims to scrutinise the mechanisms through which BIM technology transforms into a functional boundary object within individual practice. It also examines the collective boundary work that is mutually constitutive. By incorporating the concepts of organisational activity systems and project activity networks, this study will explore the organisational shifts mediated by BIM technology and the resulting connections and contradictions in project-based structural interactions. As objects and boundaries in practice co-evolve, it is argued that the structure of the system and network—termed the "baggage" of collaborative activities (Karanasios, 2018)—is concurrently developing. The parallel dynamics between cross-boundary collaborative processes and the collaboration context are intertwined within the multifaceted roles of BIM technology and the evolution of BIM collaboration.

The theoretical framework presented here provides a robust foundation for enhancing the understanding of digital collaboration across boundaries. This framework proposes two primary conceptual directions: 1) enriching the understanding of project-based digital collaboration across knowledge boundaries from a system perspective and 2) comprehending the dynamic relationship between digital technology implementation and project-based collaboration. This integrated framework offers a system view on Project-Based Digital Collaboration, identifying the components of the activity system in project-based digital collaboration across boundaries.

This theoretical framework forms the basis for answering the three sub-questions from a holistic perspective on both practice and system. Current research (Rosenkranz et al., 2014) explores collaborative relationships and knowledge boundaries in project-based digital collaboration, but few studies focus on the dynamics of the role of digital technology in collaboration. This study reveals project-based digital collaboration as an activity network and the result of digital technologies' transformative role in shaping and being shaped by the participating organisational activity systems. Contradictions within the project-based activity network spark the transformation process within an organisational activity system. Digital technologies, utilised in boundary work and boundary spanning, can help address these contradictions. The resulting dynamic relationship between boundary objects, subjects, and environments is an area this theoretical framework aims to highlight.

The components of this theoretical framework hold various ontological, epistemological, and methodological assumptions (Jabareen, 2009). Firstly, practice and system views have differing assumptions about the role of digital technologies. This leads to the theoretical understanding of how digital technologies are implemented and used in facilitating collaborative activities across knowledge boundaries. There's an emphasis on the capabilities of digital technologies in current research (Carlile, 2004), but digital technologies may not always effectively facilitate collaboration across organisational boundaries (Neff et al., 2010). More studies are highlighting the importance of effective implementation and use of digital technologies to ensure project-based digital collaboration. BIM technology, depending on the situation, can play various roles, which in turn may influence different kinds of boundary work in the context of BIM collaboration.

Finally, theorising a digitalised organisational activity system and project-based activity network shed light on the changing role of digital technology in professional interaction. It is suggested to relate to the cultural-historical explanation of the organisational collaborative activities, which could shape the role of digital technologies in knowledge practice (Carlile, 2004). This framework contributes to the understanding of project-based digital collaboration as a multi-level activity system. It explores influences from both the project and organisational levels on how collaborative activities shape the implementation and use of digital technology. BIM-enabled boundary work and the emergence of BIM technology can have varying implications on the context, and these implications might be dynamic and interrelated. The dynamic relationships between the various contexts might recursively influence the boundary work.

6.4 Configuration of Collaborative Activity

This section is dedicated to answering the first sub-question of this research: *'How are collaborative activities across knowledge boundaries organised in a construction project?'* From our literature review and synthesised theoretical framework, collaborative activities across knowledge boundaries are viewed as purposeful boundary work. purposeful boundary work is viewed as an individual and collective effort to influence the boundaries, and diverse boundary work efforts coexist in collaborative activities for achieving different consequences (Langley et al., 2019). Moreover, the interplay of individual, organisational, and project-level contexts co-configures the collaboration across knowledge boundaries, responding to BIM-induced changes. Professional work practices on each level hid varied interests, motivations, and considerations, subsequently influencing BIM technology-enabled boundary work in diverse ways. These influences and their consequences manifest in activities oriented by distinct objects. As per our data analysis in the Findings chapter, these influences are categorised into three intertwined subsystems that are constructed by the drivers of boundary work, practical boundary work effort and their relations. These sub-systems include relational system, strategic system, and institutional system, informed by various levels of collaboration co-configuring the collaborative activities.

Through concentrating the purpose of collaborative activities at each level, each subsystem is oriented towards a different type of object: relational systems focus on objects of model cocreation based on relational view of activities; strategic systems focus on BIM adoption and implementation based on strategic view of activities; and institutional systems are oriented by the congruence of project objects based on institutionalised view of processual activities in construction project. These diverse object-oriented activities are connected via by the shared goal of digital technology being implemented and used to facilitate collaboration. From relational, strategic, and institutional view to observe the drivers, orientation, and consequences of professionals' activities (Langley et al., 2019), it illuminated that boundary work effort contains not only micro-interaction among individuals, but also macro-interaction among organisations and processual interaction within project. By understanding the efforts from different activity systems that configure BIM-related collaborative activities, this study enriches the understanding of boundary work in a digital context across professions, groups, and organisations (Langley et al., 2019). This result is important for exploring boundaries from a systematic view to identify boundary work efforts, including creating, maintaining, blurring, or shifting boundaries (Comeau-Vallée & Langley, 2020).

6.4.1 Relational system for enacting boundary work

This section interprets the findings of this study emphasising that professionals who see model creation as their object actively engage in collaborative activities based on their professional relationships. The findings at the individual level suggest that most professionals, for example, architects and engineer designers or MEP designers, display intrinsic motivations for aligning goals with their peers, pursuing decision-making autonomy, and clarifying their contractual responsibilities. The introduction of BIM technology brings about new work relations among professionals due to differences in technological knowledge and work practices. These digital technology-induced changes in work relations and practices affect the original work jurisdiction and professionals' roles. Similar findings have been reported by Barrett et al. (2012). Their research on the impact of technological innovation on boundary relations revealed that technological innovation reconfigures three types of boundary relationships, namely, boundary collaboration, boundary neglect, and boundary tension. This reconfiguration is achieved by causing changes in work jurisdiction, professional knowledge, and professional status among different professional groups. In their analysis, they emphasised the influence of different professional groups' perceptions of their professional status and work jurisdiction on boundary relations during the cooperation process. Particularly in collaborative activities involving digital technology innovation, when certain work content is replaced by emerging technology, the work content of different individuals changes accordingly. This leads to a redefinition and readjustment of professional status and work permissions among different professional groups.

In this study, although the functionalities introduced by BIM technology and the changes to designers' work scopes have not explicitly caused tension or potentially replaced or covered conventional designers' work jurisdictions, the relations and collaboration process between different professional designers have been altered by the emerging BIM-related practice, such as digital model creation or clash detections. These changes have triggered their proactive interaction to configure their new work and responsibility boundaries and compete for their blurred autonomy boundaries. Such motivation-driven mechanisms in the relational system elicit the boundary work effort surrounding the purpose of reconstructing the BIM-engaged work relation and new professional practice among different professional practitioners. These driven boundary work practices are in line with studies in organisational work and cross-boundary collaboration research, which suggest that intra- and inter-professional relations constitute unstable boundaries and have implications on professional boundary practices (Ahuja, 2023; Faulconbridge et al., 2023). Additionally, the feature of contract-based collaboration in construction projects highlights such a relational activity system among professionals via significantly influencing the professional collaborative climate, including perceived fairness and relational trust (C.-Y. Lee et al., 2020).

On the other hand, as the results show, the incorporation of BIM technology has led to changes in the professional authority determined by the original professional knowledge, which has created tension between BIM professionals and traditional technical personnel. BIM-related professionals try to reconstruct the dominant discourse and decision-making power of BIM technology in collaborative activities through their rich BIM professional knowledge, understanding and interpretation of BIM artefacts. There are conflicts and tensions in boundary work. From the results of this study, the main motivation for these boundary conflicts and tensions is that of grasping the dominant position in decision-making relationships in collaborative activities following the introduction of BIM technology. Gieryn (1983) proposed that defining boundaries and constructing boundaries is conducive to the pursuit of professional goals. Determining boundary work may be an occasion for the literary resources of a certain profession or ideologue. When the goal is to extend authority or professional knowledge to the fields of other professions, boundary work will strengthen the contrast between the two. The emphasis is on constructing boundaries. When the goal is expansion, monopoly, and protection of autonomy (which is a general feature of 'professionalisation'), boundary work is used to demarcate boundaries (Kellogg et al., 2019). This corresponds to the collaborative activities of professionals in this study with decision-making power as the motivation. Akintola et al. (2020) emphasise professional connectedness that influences the stability of organisational activity systems and project activity systems. Liu (2018) offers insights into the relationship between professions and boundaries, theorising that boundary actions represent a process among professions aimed at controlling jurisdiction(s) through boundary work. These insights underscore the fact that professions exist within a relational system, seeking to maintain a balanced relational status even as they adapt to changes introduced by new technology. Collaboration between different professional groups aims to cooperate, exchange knowledge and resources, and achieve common goals and meet individual interests. However, different professional groups have different understandings of the goals of collaboration, and effective collaboration between different professions requires the co-construction of the scope and deliverables of the collaboration goals.

Another finding of this study indicated the other type of relationship between professional collaborative activities – the extrinsic interdependence, which is mediated division of labour, demonstrating the mechanism through which direct boundary relationships are formed among different professional practitioners. This observation aligns with recent research emphasising the impact of work interdependence on professional boundary work. For instance, Comeau-Vallée and Langley (2020) suggest that social status influences cross-professional boundary work. This study corresponds with their call for attention to professional-level boundary work, illustrating how personal motivation and dependence drive professional boundary work, further exploring how the interaction between motivation and path dependence impacts internal boundary work.

The results of this study demonstrate that collaboration activities involving BIM technology are mainly driven by professional relations between interaction and work path dependencies. When collaboration activities related to BIM are launched among professional practitioners, the interactive mechanisms of each professional practitioner are reflected in the construction of common goals for BIM-related tasks, the interaction of professional knowledge and autonomy under BIM participation, and contract-driven responsibility allocation. The sources of collaborative motivations reflect that changes in boundary relations have become the focus of professional practitioners' attention following the introduction of BIM technology in collaborative activities. Compared with passive changes and negative boundary relations, mature and experienced professional practitioners tend to achieve the reconfiguration of boundary relations through active interaction activities.

6.4.2 Strategic system for planning boundary work

The findings suggest that AEC organisations are strategically planning BIM implemented and used it to form an innovation-driven strategic activity system among professionals. For diverse organisations involved in a construction project, innovations in management and business based on BIM technology and BIM-engaged collaborative process become the focal object to facilitate organisational digital transformation, which devotes the planning boundary work efforts to professionals' collaborative activities. Such organisational digital transformation is business and management-centric rather than technology-centric, and this type of strategic practice can widely influence different parts of organisations (Chanias et al., 2019). In essence, these organisational strategic actions facilitate boundary work by planning for professionals to strategically collaborate and interact to achieve their joint goals of organisational innovation.

The findings show that organisations strategically plan management innovation activities through professionalising technological knowledge and legitimating BIM specialists, thus underscoring the necessity of BIM-related knowledge and reinforcing the professional identity of BIM experts within organisations. Different stakeholder organisations treat BIM-related work as individual professions, thus optimising the division of labour since BIM technology engaging in business process and management, especially for inter-organisational collaboration, enhances the communication across knowledge boundaries in terms of BIM-related technological knowledge. Such strategic actions improve organisational management through translating BIM technological knowledge via BIM professionals. However, in Ahuja's (2023) study, a strong professional identity can sometimes constrain architects, locking them into resistance and inhibiting structural change. The discrepancy might be due to different motivations behind the transformations in professional identity. Ahuja (2023) indicated that the motivation and adopted actions of professions are to respond to the threats of competing values in inter-professional collaboration, e.g., architects, and thus they try to enhance their professional identity through highlighting identity distinctions and modifying identity and practice. This research emphasises the organisational motivation to proactively face the emerging digital technology and new technological knowledge via management actions. Through emphasising the role of professionalised technological knowledge and BIM-related professional identity, organisations safeguard the emerging work jurisdictions of professions and mediate labour division. These strategic actions enable organisations, especially contractors, to drive their digital innovation strategies and keep system stability in the face of emerging BIM technology-enabled inter-organisational collaboration. These strategic actions, by underscoring the collaborative and configurational efforts in inter-professional boundary work through strategic professionalisation within organisations can therefore contribute to productivity in inter-professional collaboration and organisational competence advantages in the emerging digital technology conditions.

Another important finding related to the strategic system comes from professionals' view on organisational strategic actions. This study showed that one observed contradiction is between the enhanced professional identity and the changed power dynamics in decision-making and authority. Within organisations, management support on digital technology adoption and implementation is significant for knowledge sharing practices, and power dynamics is viewed as a kind of restrictive force to prevent the adoption of new digital technology in organisational change (Simeonova et al., 2022). These dynamics on political actions in organisations might pose threats to professionals with relatively weak positional power, whilst enhancing expert authority (Medaglia et al., 2022). Akintola et al. (2020) proposed that the power dynamics is manifested in the tension arising between existing role and new role due to changed authority structure. The change in authority can be manifested in the decision-making process between BIM experts and high-status managers. The differences in the legitimacy of their professional identities should be combined with their legitimate position in the decision-making process through increased autonomy. Within organisations, organisational management strategies reflect the recognition of emerging technology knowledge, and organisational decision-makers restructure the internal division of labour by establishing BIM-related work as independent professional positions. At the same time, organisations enhance the legitimacy of BIM experts' involvement in decision-making. This recognition increases the knowledge weight of BIM professionals involved, thus altering the professional legitimacy and power relations of collaborating parties in boundary work. Internal organisational configurations strategically enhance digital capabilities in boundary work for cross-boundary management knowledge. Organisations tend to deploy digital capabilities (human and digital) as the foundation for boundary work. The focus of inter-organisational arrangements is on how strategic technology development improves digital capabilities, facilitating the adoption of relevant value into the knowledge ecosystems of different organisations, and improving inter-organisational BIM-related practices in collaboration.

This research indicates a kind of power dynamics in the form of 'power dynamics and expert legitimacy' among participants, in which BIM experts intend to grasp more autonomy when they have more BIM-related knowledge and purposely emphasise their expertise autonomy for more control in the decision-making process. This is similar to the study by Bucher et al. (2016) that used a framing approach to observe discursive boundary work strategies. The framing strategies are related to field positions. People show the exclusiveness of their knowledge fields to others against the incursion through different patterns of framing. High-status people tend to embrace and maintain the status quo, while low-status people tend to break the boundaries based on evidence-based framing.

The influence of organisational strategy on the configuration of collaborative activities in inter-organisational relationships is reflected in the imbalance of knowledge and the changing power dynamics across different organisations. In order to expand the current power base concept, Collien (2021) argues for the importance of discussing a resource-oriented power perspective in boundary work, specifically emphasising the study of how power derived from different resources affects the outcomes of boundary work. This also determines the significance of this study's viewpoint, which posits that dynamic power in boundary work originates from organisations using knowledge and capabilities as their expert power resources to expand power relations in construction projects. Collien (2021) indicates that when it comes to inter-organisational knowledge asymmetry, i.e., knowledge differences between individuals from different organisations in construction projects, it manifests as struggles in the decision-making process (partial findings), but other organisational capabilities can offset this knowledge asymmetry to some extent. Boundary work is a social and cognitive construction process of overcoming boundary challenges through knowledge sharing (Paraponaris & Sigal, 2015). Pelizza (2021) suggests that the skills and knowledge required for digital technology will cause knowledge asymmetry, leading to the emergence of boundaries. This study advances the findings to show how digital technology induces knowledge asymmetry through different organisational digital innovation strategies, resulting in practice knowledge differences and reflected in individual practices.

The other contradiction points out that such organisational strategic actions intend to improve the productivity of both conventional practice and BIM-induced practice. However, it may also increase the knowledge boundaries between professionals who create BIM models and professionals who use the BIM model as an efficient tool. This study also underscores the importance of congruent digital capabilities in inter-organisational interactions within strategic systems. A lack of alignment in digital capabilities is thought to be tied to actors' varying levels of BIM knowledge and perceptions. This discrepancy could influence the decisions and practices of actors during the implementation and use of BIM, particularly those with a limited understanding of its potential benefits. These actors are likely to fall back on their traditional experience and revert to familiar practices. This finding is substantiated by the prominent role of cognitive entrenchment (Arvidsson et al., 2014), which is seen as a factor influencing strategic intent and the integration of digital technology into practice. Such cognitive entrenchment leads to actors being blind to the opportunities afforded by digital technology, and therefore reduces the realisation of strategic intentions to organise the implementation and use of digital technology into practice (Arvidsson et al., 2014). Achieving organisational strategic intent into practice on the implementation and use of BIM technology in inter-organisational interaction requires shared perceptions on BIM outcome and benefits, in this case, congruent digital capabilities encompassing BIM-related knowledge and cognition reveal its crucial role in the realisation of strategic intent in the strategically configured activity system.

Additionally, this study found that the introduction of BIM technology introduced uncertainty to the delivery results, and instability in the collaboration process to previously mature cross-boundary collaborations. In this regard, the study sheds light on the strategic system's efforts to build on inter-organisational strategies in light of this. BIM professionals are detached from different organisational collaborative activities and work tasks, and the boundaries between BIM operators and traditional designers have become blurred, challenging their self-professional identity. Such potential changes to business processes based on emerging technologies played a significant role in the transformation happening on the pattern of actions in collaboration (Pentland et al., 2022).

6.4.3 Institutional system for regulating boundary work

The findings indicate that project-based collaborative activities are embedded in an emerging BIM-engaged institutional system, and that they exert a regulating force on professional practice and interaction. The findings show that in construction projects, professional collaborative activities are embedded in a collaborative business ecosystem for the shared project goal. The boundary work among professionals intends to adopt BIM technology use into their processes and norms, even though sometimes, there are some new norms and practices emerging and becoming institutionalised in the project network. The need for such boundary work arises due to tensions between the establishment of BIM norms and practices – stimulated by proactive BIM management – and the adherence to, or adaptation of, existing conventions in project management practice (Bosch-Sijtsema & Gluch, 2019). The institutional system, which is generally stable and comprises shared values, beliefs, and norms (Orlikowski & Barley, 2001), influences boundary work efforts and practices. These findings show that this influence unfolds through the interplay between the tensions generated by evolving practices and the adaptations made by individuals and organisations within the system. These shared values, beliefs, and norms guide the way in which boundary work is performed, managed, and understood within the context of the construction project.

When collaboration activities are project-based, relationships, tensions/struggles, and emerging institutional logics arise both between and within organisations. BIM technology may affect the nature of different boundary environments. Institutional logic (Gegenhuber et al., 2022) in project-based collaboration shows that the AEC industry's institutional logic influences the project decision-making process for the implementation and use of BIM in construction projects. Policy-supported initiatives encourage project teams to use BIM technology-supported solutions to deliver results among project teams. Institutional pressure is regarded as necessary for different organisations to adopt and implement digital technology in the assimilation stage (Liang et al., 2007). With the conventional business model in the AEC industry before the introduction of BIM technology, the design and construction phases are divided clearly (Eastman et al., 2011), which means the designers' or engineers' work will primarily dominate the work operation in the construction phase. While this study found that due to the BIM-oriented collaborative relations changes, the tension arising between design organisations and construction organisations after BIM technology engages the collaborative process and organisational development compels construction organisations to seek changes in their collaborative pattern by reconfiguring their boundaries.

The findings of this study further reveal that the emphasis professionals place on the institutionalised norms based on contracts reflects the structural impact of collaborative activities in the AEC industry. As a highly institutionalised industry (Gal et al., 2008) the AEC industry motivates goal-oriented collaborative activities and establishes a contract-based division of responsibility to create a more robust collaborative boundary. The introduction of BIM technology generates uncertainty, necessitating a more specific delineation of BIM-related responsibilities. Gil-Garcia et al. (2019) demonstrated that a clear division of roles and responsibilities is a crucial condition for cross-boundary collaboration, particularly when encouraging participation in the use of boundary objects. This study suggests a potential extension of concepts on boundary work concerning tensions among different types of boundary work. For instance, contract-based institutionalised responsibility divisions can provide clearer and more stable collaborative premises for regulating professional boundary work.

The existing research suggests that institutional pressure in the AEC industry influences the adoption of BIM technology, especially institutionalised practice and norms (Zomer et al., 2021). Different organisations, owing to their diverse business types, will experience varying degrees and paths of pressure that influence their adoption. For designer organisations, the normative pressure will directly affect top-management decision-making, whereas construction organisations have an independent influence on BIM adoption (Tavallaei et al., 2022). This supports the findings of this study that the configuration of collaborative activity is embedded within an institutional system. Specifically, the collaborative business network provides the groundwork for regulating boundary work occurring within construction projects. These findings contribute to the field of project management by extending the understanding of the boundary dynamics of collaborative activities and tensions arising from challenges to institutional logic.

6.4.4 Inter-system structure

Inter-system relationships reflect the interaction of varying boundary efforts in BIM-enabled collaborative activities, which are deeply linked to the interconnections among different systems. When these boundary efforts interact during professionals' collaborative activities, the tensions generated may stem from different systems. This study advances the theoretical understanding of knowledge boundaries from a boundary work perspective by exploring organisational digital innovation strategies and project-based collaboration. It demonstrates how knowledge practices are driven by the internal and external influences of professional work, organisational digital innovation strategies, and project management. It also investigates how BIM technology intertwines with the configuration of collaborative activities, influencing decisions and relationships. These influences validate the boundary dynamics embedded in knowledge practices, which are subject to the systemic activities of BIM technology knowledge practice participation, namely the strategic configuration of organisations' digital capabilities and the inherent institutional logic. The findings of this study indicate that both intra- and inter-organisational developments in technology innovation strategies have significant external impacts on the configuration of collaborative activities.

Recently, many scholars have called for an exploration of the relationships among different forms of boundary work (Bucher et al., 2016; Langley et al., 2019; Lindberg et al., 2017; Quick & Feldman, 2014). This study contributes to the understanding of these relationships by observing the driver mechanism of boundary work. A variety of driver factors of boundary work effort have been identified. Differentiation and integration through BIM-enabled boundary work are based on various types of digital technology-enabled boundary work. Boundary work is frequently discussed as a purposeful effort, the practice and consequences of which involve changes in boundaries. This research analysis provides insight into systematically discussing boundary work, considering not only the multiple motivations to act, but also the situated influence embodied in organisations in the AEC industry and construction projects. Boundary work is relational, strategic, and institutionalised, offering insight into the changeable boundary status inspired by the current debate on the nature of boundaries. These results revive debate on the nature of boundaries, emphasising their instability and constant rebuilding, driven by project progress and determined by the actions of organisations and individuals.

This study examines how cross-boundary collaborative activities are configured by analysing the consequences of enacting boundaries influenced by professional relationships, organisational strategies, and project-based collaboration. The findings reveal the internal and external factors driving cross-boundary collaboration activities. Notably, these results resonate with recent studies on boundary work mechanisms, which are considered a set of competitive, collaborative, and configurative activities/actions taken by groups of people interacting around boundaries (Langley et al., 2019). Several studies have investigated the nature of boundary work from its incentives, strategies, or consequences in recent years (Bucher et al., 2016; Comeau-Vallée & Langley, 2020; Langley et al., 2019; Quick & Feldman, 2014; Thompson et al., 2019). Recent studies call for an evolving perspective on boundaries as unstable and always rebuilding. Quick and Feldman (2014) have shown that most boundaries cannot only be viewed as barriers derived from knowledge differences, but also as junctures for creating connections between groups to propose innovative ways of addressing problems. The findings in this study suggest that boundary work is defined by the relationship between actors and boundaries and the consequences of their interactions. Theoretically, this can be explained by Langley et al.'s (2019) clarification on the status quo of boundary work, which is defined as a purposeful individual and collective effort to influence the social, symbolic, material, or temporal boundaries, demarcations, and distinctions affecting groups, occupations, and organisations.

This study suggests that professionals' motivations and their mutual dependence are significantly influenced by organisational strategies for BIM implementation and the project goals that advocate BIM innovation. Faulconbridge et al. (2023) demonstrated that professionals' boundary work efforts respond to changes in digital technology (such as AI) to safeguard their professional interests and resources. The linkage between different modes of boundary work is due to the interdependence among professional interests and resources. This study reveals this interdependence from a procedural view, showing task and process interdependence among AEC professionals. Consistent with the study by Faulconbridge et al. (2023), professionals engage in competitive modes of boundary work in digital technology-triggered interactions to protect their boundaries.

Akintola et al. (2020) showed a similar focus on BIM implementation and use in an organisational and multi-organisational project by developing insights into BIM-induced changes in professional practices. By demonstrating the nature of changes in professional work practices derived from the organisations, their findings reveal an evolutionary feature in the changes. It is notable that their study equally applied both organisational context-activity system analysis and project context-activity system analysis of BIM-induced changes. In our study, the findings expand their results by revealing the activity system is unstable due to its interaction with digital technology, as it is consistently evolving with the original boundaries of the activity system. In this study, we aimed to understand the organisation and project as different situations that embraced the fundamental feature of activity systems to contribute to BIM-enabled collaboration.

6.5 BIM technology's role as both object and mediator

The discussion of this section focuses on the identified, multifaceted role of BIM in the Finding chapter. Through an examination of the varying roles of BIM technology across three different levels, the findings of this study revealed the multifaceted nature of BIM technology and their implications for cross-boundary collaboration. The dynamics of BIM technology-enabled collaboration is not only about BIM technology itself evolving with the collaboration (Leonardi et al., 2019), it is also a mediation process on collaborative activities (Allen et al., 2013). In the literature review chapter, it was found that the adoption of digital technology involves a process of integration during cross-boundary collaboration, comprising three stages: emerging; implementing; and using (Karanasios & Allen, 2014). The investigation of this study shows that distinct roles of BIM technology have been perceived in collaboration. Some studies also indicate that actors' perceptions of the characteristics of digital technology or digital artefacts in the collaboration process are believed to change continuously and will recursively influence individual and collective practice by changing their knowledge boundaries (Leonardi et al., 2019). This process is identified as the evolution of digital technology with the collaboration process proceeding. This study suggests that the evolution of BIM technology is derived from the developmental perceptions on BIM role underpinned by its influence on individual and collective activities. These activities are settled at the individual, organisation, and project level, which is related to the interaction between professional expectations and BIM's implication.

A common presumption in many studies is that digital technology assumes various roles across different actions. However, these studies often overlook the possibility that collaborative activities between actors in different actions may alter their perceptions of digital technology. This is especially pertinent in situations where a new technology is being progressively adopted within the collaboration process. It is important to note that this is not only due to the evolving nature of the digital technology itself (Leonardi et al., 2019), but also because of its mediating effect in collaborative activities. Actors' perceptions of digital technology and the materiality of digital technology collectively affect the enactment of technology's affordance and constraints in practice (Leonardi et al., 2019). For the individual's use of BIM technology, the expectation of BIM technology builds on the congruence and incongruence between their work practice with BIM technology and their work objectives. Individuals' perceptions of BIM technology are formed primarily from their immediate experiences and focus on their daily activities due to the immediate consequences of their actions.

The evolutionary process and mediation process of BIM technology are manifested by the attributes of BIM technology as both mediator and object in cross-boundary collaboration in the project-based setting. In this study, as part of its role, BIM technology takes on five different facets across individual, organisational and project levels, which will influence different levels and interplay with each other: The role as a tool reflects its socio-materiality; the perceived practice role reflects professional habitual digital capability; the structure reflects its externalisation capability, the symbol reflects its performativity; and the facilitator reflects its shaping capability.

On one side, the findings of this study present the role of BIM technology can be perceived differently by actors. The way that BIM technology is used as a boundary object is dynamic with a professional's progressive perception of BIM technology. The time constraints are related to how people evaluate the BIM technology performance at different levels and thus will influence how to posit the BIM technology in the decision-making process and allow for the engagement of BIM technology into their practice, business models, or project collaboration. The roles performed by BIM technology will be related to immediate, long-term, or situated situations. Based on the findings, it is found that the roles of objects changed. The role of objects-based BIM technology has a temporal nature in enacting BIM technology. In other words, different levels reflect distinct degrees of time constraints that influence decision-making. Individuals' practice of BIM technology always has immediate consequences. Thus, their perception of BIM technology is primarily determined by their daily experience and application of BIM technology, such as learning technical information about BIM, modelling with BIM software, and identifying building information with 3D models or other BIM artefacts. The BIM technology is usually evaluated directly by them. This has been discussed in detail in section 5.3.1.

On the other side, the different roles of BIM technology influence collaboration in different dimensions: individual collaborative initiatives; organisational BIM development and digital readiness; and project BIM qualities among stages. These Findings echo the call study from Nicolini et al. (2012), which considered the interrelations between various roles of BIM objects in cross-boundary collaboration and its situated context when it exerts influence. As a mediator, BIM technology is used as a tool to help the subject to achieve their objects, for example, the visualisation of complex pipeline designs by BIM software affords the MEP engineers in sub-construction to effectively transfer their detailed designs into a 3D model, resulting in a more detailed design examined in their designing practice and achieve the high-quality design object. This has been discussed in detail in section 5.3.2.

6.5.1 BIM artefacts as an evolving object

This section focuses on the evolutionary nature of BIM technology in project-based collaboration, which includes evolved aspects and its performance. Digital artefacts are created by actors and used by them to yield other digital artefacts through its technological influence (Karanasios, 2018). The interactive process of creating and exerting these digital tools/artefacts (i.e., BIM artefacts), constitutes the existence and meaning of this entire digital technology itself, it emerges the evolving nature of this digital technology in activities. BIM technology evolved different usages depending on the individual, organisational, and project level, due to the diverse ways in which it is engaged in practice. As mentioned in the Literature Review chapter, BIM technology is regarded as a boundary object at the individual level, which evolves with its process from object to boundary object-in-use (Levina & Vaast, 2005). At the organisational level, BIM technology is regarded as a digital innovation, which evolves with the innovation initiatives following the hierarchical management and the operation of organisational digital innovation (Nambisan et al., 2017; Tiwana et al., 2010; Yoo et al., 2010). At the project level, BIM technology is seen as a transformative object, evolving with its changing capabilities in the way of project collaboration (Boland et al., 2007). Therefore, different trajectories are embedded in the BIM's role and its practical engagement in boundary work.

This section conceptualises the multifaceted BIM technology on different levels. The findings reveal the different facets of BIM technology by showing: 1) how actors' technology practice is conducted by working on BIM technology; 2) how organisations strategically implement BIM technology to relate to their capabilities; and 3) how the project situates practice in BIM technology, which catalyses the innovation that might facilitate process change in the way conventional project collaboration in the construction industry works. These facets of BIM technology interrelate across different levels. These include BIM as a practice, BIM as a tool, BIM as the emerging structure, BIM as a symbol, and BIM as a facilitator (these shape the environments). This section presents the diversity of the role of digital technology implemented and used within cross-boundary collaboration. In addition to showing how actors act in relation to digital technology, this diversity demonstrates how digital technology shapes collaboration.

Similar findings about the evolutionary view of BIM-induced changes can be found in Akintola et al. (2020). The evolution of digital technology into a project-based collaborative network and organisation-based system will involve several phases with the emerging implementation and use of digital technology. The evolution of BIM technology is related to the process of changing objects to boundary objects. BIM technology is seen as a boundary object when introducing personal practices, organisational development, and project management (Neff et al., 2010). Neff et al., (2010) recognised that BIM immediately became a visualisation tool for representing buildings in four dimensions; a building component database that can be queried, filtered, and analysed; a collaborative communication tool that connects various expert teams working in temporary project organisations in commercial construction; a tool for translating specific discipline software files; and a building data set that reflects the different disciplinary perspectives of architects, engineers, and contractors. Although BIM currently brings project participants closer together technologically, there remain disagreements in management at the organisational level, often resulting in the inability to access critical information and make timely decisions. Work practices that support strengthened collaboration and knowledge sharing across organisational and disciplinary boundaries have been slow to emerge.

This study reveals the evolving roles of BIM from different levels, which arise from the interaction and actors' progressive expectations of BIM technology with different levels of consideration. This fine-grained exploration of the variability of BIM-related objects in boundary work reinforces Leonardi's research (2019) on the co-evolution of objects and boundaries. In the process of cross-boundary collaboration, the role of BIM technology constantly evolves. This study echoes the findings from Leonardi's research, by revealing that the evolving nature of BIM technology in cross-boundary collaboration is accompanying with professional practice, company strategic development, and industry structural transformation. The subsequent section discusses the changing role of BIM technology in the implementation and adoption process, as well as the technological changes brought about by BIM technology in various aspects of the AEC industry and construction projects. By analysing the evolutionary nature of BIM technology, this section demonstrates how BIM technology participates in cross-boundary collaboration activities. This echoes the recent BIM-related study calling for seeing BIM implementation as an open-ended process where different professionals' use and implementation of BIM implementation is continually adapted in organisational collaboration activities (Miettinen & Paavola, 2014). BIM technology is considered as a boundary object that facilitates the sharing of syntax and semantic knowledge for effective work among different professional groups, especially for the AEC industry, where construction projects always involve multiple stakeholders from different organisations, requiring the conversion of practical knowledge to establish common goals (Carlile, 2002). With the development of digital innovation by various organisations in the AEC industry, BIM technology has been integrated into individual knowledge practices. Some studies have shown that the role of digital technology in practice is changing and that IS artefacts of different groups in different scenarios have different meanings (Leonardi et al., 2019).

6.5.1.1 Exploratory stage of perceived BIM technology's role as boundary object

The findings of this research indicate that professionals' preliminary perceptions of the impact of digital technology on collaboration primarily focuses on their professional engagement with BIM tools and artefacts. This perception represents the exploratory stage of the role of digital technology in collaborative activity. When professionals integrate BIM technologies into their practice, their initial understanding is derived from exploring the capabilities of BIM technology through the use of BIM artefacts and their interaction with BIM tools (Papadonikolaki et al., 2019).

Professionals with limited experience in BIM technology often engage in extensive trial and error, leading to rapid changes in practice due to immediate feedback gained from using BIM models. Eventually, they come to understand the capabilities of BIM technology. Their primary perception of the role of BIM technology in collaboration is usually focused on its short-term effectiveness and productivity for specific tasks. However, professionals whose practice does not directly involve creating BIM models or using BIM artefacts might only have a vague understanding of the capabilities of BIM. For example, project managers from the owner organisation may hold assumptions about the capabilities of BIM but lack specific evaluations or awareness of actual user practices with BIM. This is evident in the contrasting perspectives from construction engineers who often identify gaps between the designed BIM model and the actual on-site situation – a discrepancy that clients may not understand until explained. Construction engineers clarify the role of BIM by defending their practices involving the use of BIM technology. The use of BIM as a practice contributes to the completion of the infancy stage of digital technology, allowing professionals to establish their perceptions of BIM objects in interaction.

During the exploratory stage of the perceived role of BIM technology, professionals rapidly define BIM technology from a tool-oriented perspective, aligning it with their current practice. Using BIM as a tool represents their belief in BIM's role in their practice. They find effective ways to address the changes brought by BIM technology to align with their familiar practice, a finding that aligns with a study on individual adaptation to digital technology (Majchrzak et al., 2000). When digital artefacts become boundary objects in use, which delineates the exploratory stage of the perceived role of BIM technology in collaborative activities, the boundary object may change as professionals face different boundaries. In other words, changes in boundaries can lead to changes in the used boundary object (Leonardi et al., 2019).

As BIM evolves from an object to a boundary object in use, professionals must navigate synthetic and semantic knowledge boundaries. They tend to engage in negotiating and merging boundaries. Shaping BIM as a boundary object appears to be a prerequisite for dominating a discourse field (Collien, 2021). However, Fang et al. (2022) critically reflected on the dichotomy of 'use or non-use' and the predetermined properties of boundary objects in prior research on digital artefacts as boundary objects. In their study, they proposed that the production and replication process of digital artefacts co-evolve in practice.

This view aligns with the argument posited in this study that the adoption of digital technology as boundary objects exhibits evolutionary characteristics. Recent studies on technological affordances suggest that when people recognise BIM's affordances, they are more likely to implement BIM-related practices. These practices can include spreading knowledge about potential values and types of BIM usage in communication and negotiation, thus increasing the chances of enacting BIM artefacts as boundary objects. However, such technological affordances also depend on others' perception and experiences, which has not been clearly mentioned in prior studies. According to this study, whether a BIM artefact becomes a boundary object in use greatly depends on the users or creators' project experience and knowledge domains. Even though BIM artefacts are sometimes assumed to be used as boundary objects, professionals take different actions on BIM artefacts to achieve their goals. For instance, if on-site managers aim to use a building model to explain their construction schedule or raise site issues, they may use drawings or BIM models in their collaborative activities. Their goal is to reach a consensus on solutions to their construction schedule or site issues. If they utilise a digital model to achieve this activity goal, the digital model can be designated as a 'boundary object in use'. Otherwise, it is an intermediary object in its production process—digital model creation.

In the context of an engaged construction project, the uniqueness of BIM technology lies in the creation and assessment of BIM artefacts by different interconnected professionals at various stages. For instance, BIM artefacts created by one set of professionals might serve as tools for others. This multiplicity of roles played by BIM technology is embedded in interrelated and continuous processes within the construction project collaboration (Miettinen & Paavola, 2018). The complexity of the perceived affordance process of BIM technology leads to changing roles of BIM artefacts in collaboration. This is evident in the relationship between the engagement of digital technology in practice and professionals' perceptions of BIM roles.

The exploration of digital technology's role in collaboration depends not only on its impact on participants, but also on the relationships between collaborating participants. Architects, engineers, contractors, and project managers all perceive BIM roles differently, and their impact on the evolution of BIM objects also differs. This reflects the fact that when BIM technology is embedded in different activities, BIM artefacts manifest in different forms: "The new object is usually not the intentional product of a single activity but the unintended result of multiple activities" (Engeström, 2008, p. 3). Due to the intertwining of various activities, then, the object produced carries different expectations of its performance and meaning.

The different roles of professionals correlate with their distinct perceptions regarding the availability of BIM technology, which in turn is associated with their different expectations and perceptions of BIM tools and BIM artefacts. This indirectly reflects the cognitive diversity of BIM technology's availability. For BIM technology, since BIM software serves as a digital tool and its produced BIM models and other digital artefacts form the core of BIM technology, different professionals' perceptions towards BIM digital tools and BIM digital artefacts relate to their knowledge domain and interaction patterns with BIM technology.

When BIM is used in practice, participants are more actively engaged in BIM-related activities, including learning about BIM and exchanging BIM-related knowledge. When different professional groups communicate with each other about BIM performance and BIM-related goals, they are more likely to accept BIM-related values and engage in adaptive behaviour. When BIM is used as a tool, the roles of BIM tools and artefacts are similar to those of other artefacts. Participants will judge and predict whether BIM-related tools can achieve their goals based on their experience and understanding of BIM. This comparison will lead to different choices. When actors perceive that BIM technology can achieve their goals, they are more likely to spend more time and energy producing BIM products, such as BIM models. However, when actors cannot perceive the advanced nature of BIM technology, they will try to avoid investing energy in BIM technology, which also makes it difficult for them to produce BIM-related products that can meet practical purposes. This could negatively impact the work of other project participants.

In this study, BIM technology is perceived, evaluated, and anticipated by professionals when used as a tool. Most experienced professionals in construction project, especially those in high and low positions, tend to judge BIM based on their own project experience or rely on their perception of BIM performance in previous projects to make performance-based predictions about BIM. Decision-makers in high positions are more likely to see the long-term advantages and disadvantages of BIM's performance, but may overlook potential challenges and differences between different groups of people in practice, such as attributing the reluctance of experienced technicians to use BIM models to their refusal to learn new knowledge, when in reality many 'old hands' have a positive attitude towards BIM technology but have only a one-sided and incomplete understanding of its potential due to a lack of organisational support for learning resources. At the same time, those in lower decision-making positions are more likely to evaluate BIM based on specific usage experiences, because they are less involved in the overall project decision-making process. Therefore, they tend to perceive the material availability and constraints of BIM from their own usage experiences, while those with less experience using BIM may find it difficult to perceive its availability and constraints from its materiality, and instead form their cognitive understanding of BIM from its social dimension.

6.5.1.2 Absorption stage of perceived BIM technology's role as boundary object

Another finding of this research is that professionals' perceptions of the impact of digital technology on collaboration in the next stage is primarily focused on the well-established and widely accepted implications and consequences of BIM technology for collaborative activities, which presents the absorption stage of digital technology's role in collaborative activity. The perception and expectation of digital technology is no longer novel, and its use in collaboration is standardised and efficient. Mutual practices in collaboration have been defined and are widely followed. Actors have moved beyond basic familiarity and are now absorbing the technology into their regular workflows, which is mainly occurring with a consideration of organisational development. They understand how to use BIM effectively and are starting to see its benefits for their collaborative projects. In this stage, the role of BIM technology is evolving from a boundary object-in-use to a boundary object-in-signify, which is concerned with the way in which BIM technology functions as a device for managing boundaries derived from the existing organisational structure and culture through shedding light on the value. For example, BIM specialists in a sub-construction organisation create the adapted work routine with managers to innovatively address project changes by applying BIM platform-based routines into their conventional practices. Thus, the BIM platform-based work routine functions as a bridge to incorporate the innovative process into the existing process.

Such absorption of the perceived role of BIM technology from practice also reflects on the adjusting of organisational culture with BIM technology's symbolic meaning in the AEC industry. Top managers, whether they come from a design organisation, construction organisation or owner organisation, indicate that the implementation and adoption of BIM technology can be related to organisational innovative techniques and a pursuit of quality excellence. Such shared symbolic meanings of digital technologies to related but different organisations serve to build partnerships between them.

Their organisational long-term innovation development means that they transform their perceptions of BIM technology's role in the organisational decision. When professionals view BIM technology as the emerging structure with concerns may change due to the project-based context. When the transformative aspect of BIM technology evolves in facilitating, professionals face the pragmatic knowledge boundaries, and they engage in negotiating and downplaying boundaries. The evolution of BIM artefacts exhibits similar characteristics to what is referred to as "runaway objects" in current research, which pertains to objects in activities that are both dispersed and concentrated (Karanasios, 2018, p. 144). BIM artefacts can serve not only as tools shared among different participants, such as subcontractors and project managers, but also as objects that are unfinished and can be redefined by some actors, such as architects and structural designers. BIM technology, then, can function as both a mediator and an object in cross-boundary collaboration in a project-based environment.

This finding extends theoretical understanding on the nature of boundary objects from its symbolic meaning by relating the perceptions of BIM technology role with its meaning and implications. Compared with boundary objects used in practice and immediately from Levina and Vaast (2005), the incorporated BIM technology shows that professionals generate a more mature and long-term-based perception of BIM technology that sits alongside their existing experience derived from their use of BIM technology.

6.5.1.3 Transformation stage of perceived BIM technology's role as boundary object

The findings show that the professionals' perception of the impact of digital technology on collaboration in further stage is mainly focused on the role of digital technology in collaboration changes significantly due to advancements in the technology itself or changes in the collaborative context, which presents the transformation stage of digital technology's role in collaborative activity. The transformation stage might involve new uses for the technology, shifts in how it is integrated into collaborative processes, or changes in the nature of the technology itself. During this stage, the established perceptions of BIM technology from the exploratory and absorption stage will have interacted in the project-based context across project partners' knowledge boundaries.

6.5.2 The mediator effect of BIM technology in transformative change

The mediating effect of BIM technology is evidenced in how it influences the emergence of boundary changes through varying degrees of impact on collaborative activities. This aligns with existing research, suggesting that different object-oriented activities intertwine, with digital technology serving as a mediator that affects the outcomes of these activities, and the consequence of one activity, mediated by digital technology, can influence the consequence of others (Karanasios & Allen, 2014). This study posits that this intertwining effect is tied to the impact of BIM technology on the boundaries within the mediation process of collaborative activity participation. The results of this study reveal that in multi-stakeholder construction activities, BIM technology assumes different roles at the individual, organisational, and project levels of collaborative activities as it emerges, is implemented, and is used. This gives rise to different changes in individuals' perceptions and practices, organisational structure and culture, and project goals. The interrelationships between these changes are believed to be connected to the emergence of contradictions and congruences in BIM-mediated collaborative activities (Karanasios & Allen, 2014). Upon further investigation of the intermediary processes involved with BIM in this study, it has been found that different BIM mediating processes significantly impact the boundaries between professionals. This includes the processes of empowerment, accommodation, and navigation. The far-reaching influences of these mediating processes are considered to be associated with cross-level contradictions and consistent or inconsistent interrelationships.

The research results indicate that professionals, by applying and implementing BIM technology in their work practices, enhance their interactivity and foster more transparent and effective communication in collaboration with other professionals. Owing to the affordances of BIM technology itself, this BIM-based professional interaction expands their knowledge and capabilities. This study observes the role of BIM technology at the individual level and its connection and interweaving with collaborative activities at the project level. After comparing and contrasting the influences of BIM technology on the work practices of different professional groups, it was found that BIM affects the professionals' abilities and cognitive levels. This enhancement of abilities and heightened cognition of other professions alters professionals' discursive authority in project-based collaboration. That is, BIM technology influences target management in construction project activities by empowering professionals' technological capabilities and their perception of other professions.

The research findings indicate that the adaptation process of BIM technology involves the restructuring of boundaries, mediating collective groups through adaptation and value recognition. A result of this study suggests that BIM technology is perceived at the organisational level to introduce a novel structure for managing collaboration. This corresponds with the views of Akintola et al. (2020) in their activity theory-based BIM implementation research, which also emphasised the transformative potential of BIM technology at the organisational and project levels.

Their research observed minor changes in the work practices of in-house professionals from a tool-centric perspective, introduced by the implementation of BIM. These slight shifts gradually led to the evolution of organisational activity systems and were associated with the backdrop of project activities, thereby causing the evolution of project teamwork practices. Comparing with the existing study from Miettinen and Virkkunen (2005), their study shows that the representational artefacts such as digital model can play an instrumental role in inducing change in organisations. The results of this study confirm this viewpoint, suggesting that BIM technology, while impacting the structural elements of organisational interaction systems, concurrently holds symbolic significance for cultivating a new organisational culture.

For instance, the transformations that BIM technology introduces to an organisation are manifested in the dissemination of emerging rules, norms, and technical values amongst different professional groups in organisational strategy and decision-making. Examples of this include the work procedure proposed by the design organisation for BIM collaboration, which has standardised the unfolding of collaborative activities in the project, and the trust in technological innovation within the project, established by subcontracting organisations. These organisational transformations provide both structural and cultural preconditions for the application of BIM technology in projects.

In contrast to the study by Akintola et al. (2020), this research does not solely observe the specific changes in professional collaboration practices brought about by BIM from a tool-centric perspective. It also investigates the cultural and structural environment created at the organisational level for project-level transformations, proposing that BIM technology, through its structural processes and symbolic implications, holds the potential to instigate more profound transformations in the project institutionalised practice and organisational collaborative cultural aspects.

Furthermore, the ability of BIM technology to undergo structural changes is believed to be linked to its symbolic significance in the AEC industry, driving cultural change within organisations through symbolic roles. Although digital technologies have the potential to disrupt organisational inertia (Thompson et al., 2019), they face obstacles in the form of boundaries. The results of this study indicate that organisations are beginning to focus on actively innovating through boundary work with digital technologies to adapt to current disruptive changes, which may enable them to develop more capabilities in different aspects. Consequently, this can stimulate digital innovation in organisations. In this context, BIM technology, as a symbol, possesses the ability to effect change. Through the symbolic use of BIM technology, organisations can showcase their digital capabilities and ideas to the outside world, with the aim of creating a digital innovative organisational image. The symbolic significance of digital technology is advantageous in enhancing organisational competitiveness.

However, this study also found that certain symbolic technological determinisms exist among senior management within the organisation. This implies a view of technological bureaucracy and functionalism towards digital innovation, as well as a one-sided perspective that focuses more on how digital technology affects project teams rather than how project teams affect it (Papadonikolaki et al., 2022). Nevertheless, Swan et al. (2007) have argued that symbolised objects are more likely to be used in a tool-oriented manner, with social participants utilising their inherent ambiguity in interactive activities to manipulate the meaning of objects. If the symbolic value conveyed by symbolised objects is not closely related to practice, unrealistically high expectations may result in a reduction in new innovation or potential conflicts.

The current research results demonstrate that the mediation process of BIM technology serves as a navigator and facilitator for organisational and individual strategy and work transformation in project collaboration practices. The findings of this study highlight that at the project collaboration level, the introduction of BIM technology has brought more variation to the temporary collaborative relationships established within project networks. Simultaneously, however, the enhanced functionality of BIM technology has increased interactivity between different professions and organisations. For instance, while the visibility of the BIM model has introduced much unnecessary information, it has made previously difficult-to-notice pipeline collisions more apparent. This provides design professionals with greater opportunities to anticipate potential issues, thereby reducing potential conflicts with constructors during the subsequent construction.

Furthermore, this discovery also reveals that BIM technology's role in mediating relationships between different organisations within project activities also serves as a guide for future organisational transformations. For example, professionals from various organisations mentioned that in projects involving BIM, the distinction between the design and construction phases of the project cycle has gradually blurred. This change is mainly due to the enhanced knowledge transmission capabilities of BIM technology during project collaboration compared to traditional 2D design. The knowledge boundaries between the design and construction parties are crossed in advance under the influence of the BIM model, thereby resolving potential issues during the design stage that might have been discovered in the construction stage. This change in the project collaboration process directly impacts the roles of various stakeholders in organisational work practices.

6.6 Contextual conditions of BIM-enabled cross-boundary collaboration

This section delves into the interpretation and analysis of the contextual conditions identified at different levels of BIM collaboration in the Findings chapter. By observing the feedback and changes in the structure of IT embedding through the lenses of individual knowledge boundaries, organisational activity systems, and project networks, the Findings chapter analysed the three levels of BIM collaboration and identified significant contextual conditions influencing BIM implementation and use. At the individual level, the identified contextual condition is the model creation process underpinned by institutional logic. At the organisational level, the identified contextual condition is the top-down digital innovation process. At the project level, the identified contextual condition is the stages of the project life cycle. These contextual conditions are intertwined and shape BIM-enabled collaborative processes and professional behaviours.

Research findings reflect that, in the AEC industry, construction projects allow various stakeholders to be embedded in a cross-organisational and professional interaction linked by shared interests and the process of construction project management. In this context, the core goal of all stakeholders is the completion of project goals and the creation of different organisational values. And these stakeholders' activities are embedded in the complex rules of the AEC industry's activity system; in other words, the project activity environment has predefined what actions and deliverables are allowed and preferred (Aksenova et al., 2019). Through the theoretical lens provided by the activity system to explore the environment of boundary reconstruction and maintenance in BIM collaboration, the nature of BIM-enabled construction projects is that of collaboration in a multi-activity environment, and the collaboration between project members is embedded in an environment constituted by different disciplines, industries, institutions, and organisations of the AEC industry which create boundaries, and it is this that brings about the reconfiguration of knowledge boundaries. From an organisational cultural history perspective, the social culture and structure conveyed by BIM-related practices will be related to the multiple environments of BIM collaboration in the project. Cross-boundary collaboration has been regarded as a value co-creation process of the construction project. The shared logic in the collaboration defines the acceptability of value creation from a social perspective and guides the formation of expected goals (Aksenova et al., 2019). The cross-boundary collaboration will show how organisational interests are entangled with each other. Therefore, the BIM-involved knowledge boundaries in the project are shaped by the value co-creation process. Moreover, based on the theoretical understanding and debates about cross-boundary collaboration in the extant literature, the organisation as a relatively stable structure of the activity system provides the foundation for contradictions emerging when digital technology evolves and mediates in collaboration activities (Sackey & Akotia, 2017; Simeonova, 2018). Contextual conditions determine the cause of knowledge boundaries; specifically, the characteristics of the context determine how the knowledge boundaries will potentially change, and this will affect the properties of knowledge boundaries (Gal et al., 2008). Therefore, the exploration and interpretation of the situational conditions of BIM collaboration can supplement an understanding of the stability and interaction of the activity systems at different levels in the current research, as well as an understanding of the impact and dynamics of the environment on the boundary work in collaboration among different professionals accompanying the implementation and use of BIM technology.

This section elaborates on the temporality, materiality, and interactivity of the identified situational conditions in the research findings, which are believed to be the characteristics of the activity environment that simultaneously affect the dynamics of collaboration in BIM implementation and use. These situational conditions answer the third sub-research question by reflecting on the characteristics of collaboration based on the BIM process at different levels, through observing the occurrence and resolution of contradictions and conflicts in different collaborative activities between professionals in the model creation life cycle, management life cycle, and project life cycle in the results section, as well as the changes in the objectives of professionals in initiating boundary work with BIM technology. The findings show that the three features of the situational conditions shape the collaboration based on the BIM process. These include temporality and permeability. From the research findings, the situational conditions underpinning digital innovation are a socio-material condition, encompassing inherent collaborative relations and processes capable of persistent changes (Avgerou, 2019). The dynamics of situational conditions are essentially the interactions between three environmental levels: the individual environment; the organisational environment; and the project environment. They shape the application of BIM technology in professional practice, AEC organisational innovation, and project management. The findings reveal the dynamics of situational conditions based on these potential context-shaped trajectories; these trajectories are displayed at three environmental levels.

6.6.1 Temporality conditions of activity context

Observing the activity system from a cultural-historical perspective reveals that changes in different components of the system can cause contradictions and tensions in other parts of the system (Dennehy & Conboy, 2019; Kamanga & Alexander, 2021; Karanasios & Allen, 2014). The gradual introduction of digital technology into the practice and management of construction project activities may result in changes in all parts of the activity system, which is composed of different professional backgrounds, different organisational cultures, and different stages of the project life cycle. These changes are considered by some researchers to be challenges and contradictions caused by different practices and decisions taken to address the application of emerging digital technologies (Allen et al., 2013), or related to the evolution of interactions between digital technologies and users (Leonardi et al., 2019). In short, these changes in collaborations involving digital technologies are considered to present correspondence with their related situated conditions over time (Mousavi et al., 2021), a hypothesis consistent with the results of some related studies, such as certain contradictions in extended learning presenting stage-like and continuous characteristics (Engeström, 2001). This suggests that each component within the system is transient and will change, and that the timing of these changes is inconsistent. In this study, by analysing the construction of collaborative activities at the individual, organisational, and project levels, and the results of boundary work between professionals, the ingrained temporality in the activity environment, which is shaped by different boundary relationships and purposes and is commonly manifested in the different intertwined activities. Specifically, in different BIM technology application activities, the collaboration of professionals sets temporary rules and assigns temporary roles for BIM use and implementation, thus establishing a temporarily stable environment to fulfil task requirements and project objectives. The temporality of this collaborative environment is mainly manifested in the temporary order established in the changes of collaborative situational conditions about BIM use and implementation activities, the result of which is specifically embodied in environments at various levels.

At the professional level, the connections between digital artefact development processes become the situational conditions for collaborative activities. As professionals use BIM technology together to complete the development, testing, and review of architectural digital models, this basic collaborative linear process elucidates that the implementation and use of digital technologies among different professional groups are based on the intrinsic logical relationships between different professions (Berente & Yoo, 2011; Burton-Jones et al., 2020; Slavova & Karanasios, 2018). The interaction between BIM artefacts and professional collaboration activities reveals the directions of action of different professional groups during different collaboration activities. In BIM-supported collaboration, the development of digital artefacts centred on BIM models connects professionals from different disciplines through work tasks and digital technologies. The connections between these activities, from the perspective of the activity system, mainly reflect that as the participation stages of digital technology in activities differ, the embedded system rules and driving forces will also change, and these changes between activities are based on the nature of BIM collaboration being a digital artefact development process and not just a purpose realised by digital technology (Lu et al., 2018; Papadonikolaki et al., 2019). BIM-based collaboration scenarios effectively connect the interaction of professional knowledge practices and the interaction generated by the adoption process of digital technology through the development process of digital artefacts (Akintola et al., 2020; Papadonikolaki et al., 2019). Further, it encourages professionals to find professional positions through interaction in the adoption, development, and adaptation of BIM technology, generate practice adaptability, develop BIM capabilities, and perceive the value manifestation of the results created using BIM technology. In the actions before and after this process, professionals show different value-driven BIM usage behaviours, indicating that the actions of each stage in the BIM artefact development process are influenced by the profession. This is confirmed by Wang et al. (2022), that professional differences can have a transformative impact on the implementation and use of BIM in collaborative interactions. According to an ethnographic study with an activity theory-based lend on different professional's practice on BIM technology, Miettinen et al. (2012) suggest that the variety of specific ways of using BIM technology need to be paid more attentions in studies.

At the organisational level, the research results found that the temporality of scenarios based on BIM collaboration is mainly reflected in the long-term strategic decisions and the inconsistency of short-term benefits in the top-down implementation of organisational digital innovation in the construction industry. Notably, this will affect the expectations for the performance and results of BIM technology in collaboration. Different organisations within the AEC industry need to improve their digital innovation capabilities through digital transformation to adapt to the development of the AEC industry when promoting the digital transformation of organisational management and business, guided by senior leadership. However, middle management in the long-term development of the organisation bears the pressure to promote digital transformation. Technology-centric learning within the organisation, as opposed to practice-centric learning, has led to a significant difference between the feedback received from actual long-term learning and the immediate feedback received in work practices, thereby dampening the enthusiasm of technical personnel. This strong contrast between high-level decisions based on long-term development and the short-term benefits brought about by BIM technology in actual practice presents obstacles within the organisation, whether it is the leadership at the middle and high levels promoting digital innovation measures, or technical personnel applying BIM technology in practice. Elbanna and Newman (2022), in their critical analysis from a leadership perspective, showed that excessive optimism of senior managers towards the implementation of information systems could also lead to negative results. Their research, based on interpretivism, combined the descriptions of senior managers about the implementation of information systems and the exploration of their operating environment, revealing contradictions and conflicts between high-level decisions and actual conditions. This confirms the findings of this study regarding the inconsistency between the purpose and direction of high-level strategies within the organisation and actual practices. Moreover, this indicates that the time lag in the promotion of BIM digital transformation within the organisation's internal environment will affect the expected effectiveness of BIM technology in collaboration.

At the project level, with the different stages of construction project life cycle management, the joint ground (Levina & Vaast, 2005) promoting effective cross-boundary collaboration among different professionals in BIM collaboration is changing. For example, during the project planning phase, the division of BIM collaboration deliverables and the assessment of BIM team performance, all based on the shared collaboration vision of different project teams, lays the foundation for effective cross-boundary collaboration in subsequent project stages. The design phase, construction phase, and operation and maintenance phase, each reflect the considerations and trade-offs in different aspects of BIM collaboration, showing changes in the requirements for common goals in the collaboration environment over time in effective BIM technology collaboration.

Different temporal conditions become the prerequisite for the occurrence of contradictions and consistencies in the interaction of activity systems. The findings of this study reveal the complexity and variability of digital collaboration in cross-boundary environments, especially in the AEC industry that is undergoing digital transformation. The implementation and use of BIM are embedded in three collaborative processes with different temporal conditions: the professional collaboration process oriented towards the development and application of digital artworks; the long-term organisational strategic collaboration process oriented towards top-down digital innovation; and the project collaboration process oriented towards the management of the project life cycle. The temporality of these three activities explains the differences in collaborative activities involving BIM under different collaborative processes. This reveals the impact of different levels of goals and process differences in the construction industry under digital transformation on cross-boundary collaboration involving digital technology, as well as the contradictions and challenges of such collaboration in multiple temporalities.

6.6.2 Permeability condition of activity context

The second recurrent condition shaping the boundary work in the BIM implementation and usage process is the permeability condition of the activity context. This reflects the permeability of knowledge practices in activity contexts with different material properties. The outcome of boundary work is the process of establishing, crossing, breaking, and blurring existing boundaries between different professions, reflecting changes in boundary states (Lindberg et al., 2017). Thompson et al. (2019) observed that boundary work involving digital technology enhances boundary permeability, thereby changing boundary forms. The findings of this study show that boundary work involving BIM among professionals reshapes boundaries through interaction in different activity system environments. From the perspective of activity theory, differences in the environment and volition of the activity system will affect the realisation of activity purposes among subjects, such as rule/norm consistency (Groleau et al., 2012). The contradictions and inconsistencies that emerge during interaction between activity systems can also lead to changes in the activity system itself (Allen, 2013). In other words, the stability of the activity system depends on how the contradictions generated in the activity are transferred and resolved. The environmental conditions of boundary work involving BIM show different permeabilities, specifically reflected in the different environmental restrictions on how different contradictions and conflicts are transferred and resolved in boundary work when professionals interact in knowledge practices, and these restrictive conditions for knowledge flow are considered to be related to boundary permeability (Thompson et al., 2019). The results of this research show that the permeability of boundaries reflects the flexibility of the structure in the activity system, and the structure of the activity system is determined by work relationships, hierarchies, or rules/norms. Under individual-level conditions, the process of creating a BIM model is based on work relationships established on professional logic (Gieryn, 1983). This is due to the continuity of the process of creating architectural products - the work between professionals in the collaborative process requires intensive and flexible interactions of knowledge practices through extensive communication and negotiation. This increases individuals' perceptions of each other's BIM-based work, facilitating the resolution of contradictions in activities. Overall, this suggests that environments primarily structured by work relationships based on professional logic have strong permeability at the individual level.

At the organisational level, the BIM-driven digital transformation of the AEC industry promotes organisational change through the strategic implementation and use of BIM, both internally and between organisations. This is a part of organisational digital innovation. According to the results of this study, various digital initiatives have been adopted and embedded in intra/inter-organisational collaboration. Organisational management and innovation processes are top-down, through various strategies in BIM technology implementation. Generally, participants indicated that top decision-makers within the organisation evidence a willingness and recognition for BIM-enhanced business development. However, the management layer responsible for supporting substantial operational changes is absent, especially in the case of construction and subcontractor organisations. For example, in the absence of clear industry guidelines on BIM collaboration in the AEC industry, design organisations tend to establish a BIM product evaluation mechanism to offset potential quality control risks in inter-organisational collaboration. As a result, an evaluation system has been created for the management and delivery of BIM implementation, both internally and between organisations. Although a learning culture for BIM usage has been established within the organisation, technology-centric organisational learning models and user resistance still lead to the formalisation of BIM implementation. This is primarily viewed as a result of the expressiveness of the upper management layer committed to digital innovation and performance-driven value creation. Therefore, this suggests that the main component constituting the highest permeability of knowledge boundaries at the organisational level is the top-down management structure. This structure affects the substantive cultural change and paradigm shift in the BIM collaboration environment within the organisation. This shows that the boundary permeability at the organisational level is relatively low.

In recent related research, Wilhelm and Dolfsma (2018) explored the permeability of organisational boundaries and introduced the concept of knowledge boundaries within the organisation, regarding them as adjustable structures. Their research found that a 'purposeful knowledge flow' is generated within the organisational structure, which in turn leads to structural consequences that affect organisational boundaries. In other words, the knowledge boundaries within the organisation are a temporary structure that undergoes structural changes under the influence of boundary work. This study extended their viewpoint by exploring the circulation and effectiveness of digital innovation management strategies within the top-down knowledge boundary structure of the organisation, thus realising that the flow of knowledge based on digital technology is circulated with management strategies within a top-down structure. However, this management structure within the organisation has weak permeability, making it difficult for this knowledge based on digital technology to circulate. This led to a delayed response in the innovation of the organisational management paradigm based on BIM collaboration.

Based on activity theory, this study links the structure that constitutes the collaborative environment with inter-professional work relationships, organisational management paradigms, and institutional factors. This research found that the environments of individuals, organisations, and projects have different impacts on BIM-enabled collaboration, and the attributes of boundary permeability at various stages shape the environment of BIM collaboration.

6.7 Chapter Summary

This chapter offers a comprehensive discussion drawing from the 'Findings' chapter. It shows a theoretical framework drawing from the findings and plural theoretical perspectives, linking the discussion of the findings to the research questions relates these findings to the existing literature and delves deeper to explain and elaborate on the digital collaboration across boundaries. Furthermore, this chapter discusses the implications of these findings and acknowledges their limitations. Central to the interpretation of the findings is the exploration of multi-driver boundary work across different activity systems, the evolution of digital technology, and the temporal and permeable nature of conditions that shape digital technology-enabled collaboration. By reflecting on the synthesised theoretical framework and considering concurrent similar studies, light has been shed on the theoretical understanding of interactions among multiple activity systems, especially emphasising the hierarchical and temporal nature of these systems. In addition, the discussion on boundary work considers the purpose and consequences of such work, highlighting the importance of digital technology-enabled boundary work.

7 Conclusion Chapter

7.1 Overview of this study

This research aimed to explore digital collaboration across knowledge boundaries in construction projects, within the context of BIM technology emerging in different individual practices within both intra- and inter-organisational collaboration in the AEC industry. Therefore, primary research question was: How does digital technology enable collaboration to occur across knowledge boundaries in BIM-enabled construction projects? This question was approached through a qualitative case study based on the integrated theoretical framework derived from the literature review (see Section 2.6).

In analysing the embedded case study, a multi-level investigation was conducted, encompassing individual, organisational, and project levels. The primary findings emerged from three dimensions:

- The configuration of collaborative activities, with the analysis grounded in the driving mechanisms behind these activities.
- The evolving role of BIM technology, as perceived by participants, especially in the implementation and use of BIM technology in collaboration.
- The dynamic contextual conditions that support BIM-enabled collaboration. Within this dimension, the temporal characteristics of BIM-driven activities and their associated collaborative objectives were highlighted.

The results revealed diverse perspectives from participants, including points of contention. These findings reflect the different participants' diverse perceptions of BIM. Subsequently, these results were discussed in relation the existing literature on digital technology-engaged boundary work, the interaction of activity systems, and BIM-enabled project management, and this was followed by developing the study's contributions to practice and the recommendations for future research.

7.2 Research contributions

7.2.1 Empirical contributions

This multidisciplinary research enhances the understanding of BIM technology-enabled cross-boundary collaboration in construction projects. The empirical evidence presented not only enriches the current body of practical knowledge about BIM technology adoption, but it also provides significant insights into the digitalisation of the AEC organisation/industry. The first empirical contribution is the elucidation of professionals' practices with BIM technology in collaborative activities. The study reveals the varied motivations that professionals have for integrating BIM technology into their collaborative efforts by distinguishing between their intrinsic motivations and extrinsic motivations for collaboration. These diverse motivations have been found to influence the manner in which BIM technology is incorporated into practice to support knowledge-based activities. The examination of individual motivations for BIM technology-engaged collaboration for the purposes of this research offers a fresh perspective to existing studies on interprofessional collaboration within BIM-enabled construction projects (Akintola et al., 2020; K. Wang et al., 2022). Furthermore, the research delves into professionals' varying perceptions of BIM technology and elucidates their dominant perceptions—both practice and tool-oriented—based on their work habits influenced by BIM technology and their assessments of digital collaboration. This particular facet of the incorporation of BIM into professional practice has not been thoroughly explored in prior research, despite being considered crucial in recent studies (Ahuja, 2023). Additionally, the research underscores the importance of the building model creation process in shaping how BIM technology is employed in a professional collaboration. The identified methods of adapting BIM to this overarching process offer a novel perspective on understanding the adaptation of BIM technology in professional collaborations.

The second contribution is situated on the understanding of BIM adoption in AEC organisations. Zomer et al., (2021) have explored the changes in situated context due to BIM implementation by observing the contradictions between the situated practice and institutionalized practice within the project context. It reveals the role of BIM as a new tool in the situated practice and the influence of implementation strategies. This study illustrates the BIM implementation strategies within AEC organisations; explained the collective perspective on considerations of BIM technology's role, the perceived value, and the influence of BIM technology implementation for AEC organisations. It explains the organisational objectives of

BIM implementation which contrasted with the varying role of BIM technology in individual practice and project-based practice. It revealed collective perceptions of BIM technology, which differ from that of individual perceptions, shed light on the symbolic meaning and structural influence of BIM technology for AEC organisations. by providing a novel insight into studying the emerging influence of BIM technology as a new technology implemented in organisations involving inter-organisational collaboration. Moreover, this study also reveals the hierarchical digital innovation management and operation in AEC organisations that provide an interpretation of current experienced challenges in BIM-oriented AEC organisational digital transformation (Oti-Sarpong et al., 2021; Papadonikolaki et al., 2022).

The third contribution from this study is that it improves our understanding of the process of the use of BIM technology in construction projects, especially concerning the collaborative network of construction project teams for BIM-related practice (Oraee et al., 2021). Specifically, currently there are knowledge gaps in terms of the project process-oriented BIM use and as a result of the fragmented nature of project management in existing research (Cao, Li, Wang, & Huang, 2017). Through an analysis of the project lifecycle management, this study provides a thorough understanding of the required capabilities and outcome-driven value of the use of BIM technology to facilitate different stage-based goals in a construction project. The study further categorised the contextual features for BIM-enabled collaboration and showed that the business ecosystem-oriented collaborative network and policy-oriented innovation drive the collaborative activities in construction projects. Additionally, for construction projects, BIM technology plays a role as a facilitator for the emerging BIM collaboration within project teams, contributing an understanding of the dynamics of project-based collaborative relations and innovation happening.

The fourth contribution is that this study shows the association of the elements among individual practice on the use of BIM in their work and interaction, the AEC organisations' BIM implementation strategies and its implications, and the situated situation of BIM used in construction projects. Previous studies have not presented such an interconnection among different levels in the construction industry, which is the research gap identified in section 2.4. Through applying multi-level analysis, the comparison of the same categorised dimensions at each level identified the interrelations between individual, organisation, and project. The specific deployment, use of BIM technology, and the consequence of BIM technology in practice have been identified, thus providing an insight into the role of BIM technology for different needs.

7.2.2 Theoretical contributions

The theoretical contribution of this study is rooted in its development of the conceptual insights into BIM technology-enabled project-based collaboration, drawing upon the understanding of digital collaboration across knowledge boundaries. Specifically, this research synthesised boundary theory and activity theory as the integrated theoretical lens to probe BIM technology-enabled cross-boundary collaboration. Based on the existing theoretical foundations of digital technology implementation, use, and cross-boundary collaboration, this study enhanced theoretical understandings of BIM technology-enabled collaborative activities, the role of BIM technology in collaborative activities, and the context of BIM collaboration. Additionally, the study leveraged the interpretation of the notions of interaction among activity systems, the evolving role of BIM technology as a boundary object, and the nature of contextual conditions for BIM collaboration to augment the theoretical insights on boundary theory and activity theory. The theoretical contributions are articulated across four dimensions.

First, this research interprets the different purposeful boundary work that exists at various levels to improve theoretical understandings of professional collaborative motivations, organisational strategic configuration, and the operation of project collaboration. This conceptualises the purpose of applying BIM technology in boundary work. Moreover, the interpretations leverage the identification of professional boundary work to propose diverse activity system structures of BIM collaboration at the individual, organisational, and project levels. By elaborating on the purposeful professional boundary work with BIM technology, this study sheds light on the relational, strategic, and institutional drive mechanisms of BIM technology-engaged collaborative activity, and proposed a multi-level BIM-enabled collaboration activity system. Individual-level purposeful boundary work outlines a relational drive activity system. Organisational-level purposeful boundary work delineates a strategic drive activity system. Project-level purposeful boundary work describes an institutional drive activity system. This multi-level system offers a comprehensive view of BIM-engaged collaborative activity. These findings expand the current understanding of BIM collaborative activities from a single level and elaborates on the potential interconnections between different levels. For instance, Akintola et al. (2020) posited the organisational context activity system of

BIM-impact collaboration. These multi-level activity systems are manifested in various drivers of collaborative activities and jointly construct BIM collaboration. These distinct drivers arise from different purposes of boundary work and, consequently, constructs diverse activity systems in BIM collaboration. Thus, the study also contributes a novel insight into understanding the interaction of multiple activity systems (Karanasios & Allen, 2018).

Second, the evolving nature of digital technology, as inferred from this research, enriches current boundary studies, especially those investigating the changeable nature of boundary objects in collaboration (Huvila et al., 2017; Leonardi et al., 2019). This research underscores the dynamic role of BIM technology in collaborative activities, marked by its evolutionary essence as a boundary object. Most research identifies digital technology as the boundary object in collaboration and focuses on various uses of boundary objects in different situations (Gal et al., 2008; Levina & Vaast, 2005). The findings of this study supplement new insights on the dynamic nature of boundary objects by revealing that the role of BIM as a boundary object can evolve with actors' perceived implications in collaboration. This evolution derives from professionals' changing perceptions of BIM technology in their practice, indicating a progressive feature within collaborative activities. As such, this insight shifts the theoretical focus from how BIM technology becomes a boundary object in practice to how perceptions of BIM technology as boundary objects transform in practice. Furthermore, by identifying the roles of BIM technology at different levels, the research also proposes its mediating effects are related to its transformative influence on organisational structure, culture, and project networked collaborative relationships. This bolster understanding of the role of BIM technology in organisational and project-level activity systems.

Third, the proposed theoretical insights on the temporal and permeable contextual conditions of BIM collaboration from the findings enhance theoretical insights from current research on cross-boundary collaboration. Existing studies suggested the fragmented feature of construction project collaboration (Fellows & Liu, 2012; Volk et al., 2014), especially with different stakeholders involved in various project phases, but scant studies exist exploring how this fragmentation influences BIM collaboration. This study introduces a novel theoretical insight based on the different temporality features present in the construction of project-based collaboration that shape the knowledge boundaries of BIM collaboration. Furthermore, the conceptualised structural flexibility of knowledge boundaries in BIM collaboration emphasises the permeable feature of knowledge boundaries within knowledge practice amidst BIM technology engagement, thus heightening theoretical understanding of the essence of BIM-enabled cross-boundary collaboration and the nature of knowledge boundaries in construction project-based collaboration.

7.3 Practical implications and recommendations

Analysis at multiple levels, along with findings centred on collaborative activities (from individual use and organisational digital innovation to project management), bear significant practical implications both within organisations and in their interactions with other organisations. Within the AEC domain, this includes various professionals, such as MEP engineers, and decision-makers. An understanding of the diverse perceptions of the role of BIM technology can be leveraged by professionals and decision-makers to refine and enhance the deployment and utilisation of BIM technology in their respective activities. Given the findings of this study, these activities predominantly relate to collaborative practices both within and across organisations. Consequently, this provides decision-makers with insights on how to bolster BIM adoption among employees during collaborative activities.

Inter-organisational implications are also profound for the AEC industry in China. The findings are of practical significance for distinct entities involved in construction projects—such as design organisations, general contractor entities, sub-construction entities, and owner organisations. Notably, the roles of these AEC entities have evolved alongside the transformations triggered by BIM technology in production activities and project management (Eastman et al., 2011). For every category of AEC stakeholders, this study delineates practical considerations for strategizing, overseeing, and moderating organisational business and management shifts:

- Within construction projects, owners are responsible for ensuring high-quality project outcomes, overseeing financial operations, and directing project procedures. As the primary beneficiaries of BIM implementation and its effective use, they must navigate the power dynamics with other stakeholders during BIM integration. This research underscores that an owner's commitment to a BIM-centric project significantly influences BIM collaboration outcomes. Thus, owners should be proactive in harnessing BIM technology for informed decision-making. Additionally, the study shows how managers from the owner organisations view the role of BIM technology primarily from functionality perspectives, rather than considering the process-related change from adopting BIM technology. Therefore, it is suggested here that the they focus more on understanding the implications of BIM in the different project stages, rather than merely seeing it as a new modelling tool, such as CAD. Moreover, based on other organisational stakeholders' reflections, the owner organisation often overlooks the long-term advantages of BIM throughout the project lifecycle, for example, in the maintenance phase of building properties. This indicates that top management in owner organisations could exploit the benefits of BIM technology during the maintenance stages of projects.

- The role of design organisations in BIM-enabled collaborations is crucial, especially given the revolutionary shifts in their design practices with BIM technology. This is reflected in their perceived challenges in the collaborative process based on BIM models and contradictions between their work and their roles. Design organisations should reconsider the legitimacy of BIM experts within their organisations, given their significant roles in the BIM technology-based modelling process. Moreover, the reflected concerns of different professionals, especially BIM experts, about top management show that, while they have a strong desire for organisational digital innovation, more specific operational initiatives are needed. This is especially true for establishing BIM-dominated collaborative relationships with other organisational stakeholders in construction projects.

- According to this study, general contractors, who are responsible for translating project designs into reality, can accrue direct and significant benefits from implementing BIM, including time and cost efficiencies and enhanced construction quality. This study emphasises the value of their early engagement in construction project phases, necessitating not just collaborative rapport but also alignment in BIM objectives. Furthermore, refining team compositions can amplify the effectiveness of BIM integrations in projects. For construction organisations, top management is believed to be aware of the long-term value of BIM adoption but lack sufficient BIM-related training for professionals. It is suggested that general contractor organisations provide more relevant resources to support BIM technology adoption into professional practice and collaborative activities. Additionally, effective communication about BIM work with owner organisations is recommended to better define the BIM benefits in projects and to increase BIM-related decision-making engagement.

- As construction projects become increasingly complex, subcontractors play a more pivotal role, handling a broader range of components in the construction process. Their seamless coordination with other stakeholders, especially in intricate design scenarios, becomes paramount. Due to the nature of subcontracting, which is based on design and construction work completed by others and effective and efficient communication with other organisational stakeholders is essential for sub-construction organisations. Moreover, BIM-related capability is crucial for sub-construction, especially when they transition from conventional building models to BIM. They need to establish an understanding of the relationship between BIM model simulation and on-site construction for better communication with owners and collaboration with other stakeholders. This study also highlighted the pivotal role played by BIM specialists. Thus, enhancing their ability to present BIM-related work can further understanding of their BIM contributions to the project.

Additionally, from a broader perspective, this study holds implications specific to the Chinese landscape of BIM deployment, particularly in relation to its BIM-centric collaborative culture and policy impacts. According to the findings presented in this research, the changed dynamics of power relations among AEC organisations suggest that the implementation and use of BIM technology transform the original collaborative relations in the AEC industry. This is especially true for each organisational stakeholder engaged in the project lifecycle management. For the predominantly state-controlled AEC industry construction activities, the findings also show that governmental guidance plays a significant role in regulating BIM technology within collaborative activities. Therefore, future governmental policies should focus more on guiding the emerging collaborative relations resulting from BIM adoption, especially in inter-organisational collaboration.

7.4 Limitations and Directions for Future Research

The embedded case study approach adopted in this research is not without limitations. Notably, the perspectives of owners and other supervisory departments, such as governmental agencies, are underrepresented. Given feedback from participants indicating significant influence from supervisory sectors in the AEC industry—like governmental entities—on their collaboration and goals, it is evident that these viewpoints could have a consequential impact on understanding BIM collaboration. While the primary focus of this research was on organisational stakeholders directly involved in designing and building processes, future investigations might consider focusing on public sectors, notably to better understand the role of governmental agencies within BIM collaboration. This is because all commercial activity in China is state-controlled, meaning that state decisions or guidance might have an important influence on the AEC industry.

Furthermore, since the research was conducted in the context of the Chinese AEC industry, the understanding and insights related to BIM collaboration are largely anchored to this geographical and cultural context. Subsequent research could delve into the cultural variances and nuances associated with BIM implementation and use in other regions, particularly for cross-national projects as Chinese construction project activity occurs in construction projects globally.

7.5 Chapter Summary

This section revisits and reviews the primary research aim, questions, and objectives. By elucidating the findings and delineating the contributions stemming from this study, it furnishes a comprehensive overview of the research journey. The empirical contributions of this research span multiple topics in academic fields, including professional practice with BIM technology, AEC organisational digitalisation, and construction project-based management. On a theoretical plane, the research has augmented both activity theory and boundary theory. Additionally, the practical implications derived from this study are pertinent to a range of professional roles across different organisations within the AEC sector. The acknowledged limitations related to the research design and its geographical context set the stage for directions in future research.

In conclusion, the comprehensive interpretation of BIM collaboration across boundaries augments the theoretical insights of BIM collaboration based on boundary theory and activity theory. It consolidates the understanding of BIM collaboration at various levels within activity theory and broadens the perspective to examine the interaction of activity systems from an embedded systems standpoint. This research is anchored by its adoption of an embedded single-case study combined with a multi-level analysis, enriching the exploration of BIM collaboration at the individual, organisational, and project tiers. Currently, a significant portion of existing studies offers a limited view of BIM-enabled collaboration, predominantly focusing on either individual or organisational levels (such as (Alankarage et al., 2021)) While some studies delve into the integration of organisational and project levels, they neglect the intricate interplay of understanding BIM collaboration at the different levels (Papadonikolaki et al., 2019). These influences intrinsically link professional BIM-engaged collaborative practice with organisational strategies for adopting BIM technology in management and business processes, and they are further shaped by the configurations of the construction project network.

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Appendix

Appendix 1 Interview questions (Chinese version)

第 1 节：参与者基本背景了解

1. 您能告诉我您在组织和项目团队中的角色吗？

（此问题是为了了解受访者的隶属关系和职位，让受访者讨论出潜在话题主题（来自文献）

- 您能详细描述一下您的日常活动吗？
    - 在此次项目中的目的和每天的工作目标是什么？
    - 日常工作中哪些任务或活动与 BIM 有关？
- 您在项目中都需要和谁一起工作或者合作？
    - 是什么原因使你们一起工作？

第 2 节：对于知识和边界的感知

2. 您能告诉我您在项目中所依赖哪些专业知识吗？

（参与者知识的 difference：知识类别和知识量的不同）

- 教育背景是什么？
    - （学习什么专业？重点学什么方面的？尤其是关于 BIM/项目管理/以及和当前工作相关的（可以提及上一个问题的答案））

- 这些专业知识您从哪里获得的？（课堂教授？专业竞赛？专业作业如毕业设计？其他经历？获得什么成就？）

- 您如何看待这些专业知识对于您工作上的帮助或者影响？（够不够用？到什么程度？怎么感受到的？觉得为什么呢？）

3.您能聊一下您从前的工作经历或者经验对于现在这个项目中您的工作的影响吗？（参与者知识的 difference：知识类别和知识量的不同）

- 您是如何看待以前的职业轨迹对当前项目的影响？
  - 您在该领域工作了多长时间了？（都从事过什么方面的什么类型的工作？）
  - 您认为在之前的工作经历中，哪些方面的经验对你当前的工作有一些影响（技术方面，管理方面，专业知识方面？）？什么样的影响？
- 当前项目和您经历的之前经历过的项目有什么区别？（BIM 相关的或者不相关的都要谈）
  - 项目类型是什么？ （建筑物，桥梁，道路……？）
  - 项目业务模型/交付方式如何？ （设计出价构建，设计构建，集成项目交付...？）
  - 这些项目是否运用了 BIM?
  - 您在这些项目中使用了哪些 BIM 相关的工具?
- 您能举一个例子说一下在以前的所参与的项目中，您在里面运用到 BIM 的经历吗？（一个您印象最深的项目或者经历）
  - 您觉得这是一个比较成功的项目还是失败的项目？（在 BIM 运用方面） （取决于他们的回答）
  - BIM 如何在其中发挥作用？

    - 您从中获得了哪些经验或者学习到了什么？

- 对比来看，您是如何看待您在这些使用 BIM 的项目中获得的经验和在没有使用 BIM 项目中获得的经验呢？

    - 对现在这个项目中有什么不同程度的帮助？
    - 让您增加了哪些不一样的知识？
    - 哪些让您觉得是项目中共同需要注意的问题或者值得学习的地方？

4.可以谈一下您在现在这个项目中使用的 BIM 技术吗？

- 您日常工作中使用的 BIM 相关的软件或工具是什么？

    - 您为什么会选择使用这些工具？
    - 您还对其他相关的软件或工具有什么了解？

- 您认为 BIM 技术是如何影响您的个人工作效率的？

    - 在哪些程度上，您觉得 BIM 技术可以提高或者降低您的个人工作效率？（可以举一些例子）

- 您觉得将 BIM 技术应用于您的工作中都需要了解哪些方面的知识？

    - 为什么？（会有什么样的结果？怎么得出的？）

5. 您可以说一下为了要完成您在这个项目中的工作任务和目标，您都需要知道或者使用哪些信息或者任何资源（比如文件，材料或其他信息）来支持您的工作呢？

（以识别他们使用，创建和维护的“对象”，并找出领域知识之间的路径依赖关系）

- 对于这些您工作需要的这些信息或者资源（参与者回答中提到的），您是怎么获取的？
    - 在项目中，通常是谁会提供信息和资源（参与者回答中提到的）？
    - 这些信息和资源通常以什么样的形式传递（数字或物理纸质）？
    - 这些信息资源会如何影响您的个人工作？

6. 您是怎么知道您具体需要这些信息（上述提到的）或者做什么事来保证您可以成功交付您负责的那部分工作？

(要了解必需的知识并了解受访者可以识别知识的依赖性和新颖性的过程）

- 是什么让您使用或者做这些来支持您最后可以成功交付您的工作内容？
    - 从您的角度看，你觉得这些事情或者文件对您的工作来说是不是都是必需品的或者必要的？
- 如果在您完成这些你需要交付的那些东西时，您发现缺少某些必要的信息或者信息不对等，这个时候您会面临哪些挑战或者问题？
- 您是怎么确定您可以从某些地方来获取这些必要的信息？
    - 有人告诉你或材料有显示或者是你自己的经验？
- 您怎么知道获取这些信息可以从某些程度上来使您完成你的工作时更加方便或者提高你的工作表现？
    - 以往的经验或者专业知识？

- 或者谁有哪些要求？

- 这些关于你的工作内容的某些操作规则或实践准则从何而来？　（公司，研究中心，教育机构或监管机构）

第 3 节：对使用 BIM 技术进行协作实践的描述

7. 您通常是因为什么会和同事进行 BIM 相关工作的协作？

- 基于 BIM 技术的协作对您来讲意味着什么？
  - 您是如何理解 BIM 协作的？
  - 您觉得 BIM 协作是指的什么？
  - 从您自己工作的角度来看呢？

- 是什么原因使您和同事进行相关的协作？
  - 基于 BIM 软件与同事协作的时候您需要做什么或者完成哪些任务？

- 在您就您自己 BIM 相关的工作与同事进行合作时，您觉得存在哪些利弊？
  - 你觉得是什么导致的？
  - 会产生什么影响？

- 您觉得通过和同事间的 BIM 协作，在解决项目中的问题时，您认识是变得更轻松了还是更复杂了？

8. 你能告诉我一下在你日常的工作中你具体是如何跟别人通过 BIM 进行协作的吗？

- 你会采取什么行动跟同事交换，传递或共享信息？你可以说一下具体的步骤吗？我想知道具体的细节。
  - 您将以什么形式接收此信息？这些动作会发生在哪里？谁参与了这些活动？

- 在这其中你会使用哪些材料，文件或工具来帮助你更好进行协作？

- 当你在和别人协作时，你会不会在和他们一起讨论想法或者工作时，对他们的想法或者工作内容感觉有些困惑或者不能理解？
  - 如果有，这个时候一般是你在面对什么情况的时候？如果你在与他人分享你的想法或者是从别人那里获得反馈的时候遇到一些困难，你会怎么办？
  - 如果没有，你觉得是什么使你和这些人可以进行良好合作和沟通的？

9. 你可以跟我描述一些在你和同事进行 BIM 相关的协作时，你需要和他人分享你的工作经验或专业知识的情况吗？

- 是什么原因导致您与他人分享您的经验或专业知识？
- 当你和他人分享这些信息时，你是希望要实现什么目的？
- 你分享的这些信息和你自己在这个项目中的工作有什么关联？
- 当您与他人分享你的这些信息时，通常会得到什么样的效果和结果？

10. 如果您发现你的同事提供的资源或者材料中缺少某些信息，这些对于您使用 BIM 技术完成你的工作很重要，那么这个时候你会怎么做？

- 从你的角度来看，你觉得这些情况会不会经常发生？
- 你认为可能是什么导致的这些情况的发生？

11. 你可以讲一下最近的一次你或者你的同事在关于 BIM 方面的一些工作所需要做的一些更改的情况吗？

（要了解边界如何变化，以便获取有关边界的动态和交互特征的数据）

- 你们是如何确定需要做这些更改的？

- 你在自己的工作中为了处理这样的问题，做出了哪些决定或者调整？
    - 这样的决策总是这样发生吗？
    - 在什么情况下会发生？
    - 他人的想法或者工作一般会如何影响你的决定？

第 4 节：通过 BIM 技术进行知识共享的经验和看法

12. 你是怎样看待通过 BIM 技术和你的同事们共享信息的？

- 当你在使用 BIM 技术或相关的工具和同事们共享信息时，你认为你们之间的协作是变得更加轻松了还是更复杂？

- 你是怎样看待通过 BIM 技术进行的信息共享过程的表现？
    - 增进对他人信息的了解？
    - 减少对信息的误解或困惑？
    - 增进对他人的兴趣和目的的了解，别人的这些兴趣和目的是否与您不同？

13. 你是什么时候知道在你可以通过项目中其他同事共享的信息来完成你的任务的？

- 据您所知，它是否总是那样发生？

14. 你可以举个例子来说一下，你是怎样通过 BIM 技术来和同事一起解决这个项目中的一些问题的吗？

- 你怎样和来自不同专业背景的同事交流与工作相关的问题？
    - 您是始终都了解他们在 BIM 工作中所说的话吗？
    - 你们在某个问题上总是有相同的理解或关注点吗？
    - 就某些特定问题而言，你们俩都有相同的目标要实现吗？

- 您是怎样收到他人的反馈或者他们对您的工作内容有什么样的反应？

- 如何体现在 BIM 技术的运用上？

- 您可以谈一下在你和与你不同专业背景的人合作进行 BIM 协作时的一些比较好的或者不好经历吗？
    - 我想知道，考虑到不同的专业背景，你们之间在工作相关问题上的交流是好是坏。

第五节：结题

15. 你对于实施 BIM 的项目有没有什么建议？

- 关于 BIM 项目中的协作过程？
- 关于 BIM 技术？
- 关于 BIM 项目中成员之间的相关协作关系？

16. 因此，在您看来，您已经聊了 1 个小时，您还想补充 BIM 协作中我们没有在对话中讨论的其他内容吗？

Appendix 2 Interview questions (English version)

Section 1: Initial Questions about Respondent's Background and Project-based Experience

1. **Can you tell me about your role in your organisation and your project team?**
   (This question is to know the affiliation and position about the respondents)
   List for the potential item or topic discussed by interviewees (from literature)

- Can you describe your daily routine in detail?
  - The work goal or objectives?
  - What tasks or activities are related to BIM?

- Who do you work with in the project?
  - What causes you to work with them?

Section 2: Perception of knowledge and boundary

2. **Can you tell me about the professional knowledge you rely on in the project?**
   *(The **difference** of actors' knowledge)*

- Educational background?
- Where do you get from?
- What do you think about the knowledge that contributes to your professional work?

3. **Could you tell me about the previous work experience that you used for your current project work?**

- What do you think of the influence from your previous career trajectory on the current project?
  - How long have you been working in this field?
  - What types of experience do you think that is influential (technique, tool...)?

- What is the difference between the current project and the previous project you experienced?
    - What are the project types? (Building, bridge, road…?)
    - How about the project business model/delivery methods? (Design-bid-building, design-build, integrated project delivery...?)
    - Have these projects implied the BIM process?
    - What kind of BIM tool have you used in these projects?

- Can you give an example of how you used BIM in one of those projects - a very memorable example?
    - Would you say that this was a successful project or an unsuccessful one? (Depending on what they answer) Did BIM play a role in this?

- How would you compare your experience when working with BIM on projects to those where you did not use this tool?

4. Can you tell me about the BIM technologies you use in the current project?

- What types of BIM related software or tools in your daily work?
    - What caused you to use that?
    - What else do you know about the related software or tools?

- How do you think BIM technology can influence your work efficiency?
    - To what extent do you think that can make your work more efficient or not? Some examples?

- What do you need to know for applying BIM technology into your work?

5. In order to complete the task and goal of your work in this project, can you tell me what information you need to support your own work?

*(to identify the 'object' they use, create and main and find out the **dependency** between domain's knowledge)*

- From what resources can this information be obtained?
  - Who will provide the resource?
  - What format? (Digital or physical)

6. **How do you determine what you need to know in order to deliver the parts of a shared project that you are responsible for?**
   *(To know the required knowledge and knowing process of the respondents ao that can identify the **dependency** and **novelty** of knowledge)*

- What caused you to use this?
  - As far as you know, do these (each component) are always needed or necessary for your work?

- What challenges or issues will you face if you miss the information or part of the information?

- How do you know where the information can be obtained from?
  - actors or materials?

- How do you know the information can facilitate your work performance?
  - Experience or professional knowledge?

- Where do the rules or codes of practice generate from? (Insurance companies, research centres, educational institutions or regulatory bodies)

Section 3: Description collaboration practice with BIM technology

7. **Can you tell me about why you collaborate with your colleagues for your BIM related work?**

- What does the BIM collaboration mean to you?

- What causes you to collaborate with your colleagues?
  - What kinds of tasks do you need to collaborate with your colleagues based on BIM software?

- What are the benefits or drawbacks for your BIM related work when you collaborate with your colleagues?

- Are there things that can be solved more easily or more complicated through collaborating with your colleagues with BIM?

8. Can you tell me how you collaborate with others with BIM?

- What actions will you adopt to exchange, transfer, or share information with your colleagues? Could you step me through that? I need some more details.
  - In what format will you receive this information? Where does the action happen? Who is involved in the collaboration?

- What materials, artefacts, or tools will you use for better collaboration?

- What information will you need to know when working with your colleagues in a construction project?

- When you collaborate with others, do you ever get confused when discussing their ideas or work?
  - If yes, what condition do you face? How would you do if you have difficulties to share your ideas or receive feedback with them?
  - If not, what do you think that contributes to your good collaboration with your colleagues?

9. **Can you tell me about the situation that you need to share your work experience or professional knowledge with others when you collaborate with your colleagues with BIM?**

- What causes you to share your experience or professional knowledge with others?
- What do you want to achieve when you share this information?
- How is this shared information related to your own work for this project?
- In general, what are the results when you share these information with others?

10. **If you find some information is missing from the resources provided by your colleague but it is important for you to complete your work with BIM technology, what will you usually do in this project?**

- As far as you know, does this situation always happen?
- In your opinion, what may cause this situation?

11. **Can you tell me about the most recent situation in which you or your colleagues made changes on the work with BIM?** *(To know how the boundaries change, in order to obtain the data about the dynamic and interactive characteristic of boundaries)*

- How do you both determine the change should be made?
- What decisions have you made on your own work for dealing with the issue? Do the decisions always happen like that? In what condition?

Section 4: Experience and perception of Knowledge sharing through BIM technology

12. What do you think of the information shared through BIM technology when you work with your colleagues?

- To what extent do you think your work becomes more easy or complicated when you work with BIM technology or tools to share information with your colleagues?

- What do you think of the performance of information sharing process through BIM technology?
  - To increase the understanding of what others' information or not?
  - To reduce the misunderstanding or puzzle of the information?
  - Increase the understanding of others' interests and objectives which differ with you or not?

13. When do you know your task can be done with the information shared from your colleagues in the project?

- As far as you know, does it always happen like that?

14. Can you give an example of how you worked with colleagues to solve the BIM-related work problems in this project?

- How do you communicate work related issues with colleagues from different professional backgrounds?
  - Do you always understand what they say in the BIM work?
  - Do you both always have the same understanding or concerns in terms of a certain issue?
  - Do you both have the same goal to achieve in terms of a certain issue?

- How do you receive others' feedback or how do they react to your work?

- Could you talk about some good or bad experiences that you collaborate with who have a different role as yours in a construction project?

- I would like to know how, for example, good or bad was the communication on work related issues between you, considering the different professional backgrounds.

Section 5: Ending question

15. What are your recommendations for conducting the BIM enabled projects?

- As to the collaboration process in the BIM project?
- As to the BIM technology?
- As to the related collaborative relationship between the members in the BIM project?

16. So, you've been talking for 1 hour, in your view, what other things of BIM collaboration would you want to add that we didn't cover in our conversations?

Appendix 3 Information sheet and participant consent form—Interview

Researchers

Researcher: Jing Wang
Email: jwang150@sheffield.ac.uk

Dr. Pamela Abbott – First Supervisor - p.y.abbott@sheffield.ac.uk
Dr. Efpraxia D. Zamani – Second Supervisor - e.zamani@sheffield.ac.uk

Purpose of the research

This research study is part of the work towards the attainment of a PhD award for the researcher. This research is to investigate the collaboration with BIM among the construction project team members. The BIM collaboration always happen with in a construction project team. In a construction project team, members are generally from different disciplines and have different knowledge background that will cause the knowledge boundaries. Under this context, the team members might have difficulties and conflicts when they share their knowledge to others during the construction project lifecycle. Deep understanding of how the BIM collaboration process influence (enable or hinder) the knowledge sharing among team members can facilitate the better BIM application in the construction project in future.

The aim of this research is to explore what are the main factors of BIM collaboration process that influence the knowledge sharing when team members have different knowledge boundaries. This study will be conducted in China and the key objectives of this research are shown as follow:

1. To identify what knowledge is shared among construction project team members in the project;
2. To identify the boundaries existing in the process of knowledge sharing among the project team members;
3. To identify the means construction project team members, collaborate with each other using BIM technology;
4. To explore the role of BIM technology in construction project team members' knowledge sharing practices;
5. To investigate how BIM enables/hinders knowledge sharing across different knowledge boundaries;

6. To identify what factors of BIM influence knowledge sharing across different knowledge boundaries.

Who will be participating?

The participants in this research will be selected based on the construction of the BIM-enabled construction project team. According to the reviewing the relevant literature on this research area and this research purpose, the potential participants include the team members from the designer, contractor, subcontractor, owner and manufacturer, etc. who are identified to involve in the BIM process.

What will you be asked to do?

The participants will be asked to participate in a one-hour interview that talks about the BIM collaboration and knowledge sharing across different knowledge boundaries in a construction project team. This interview will be arranged for about one hour and at a selected place by the researcher. During the interview, the participants will be asked some questions about their personal experience on BIM-related work and the perceptions or views about BIM collaboration in the current project team.

What are the potential risks of participating?

There will not be major risks in this research. With the Covid-19 influencing, you can choose the face-to-face interview or the audio interview depending on your preference. If you choose the face-to-face interview, the researcher will provide the free face mask and hand sanitizer in advance. The researcher will avoid arising risk in the investigation. The potential risks have been estimated and proposed the managing methods. During the interview or after the interview, you can express any stress, concerns and nervous on the topic, questions or the environment to the researcher. In addition, the researcher has experienced the quarantine for 2 weeks when entering China and can be allowed to future travel after confirming the negative test results. So the potential risk from the researcher that might infect the participants can be mitigated.

What data will I collect?

This research is an embedded case study with three projects as the units of analysis, representing altogether a whole lifecycle of a BIM-enabled construction project. For each project, the data will be collected from observations, in-depth semi-structured interviews and the document collection. Observation is a data collection method in which the researcher will attend some project meetings or observe the team member’s BIM-related work to understand how the BIM-related collaboration process works. The observation content will be recorded. For the interview, the researcher will collect some information about the participants’ personal educational background, work experience in the current project team, and the views and perceptions of the BIM collaboration. For the document collection, the researcher will need to obtain documents of project-related information, such as the contracts, drawings, change reports, etc.

What will I do with the data?

These collected data and information will be used for the analysis in my PhD project. The interview and observation records will be stored in the School's Research Data drive under my personal folder which can be accessed by myself and the IT team. The data will be anonymized; it means any personal identifiable information which can trace your identity will be removed or certain codes used to replace it. These anonymised data will be used to for the analysis of this PhD topic and can be accessed by my supervisors for guiding my work. I will translate the data into English by myself without any online service or software. Meanwhile, I will also store an encrypted password protected back up copy on my personal laptop. Within five years after obtaining my PhD degree, all of the data will be deleted from the university storage and my personal laptop.

Will your participation be confidential?

For the face-to-face interview, it will take place between the researcher and participant without any other person. The original data from the interview and observation will be anonymized at the point of writing up findings. Your personal information will be anonymised but because of the need of the research purpose, your job role will not be anonymised. The firm name and project will be replaced by a coded name, such as 'Firm A', 'Project X'.

In addition, for the observation of meeting, it involves more than one person, the researcher will anonymise the data before analysis, but I cannot guarantee that members of the group will not discuss their participation, although I will request that they not do so.

In the future PhD thesis and published papers, your personal information, including your own identifiable information and the organisation or project information will not appear and be identifiable in the thesis or papers, unless your permission has been obtained beforehand.

What will happen to the results of the research project?

The results of this study will be included in my PhD thesis which will be reviewed by my supervisors and the examiners, which will occur at the end of the PhD study expected to be in 2023. Meanwhile, partial results of this study might be published in journal or conference papers within the course of the PhD study and up to five years after awarding the PhD.

What is the legal basis for processing your personal data?

The University of Sheffield will act as the Data Controller for this study. This means that the University is responsible for looking after your information and using it properly. In order to collect and use your personal information as part of this research project, we must have a basis in law to do so. The basis that we are using is that the research is ‘a task in the public interest’.

Declaration of consent

- I confirm that I have read and understand the description of the research project, and that I have had an opportunity to ask questions about the project.
- I understand that my participation is voluntary and that I am free to withdraw at before 31 January 2021 without any negative consequences.
- I understand that if I withdraw I can request for the data I have already provided to be deleted, however this might not be possible if the data has already been anonymised or findings published.
- I understand that I may decline to answer any particular question or questions, or to do any of the activities.
- I understand that my responses will be kept strictly confidential, that my name or identity will not be linked to any research materials, and that I will not be identified or identifiable in any report or reports that result from the research, unless I have agreed otherwise.
- I give permission for all the research team members to have access to my responses.
- I give permission for the research team to re-use my data for future research as specified above.
- I agree to take part in the research project as described above.

Participant Name (Please print) | Participant Signature

Researcher Name (Please print) | Researcher Signature

Date

Note: Further information, including details about how and why the University processes your personal information, how we keep your information secure, and your legal rights (including how to complain if you feel that your personal information has not been handled correctly), can be found in the University's Privacy Notice https://www.sheffield.ac.uk/govern/data-protection/privacy/general.

If you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, please contact Dr Paul Reilly, Research Ethics Coordinator, Information School, The University of Sheffield (ischool_ethics@sheffield.ac.uk).

Appendix 4 Information sheet and participant consent form—Observation

Researchers

Researcher: Jing Wang
Email: jwang150@sheffield.ac.uk

Dr. Pamela Abbott – First Supervisor - p.y.abbott@sheffield.ac.uk
Dr. Efpraxia D. Zamani – Second Supervisor - e.zamani@sheffield.ac.uk

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The aim of this research is to explore what are the main factors of BIM collaboration process that influence the knowledge sharing when team members have different knowledge boundaries. This study will be conducted in China and the key objectives of this research are shown as follow:

7. To identify what knowledge is shared among construction project team members in the project;
8. To identify the boundaries existing in the process of knowledge sharing among the project team members;
9. To identify the means construction project team members collaborate with each other using BIM technology;
10. To explore the role of BIM technology in construction project team members' knowledge sharing practices;
11. To investigate how BIM enables/hinders knowledge sharing across different knowledge boundaries;
12. To identify what factors of BIM influence knowledge sharing across different knowledge boundaries.

Who will be participating?

The participants in this research will be selected based on their membership in a BIM-enabled construction project team. According to the relevant literature in this research area and this research purpose, the potential participants will include team members such as the designer, contractor, subcontractor, owner and manufacturer, etc. who are identified to be involved in the BIM process.

What will you be asked to do?

The participants will be asked to participate in 30 minutes to one-hour observations that might happen during project meetings or your daily work. During these events, the researcher will record the activities that happen during the period of the observation. The researcher will try to avoid intervening in your activities and actions during the observation. You can just do anything as usual.

What are the potential risks of participating?

There will not be major risks in this research. Due to the Covid-19 issue, the researcher will provide a free face mask and hand sanitizer in advance. The researcher will avoid potential risks during the investigation. The potential risks have been estimated and mitigating methods have proposed. During the observation or after the observation, you can express any stress, concerns and nervous reactions based on the actions of the researcher. In addition, the researcher has experienced the quarantine for 2 weeks when entering China and will have been allowed future travel after confirming negative test results. So the potential risk that the researcher might infect the participants can be mitigated.

What data will I collect?

This research is an embedded case study with three projects as the units of analysis, representing altogether a whole lifecycle of a BIM-enabled construction project. For each project, the data will be collected from observations, in-depth semi-structured interviews and the document collection. Observation is a data collection method in which the researcher will attend some project meetings or observe the team member's BIM-related work to understand how the BIM-related collaboration process works. The observation content will be recorded. For the interview, the researcher will collect some information about the participants' personal educational background, work experience in the current project team, and the views and perceptions of the BIM collaboration. For the document collection, the researcher will need to obtain documents of project-related information, such as the contracts, drawings, change reports, etc.

What will I do with the data?

These collected data and information will be used for the analysis in my PhD project. The interview and observation records will be stored in the School's Research Data drive under my personal folder which can be accessed by myself and the IT team. The data will be anonymized; it means any personal identifiable information which can trace your identity will be removed or certain codes used to replace it. These anonymised data will be used to for the analysis of this PhD topic and can be accessed by my supervisors for guiding my work. I will translate the data into English by myself without any online service or software. Meanwhile, I will also store an encrypted password protected back up copy on my personal laptop. Within five years after obtaining my PhD degree, all of the data will be deleted from the university storage and my personal laptop.

Will your participation be confidential?

For the face-to-face interview, it will take place between the researcher and participant without any other person. The original data from the interview and observation will be anonymized at the point of writing up findings. Your personal information will be anonymised but because of the need of the research purpose, your job role will not be anonymised. The firm name and project will be replaced by a coded name, such as 'Firm A', 'Project X'.

In addition, for the observation of meeting, it involves more than one person, the researcher will anonymise the data before analysis, but I cannot guarantee that members of the group will not discuss their participation, although I will request that they not do so.

In the future PhD thesis and published papers, your personal information, including your own identifiable information and the organisation or project information will not appear and be identifiable in the thesis or papers, unless your permission has been obtained beforehand.

What will happen to the results of the research project?

The results of this study will be included in my PhD thesis which will be reviewed by my supervisors and the examiners, which will occur at the end of the PhD study expected to be in 2023. Meanwhile, partial results of this study might be published in journal or conference papers within the course of the PhD study and up to five years after awarding the PhD.

What is the legal basis for processing your personal data?

The University of Sheffield will act as the Data Controller for this study. This means that the University is responsible for looking after your information and using it properly. In order to collect and use your personal information as part of this research project, we must have a basis in law to do so. The basis that we are using is that the research is 'a task in the public interest'.

Declaration of consent

- I confirm that I have read and understand the description of the research project, and that I have had an opportunity to ask questions about the project.
- I understand that my participation is voluntary and that I am free to withdraw at before 31 January 2021 without any negative consequences.
- I understand that if I withdraw I can request for the data I have already provided to be deleted, however this might not be possible if the data has already been anonymised or findings published.
- I understand that I may decline to answer any particular question or questions, or to do any of the activities.
- I understand that my responses will be kept strictly confidential, that my name or identity will not be linked to any research materials, and that I will not be identified or identifiable in any report or reports that result from the research, unless I have agreed otherwise.
- I give permission for all the research team members to have access to my responses.
- I give permission for the research team to re-use my data for future research as specified above.
- I agree to take part in the research project as described above.

Participant Name (Please print)	Participant Signature
Researcher Name (Please print)	Researcher Signature

Date

Note: Further information, including details about how and why the University processes your personal information, how we keep your information secure, and your legal rights (including how to complain if you feel that your personal information has not been handled correctly), can be found in the University's Privacy Notice https://www.sheffield.ac.uk/govern/data-protection/privacy/general.

If you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, please contact Dr Paul Reilly, Research Ethics Coordinator, Information School, The University of Sheffield (ischool_ethics@sheffield.ac.uk).

Appendix 5 Research Ethics Approval Letter for the main study

The University Of Sheffield.

Downloaded: 26/10/2020
Approved: 26/10/2020

Jing Wang
Registration number: 180324679
Information School
Programme: PHD information studies(Social)

Dear Jing

PROJECT TITLE: Digital Collaboration across boundaries - A Case Study of the BIM-enabled Construction Project
APPLICATION: Reference Number 036144

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 26/10/2020 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 036144 (form submission date: 22/10/2020); (expected project end date: 30/06/2023).
- Participant consent form 1083463 version 1 (22/10/2020).
- Participant consent form 1083462 version 1 (22/10/2020).
- Participant consent form 1082320 version 3 (22/10/2020).
- Participant consent form 1081994 version 4 (22/10/2020).

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Your responsibilities in delivering this research project are set out at the end of this letter.

Yours sincerely

Stephanie Kelly
Ethics Administrator
Information School

Please note the following responsibilities of the researcher in delivering the research project:

- The project must abide by the University's Research Ethics Policy: https://www.sheffield.ac.uk/rs/ethicsandintegrity/ethicspolicy/approval-procedure
- The project must abide by the University's Good Research & Innovation Practices Policy: https://www.sheffield.ac.uk/polopoly_fs/1.671066!/file/GRIPPolicy.pdf
- The researcher must inform their supervisor (in the case of a student) or Ethics Administrator (in the case of a member of staff) of any significant changes to the project or the approved documentation.
- The researcher must comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
- The researcher is responsible for effectively managing the data collected both during and after the end of the project in line with best practice, and any relevant legislative, regulatory or contractual requirements.