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A STRATEGIC FRAMEWORK FOR ENHANCING TECHNOLOGY ADOPTION IN PROJECT-BASED AECO FIRMS

Breaking Down Barriers of Technology Diffusion in Construction

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PREFACE

Technological applications, ideas and processes are extremely necessary in modern day construction. How do I know that? Through the hard way! In 2018, I was working in one of Qatar's most prestigious projects, the Msheireb Downtown Doha. This huge, ambitious, and equally controversial project had big problems and complexities of its own. I faced a part of those problems in my role there as a project engineer. Having to manage more than ten sub-contractors, each working on components and parts adjacent to each other and with the final product requiring millimetre accuracy, doing this job using 2D paper drawings and verbal communications was a nightmare. Witnessing and sometimes refereeing blame games were a routine of my life. At that point, I started to wonder, in fact for the first time, that when the manufacturing industry were producing autonomous super cars and when SpaceX were landing rockets after boosting them to outer space, why are we in construction still working as if we are in the 2000s?

That was the question I asked myself several times which got me to the Netherlands, to pursue my master's in Construction Management and Engineering focussed on Digital Technologies in Construction. Fast forward a few years, I learned about the endless possibilities of digital technologies in the construction industry and its promising potential for long term efficiency. However, even though the sky was the limit in terms of possibilities, the implementation is still extremely low. Why? In the search for answers for that question, the literature gave me a lot of different barriers, roadblocks, and whatnots to explain the lack of digitalization in the construction industry. Okay, but what now? I learned about the disease, the symptoms, and the complications of the lack of digitalization, but what could be the treatment? That was where the literature was lacking (or vague). There, I knew what I wanted to do for my master thesis research. This report is the fruit of those questions and thought processes which have been going on in my head for the last few years. Did I find the answers? Well, I guess we will know by the end of this report.

This report entails the results of the research "Strategic Framework for Enhancing Technology Adoption in Construction Firms", conducted as a final part of the masters Construction Management & Engineering at the University of Twente, the Netherlands. The research was conducted in collaboration with Witteveen+Bos Engineering Consultants and is intended to contribute towards their efforts to scale up the use of digital technologies in their processes.

It was an intensive six months over the course of which I learned quite a lot, about the industry itself and about technology management, which would not have been possible without the immense support and help of quite some people. First, I would like to thank Arjen Adriaanse for believing in me and guiding me from the very beginning to the very end. The questions you kept asking forced me to think more and more, and our conversations ensured that I do not sway from the goal of my research and do not jump into conclusions, which was extremely important throughout this research. Further, I want to thank Lara Cariminati for first, being part of this research and then guiding me throughout the last six months with your constructive feedbacks and recommendations. Moreover, several times when I was stuck, you made sure to spend extra time and give me quick feedbacks, which helped me a lot. I would also like to thank Marc Taken and Rinze Herrema from Witteveen+Bos for believing in me and providing me with the opportunity to perform this thesis in your organization, and for your contributions throughout the research even during these difficult circumstances around us. Your suggestions, feedbacks and support were instrumental and extremely helpful especially during the beginning stages of the research. I would also like to thank all the other colleagues at Witteveen+Bos, who happily supported me through their valuable contributions and opinions, even though all their schedules were packed.

Lastly, I would love to thank my family, all my friends, and my roommates for their support and encouragements during this challenging process. I'm grateful for always having you people to go to whenever I needed some confidence boost or some distraction to refresh my thoughts. Now, it is time to celebrate with you this, perhaps the most important, milestone of my life.

Irfan Pottachola
Enschede, August 2021

"It is not the strongest of the species that survives; nor the most intelligent that survives.
It is the one that is most adaptable to change."

- Charles Darwin (1809 – 1882)

ABSTRACT

The construction industry is often widely criticised for its low productivity and efficiency. A deep transformation of the industry led by advanced technologies and processes is deemed necessary to protect all the parties in the industry from suffering further damages. Various digital technologies have been introduced to the industry in the last decades, with a central focus on the exploitation of data which can be collected and used throughout the asset's lifecycle, centralized data management, and inter-disciplinary collaboration. Furthermore, most of the prominent technologies that are available in the market today are at a readiness level to be directly used in all the phases of the AECO (Architecture, Engineering, Construction, and Operation) supply chain and the technological landscape is also very well established. However, although such digital technologies are regarded as drivers for increased productivity and efficiency, it's use in the construction industry is not at a desirable level. This essentially illustrates the existence of an apparent gap between the theoretical benefits and operational efficiencies of digital innovations advocated by various literature, and its actual implementation in the industry. This research explores that gap, what we call the grey area of technology adoption, and suggests solutions to bridge such a gap and break down barriers hindering technology implementation in the construction industry.

The clients of this research, Witteveen+Bos (W+B) engineering consultancy, are well aware of the competitive advantage and the opportunities to improve their productivity and efficiency through digital innovations. However, despite several initiatives and attempts to diffuse various digital technologies, the adoption of those technologies in the firm is not at a desired level. W+B has set the ambition to become industry leaders in digital engineering, and BIM and wants to exploit technologies to the fullest to improve their efficiency and add more value to their clients. Along these lines, they intend to scale up the rate of adoption of digital innovations in the firm and wants to instigate a natural instinct in their personnel to search for and work with technological ideas and solutions. Towards this ambition, W+B poses some key questions: 'what' are the factors which shapes the innovation adoption decisions of personnel, 'why' is it hindering the diffusion of innovations and 'how' to handle them. Following it, W+B wants to develop a strategy, which can aid their efforts to scale up the rate of adoption of digital innovations in the firm. In this direction, the objective of this research was to *"to develop a strategic framework for enhancing digital innovation adoption, which can aid firms in construction to improve their rate of adoption of digital innovations in a sustainable manner"*.

To gauge a deeper understanding into the problem context and the objective, an extensive literature review was conducted, through which two priori theoretical constructs were defined. Priori Construct A explains four key factors which determines the rate of adoption of digital innovations. These factors are 1) characteristics of the social system, 2) innovativeness of individuals, 3) perceived attributes of innovation, and 4) diffusion networks. Priori Construct B illustrates a diffusion model consisting of the innovation process in organizations, the individual's innovation decision process, and the influence of the factors affecting the rate of adoption across the diffusion process. Based on the theoretical background and priori constructs established through the literature review, main and sub research questions were formulated. The main research question was: *'what factors affect the adoption of digital innovations in the firm as perceived by their personnel and how can the rate of adoption be increased in a sustainable manner?'.* To answer the research question, an explanatory case-study research approach with solution-oriented design was used. Three cases were selected that differed on important characteristics, which contributed to an in-depth analysis of the research problem. These cases were 1) 3D BIM, which was a successful diffusion in the firm, 2) Scripting & Programming, an intra-disciplinary innovation and 3) 5D BIM, an inter-

disciplinary innovation. Data were collected predominantly through several face-to-face semi-structured interviews and focus group sessions.

The findings indicate that the initiation of digital innovation diffusions in projects within firm were led by earlier adopters who are of either strategic (project managers) or tactical (line managers, PMC leaders) responsibility. The first stage of this diffusion process, namely agenda setting, in which the perceived need for an innovation is identified, was triggered by technological advancements from outside of the organizational boundaries for earlier adopters and from within the organizational boundaries for later adopters. Such technological advancements were then matched with the needs of the projects. But in most cases a proper feasibility analysis rooted in the project context was missing. Results also indicate that the environment for innovation diffusion created by strategic and tactical responsibility personnel were key for successful diffusion processes. Furthermore, all the cases underline the importance of the third stage in the innovation diffusion process, i.e., the redefining/restructuring stage, in which innovation is redesigned to fit the project needs and sometimes the project processes are restructured to accommodate the innovation. Following this stage, when the innovation was put into full use, further redesigning/restructuring were sometimes required. This is because of the need to address the new concerns or barriers that were raised by the members of the social system as they got more aware of the innovation. The knowledge gained from the diffusion in projects is disseminated to the organization, which then triggers agenda setting in a subsequent project, several loops of which results in the routinization of the innovation in the organization.

Several factors play(ed) a key role during the aforementioned diffusion processes. The first key factor is the structure and the characteristics of the social system. The social system of the organization is a network of several autonomous sub systems (projects), each with its own decision-making authority, and its own diverse set of collaborating external parties. This complex structural characteristic of the construction industry affects the diffusion of innovations. The next factor is the innovativeness of individuals. The results indicate that while earlier adopters play a role of gatekeepers in the diffusion process, bringing in the idea of the innovation from outside the social system's boundaries, later adopters determine the rate of adoption and the pace of the diffusion process as they make up most of the population. Another very important factor is the attributes of innovation. All five attributes of innovation defined in the Rogers Diffusion of Innovation theory were identified to be instrumental in shaping an individual's attitude towards an innovation, them being relative advantage, compatibility, complexity, observability and trialability. A new attribute, affinity, was added to the attributes of innovation which influences adoption decision of digital innovations in construction, taking the total tally to six. The last factor identified are the diffusion networks, the nature and extend of which also influences the rate of adoption by contributing towards the increased awareness of and shaping positive attitude towards the digital innovations.

The strategic framework for enhancing technology adoption was developed by refining the two Priori Constructs with the results from the case studies. The strategic framework includes two parts, the factors affecting the diffusion process and a comprehensive innovation diffusion model, thereby explaining what factors affects the rate of adoption of digital innovations and how these factors can be managed through a diffusion model. The framework was validated by domain and academic experts and can aid firms in construction to plan their innovation diffusion activities and contribute towards their efforts to enhance the rate of adoption of digital innovations. As such, the results of this research contributes towards bridging the gap between theoretical benefits of digital innovations and its actual implementation in the industry.

TABLE OF CONTENTS

List of Figures and Tables

Figures:

Tables:

1. Introduction

1.1. Background and Context

Construction industry has always been under scrutiny for its low productivity. For decades, the industry has fallen behind other manufacturing industries in terms of productivity, as the later have succeeded to benefit from digitalization and automation of their processes (Karimi & Iordanova, 2020). Although direct comparison between construction industry and manufacturing industries is not fair (and baseless) (Winch G. M., 2003), it goes without saying that the construction industry has huge room for improvement in terms of productivity and efficiency. The labour productivity growth in the construction industry has averaged only 1 percentage since 1995, while the same for the global economy is 2.8 percent and the manufacturing industry is 3.6 percent (Barbosa, et al., 2017). This slow growth of productivity, illustrated in Figure 1, is significant to the global GDP as around 13% of it is made up of construction related spending (Barbosa, et al., 2017). Several studies argue that the productivity issues are because of the traditional working methods and low incorporation of technology (Rivera, et al., 2020), with some studies advocating deep transformation of the industry to adopt advanced technologies (Karimi & Iordanova, 2020). Barbosa et al., (2017) also argues the same and identified the infusion of digital technologies, new materials, and advanced automation as one of the crucial steps to tackle the root causes that cause the poor productivity of the industry. Moreover, the advent of the fourth industrial revolution, which is largely driven by digital technologies and automation, means that the construction industry is in a serious risk of further falling behind other industries, in terms of efficiency and proper usage of the technical landscape currently available, if they continue in this trend and fail to take proper steps towards the efficient use of relevant technologies in their processes.

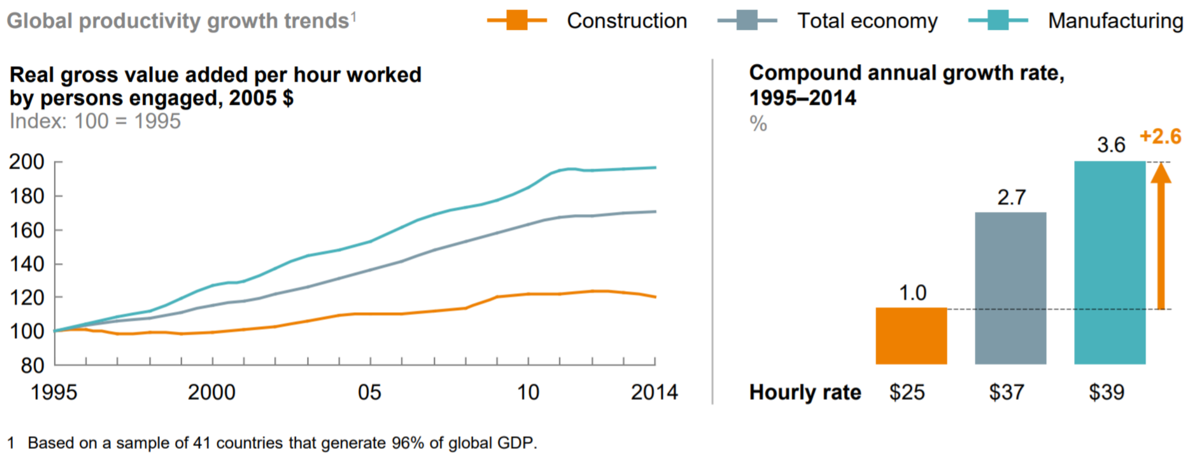

Figure 1 Global Productivity Growth Trend Indicating the Low Productivity Growth in the Construction Industry (Barbosa, et al., 2017)

Various digital technologies have been introduced to the industry in the last decades such as BIM, Digital Lean Construction, Design Automation, Internet of Things, Artificial Intelligence, and Robotics etc. According to construction management scholars, such individual technologies will be able to change the competitive landscape for construction companies and increase the efficiency and productivity of the industry (Ernstsen et al., 2021). By applying the right technologies in the right way, companies can not only reduce the whole life cycle costs and design/construction time, but also enhance the quality, productivity and improve safety and sustainability (Gerbert, Castagnino, Rothballer, Renz, & Filitz, 2016). It is thus fair to argue that digital transformation of the construction industry has many benefits and is becoming an urgent necessity to deal with the productivity issues. Indubitably, this statement does not mean that the adoption of digital technologies can solve every productivity problem in the industry; it can however be fairly seen as one of the one of the most feasible challenge to undertake.

Most of the aforementioned digital innovations that are available in the market today are at a readiness level to be directly used in all the phases of the AECO (Architecture, Engineering, Construction, and Operation) supply chain, i.e., in design and engineering, construction, and operations (Gerbert et al., 2016). The technological landscape is also set, which essentially helps with many barriers existing against the implementation of digital solutions in the industry. Various examples and pilot use cases from the industry exhibits the enormous opportunities that digitalization entails. However, although such digital innovations are regarded as drivers for productivity and tools to reduce costs, its use in the industry is still not at a desirable level (Berlak, Hafner, & Kuppelwieser, 2020). It seems to be strange that the innovations are not used much even though the benefits are apparent, but it is not as black and white as it appears to be. There is undoubtedly a vast grey area which exists in the interface of digital innovations and its implementation in the construction industry. This gap between the theoretical benefits and operational efficiencies advocated by various literature, and the actual implementation within the industry has to be filled (Gledson & Greenwood, 2017).

The difficulties faced by the organizations in adopting digital innovations are argued to be rooted into the very traditional way of working of the construction industry and its reluctance to change its conventional practices (Oloke, 2020). The practical difficulties associated with diffusion of digital innovations and the different arguments around it means further explorations are required on the implementation processes and perceptions of potential adopters towards these innovations (Gledson & Greenwood, 2017), with several literature calling for more research in this area. For instance, Lundberg et al., (2019) stated that further studies are required to understand how to facilitate innovation diffusion activities in the construction industry. Morgan (2019) and Lindgren & Widen (2019) proposed further research on the nature of digital innovation diffusions in different type of organizations and sectors of the construction industry. This research is an answer to such calls which seeks more understanding on how innovations are diffused in project-based firms and how this process can be improved.

The focus of this research is on digital innovations (technologies or solutions) which brings about profound organizational, and technological challenges and impacts. This radicality of digital innovations in the construction industry qualifies it to be expressed in terms of Rogers' (2003, p.12) definition of an innovation; "an idea, practice, or project that is perceived as new by an individual or other unit of adoption". Organizations are in need of solutions to facilitate the change brought about by radical innovations and smoothly integrate its use in their processes. Therein lies the contribution of this research as it is directed towards the diffusion process of the digital innovations, where diffusion can be defined as "the process in which an innovation is communicated through certain channels over time among the members of a social system" (Rogers, 2003, p.5). Using Rogers' Diffusion of Innovation theory, the goal is to capture explanations over three aspects of the aforementioned definition; (1) the attributes of innovations perceived as key by the personnel, (2) communication channels through which the information about the diffusion process is communicated to and between individuals, and (3) the characteristics of the social system in which diffusion is taking place.

1.2. Research Client

Dutch engineering consultant firm Witteveen+Bos (W+B) is the client of this research. The business operations in organization are divided into 4 sectors, with a set of Product Market Combinations (PMCs) within each sector. This research is focused on the Infrastructure sector of the firm, which is divided into 8 PMCs, namely Construction Management PMC, Infrastructural Engineering PMC, Life Cycle Management PMC, Replacement and Renovation of Civil Structures PMC, Smart Infra Systems PMC, Traffic and Roads PMC, and Underground Infrastructure PMC.

1.3. Research Problem

As discussed above, there is an apparent gap between the theoretical benefits of the digital technologies in the construction advocated by various literature, and the successful implementation of such technologies in the construction industry. This gap, or as we call it the 'grey area of technology diffusion', exist in the diffusion stage of digital technologies, during which firms face barriers and challenges from different dimensions, some of which are so obscure that the firms fail to understand what the barriers even are. W+B also face a similar problem in their attempts to adopt digital technologies and ideas in their processes. As a leading consultancy in the Netherlands, W+B is aware of the serious competitive advantages, and potentials for long term efficiency of different digital innovations. Along these lines, they have high ambitions regarding development and implementation of digital innovations in their processes. However, within and beyond the context of the organization, W+B faces direct and indirect resistance towards radical innovations. As such, the development and adoption of novel digital innovations are currently confined to different decentralised small groups of enthusiastic professionals (hereinafter 'development teams'). Individuals of these teams works on digitalized solutions for design questions they encounter in their respective projects and try to learn and share it with the rest of the group. By its very nature, the implementation of novel digital technologies and niche innovations takes a bottom-up approach in the organization, where new ideas are used to solve problems on projects in which individuals of the development teams are part of, which are then learned by the team (potentially) to apply on future projects in which they will (potentially) be part of. W+B intends to scale up this process, by instigating a natural instinct in their personnel to search for and work with digital innovations and solutions, and to manage it into 'good currency' by applying them in multiple projects. Along these lines, the holistic goal of W+B is to be seen as the best firm in the market for digital engineering and BIM.

However, as mentioned earlier, there exists many known and unknown barriers and challenges within and beyond the context of W+B against the use of digital innovations. The construction industry is notorious for its blame game culture (Koutsogiannis, 2020). This is also evident when it comes to technology diffusion. Construction firms usually tend to play the pointing fingers game when they try to explain why technology is not exploited to an extend it should be. They point fingers at the traditional behaviour of employees (Oloke, 2020), resistance or lack of support from clients, or at associated risks (Gambatese & Hallowell, 2011). These factors might or might not be relevant for different cases. However, as an old saying goes, 'every time you point fingers on someone, there are three fingers pointing back at you'. Are the firms doing enough to help the employees to overcome their fears about technology, or are they doing enough to convince their clients? Such questions provide opportunities for firms to reflect and recognize what the actual problem is and how can they handle it. W+B finds themselves in such a reflection stage, where they seek to have a deeper understanding of why technology is not adopted, despite their multiple initiatives and attempts targeted towards the same.

According to Rogers' Innovation Diffusion Theory (2003), it is extremely important to understand how potential adopters perceive new innovations before attempting to diffuse those innovations. It is thus logical to develop an understanding of what are the factors which enables or restrict the personnel of W+B to develop and/or adopt digital innovations as a first step towards widespread diffusion processes. It is also very important to note that such factors and perceptions are strongly associated with the respective individuals' roles and responsibilities within W+B. According to the leaders of W+B, some Project Managers (PM) are reluctant to use digital innovations because it brings along uncertainties and risks to the project and puts them under risks of schedule or budget overruns. By definition, a PMs' major concern is to keep the schedule and budget in check, and it is quite natural to stay away from whatever that threatens the successful delivery of the project, which makes majority of the PMs in the industry risk averse (Taofeeq & Adeleke, 2019). Being at the summit of the complex social system of projects, PMs' such decisions can directly and indirectly influence the adoption decisions of the rest of the personnel in the network (Ali & Chileshe, 2009). Furthermore, there are other direct factors as well which influences the decisions of the employees, such as their reluctance to change conventional methods and practices to which they are used to (Oloke, 2020). Such factors could be related to their attitude towards innovations or technology in general. This characteristic can be explained using the concept of 'innovativeness' of individuals, defined by Rogers (2003).

Innovativeness is the degree to which an individual decides to adopt new ideas relatively earlier than other members of the social system (Rogers, 2003, p.22). This concept is very important to argue against a common misconception in the industry, that some individuals are simply against innovations or are very less innovative than others. But Rogers (2003) explains that such individuals are not "less innovative" but are simply "late" to adopt innovations than others, because of their personality traits. Based on innovativeness, Rogers (2003) segmented the members of a social system into five 'adopter categories', or in general two broader categories of 'earlier adopters' and 'later adopters', with different personality traits. Such personality traits shape the attitude of individuals towards technology and innovation. Thus, it is also important for W+B to understand how different adopter categories perceive technology diffusion and how these different perceptions of different categories can be managed to ensure an efficient and smoother diffusion process.

In sum, W+B is aware of the competitive advantages and the opportunities to improve their efficiency through digital innovations. However, they feel that the adoption of digital innovations in the firm is not at a desired level. Currently, the diffusion of innovations in the firm takes a disorganized decentralised structure, in which enthusiastic individuals, members of few development teams, develop and implement digital innovations across the projects they are part of. W+B wants to scale up this process by instigating an aptitude in their personnel to search for and work with digital innovations existing within or beyond the boundaries of the firm, in the projects they are part of. However, there exists many known and unknown barriers within the firm which is hindering the diffusion and adoption of digital innovations. This includes the differences in the mindset and perspectives of different personnel, which is also influenced by the individual's roles and responsibilities within the firm and in the projects. As such, it is important to apprehend all those factors which contributes to the adoption decisions with respect to the responsibilities of the personnel and their innovativeness, underlying reasons behind those factors, and the influence that their decisions will have on the rest of the network. Thus, the key questions that W+B wants to find answers for are 'what' are those factors, 'why' is it hindering the diffusion of innovation and 'how' to handle them. Following it, W+B wants to develop a strategy, which can aid their efforts to scale up the adoption of digital innovations by their employees. As discussed before, intention is to explore the grey areas in the diffusion of innovation in the organization and to recommend solutions towards their efforts to scale up the use of digital innovations in their process.

1.4. Research Objective

As discussed in the research problem section, the overarching goal of this research is to recommend solutions towards the firms' efforts to scale up the use of digital innovations by exploring the perceptions of the individuals of the firm towards the diffusion of digital innovations and finding ways to enhance digital innovation adoption. Based on this goal, the objective of this research is *"to develop a strategic framework for enhancing digital innovation adoption, which can aid firms in construction to improve their rate of adoption of digital innovations in a sustainable manner."*

The 'strategic framework' will be an outline of important concepts and activities which influences the adoption of digital innovations, thus acting as a guide for the firms in their efforts to enhance the implementation of digital technologies and innovations in their processes. The framework will be able to act as a foundation, around which all the activities and initiatives towards the diffusion of digital innovations can be organized. The key elements which this research aims to explore in order to develop the strategic framework are the factors affecting the adoption of digital innovations in the perspective of the personnel and the role of diffusion networks in shaping the adoption decisions. Thus, the research will be focused on the characteristics and perceptions of the individuals of the firm and the structural characteristics of the social system. However, the strategic framework will be focused on shaping the perceptions of the individuals through peripheral organizational changes rather than exhaustive system wide changes. As such, the framework will not require organizations to undergo radical organizational changes.

The terms which need attention here are 'rate of adoption' and 'sustainable manner'. The term 'rate of adoption' is the relative speed with which digital innovations are adopted by the members of the social system and can be measured as the number of members who adopt the digital innovation over a certain period of time. By using the term 'sustainable manner', the intent is to ensure that the innovations will be adopted as 'the best available practice' and its use will be continued over time.

1.5. Reading Guide

The reminder of this report is structured as follows: Section 2 explores the literature on the topics discussed in the background and context, research problem, and research objective to establish a theoretical background for the research. At the end the literature review, two theoretical constructs are defined which will act as a foundation for the rest of this research. In Section 3, the research design is discussed which addresses the research questions derived using the objective and theoretical constructs, and the methodology used to conduct the research. Following to that, the findings are presented in Section 4. Section 5 builds on the findings and the theoretical constructs to develop the strategic framework. Finally, Section 6 presents a discussion into the findings and results of this research and Section 7 wraps up the report with conclusions of this research.

2. Theoretical Background

Having discussed the research problem and objective, this section attempts to gauge a deeper understanding into the problem context and the existing situation by exploring studies and theories in this area through an extensive literature review. The goal of this section is to explore the literature in this field and to identify theoretical constructs which can be used to realise the research objective. As such, the information and knowledge formed through this section will act as the foundation upon which the rest of the research will build on. To do the same, the digital technologies currently available and used in construction are first analysed to investigate the status of technical advancements in the industry. After that, the term 'digital innovation' is defined in the context of this research. It is followed by an analysis of how the construction industry is faring with the implementation of digital technologies. At the end, Rogers Diffusion of Innovation theory is discussed to analyse its potential to be used within the problem context. Using the concepts gauged, priori constructs relevant for this research will be emphasised. The literature search was carried out using the key works 'digital technologies', 'construction', 'implementation', 'barriers and enablers' 'diffusion of innovations' and 'digital transformation'.

2.1. Digital Technologies in Construction

Over the last decade, the construction industry has witnessed widespread technological advancements through technologies like artificial intelligence (AI), cloud computing (CC), ontology, blockchain (BC), data analytics, internet of things (IoT), machine learning (ML) etc. being introduced and offering tremendous benefits to the industry (Khudhair, Li, Ren, & Liu, 2021). With the idea of a central model and endless data which can be collected along all phases of construction value chain, opportunities for digital innovations in the industry are enormous. Along these lines, Gerbert et al, (2016) presented a four-layered framework (Figure 2) which explains digital technologies in the construction industry. These four layers in which digital technologies are available and can be applied along different phases of the construction value chain are (1) User interfaces and applications, (2) Software platform and control, (3) Digital/physical integration layer and (4) Sensors and equipment.

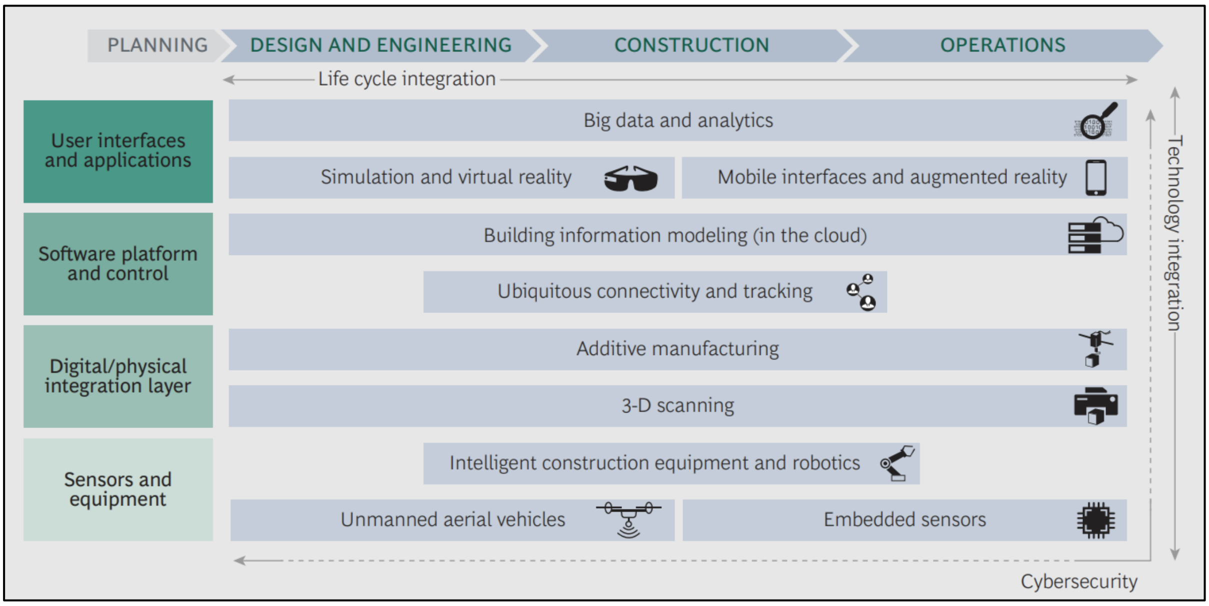

Figure 2 Digital technologies in construction (from Gerbert et al, (2016))

The key feature of digital innovations in the construction industry according to Gerbert et al, (2016) is the *software platform and control* layer, which is largely comprised of Building Information Modelling (BIM). BIM in simplest of terms, can be explained as a "set of interacting policies, processes and technologies" (Succar, 2009) which provides a digital representation of the building process by facilitating centralized data management. With its capabilities to serve all the stakeholders along all the phases of the construction value chain, BIM have transformed the data and information modelling and management of a built facility along its entire life cycle. As such, BIM is regarded as a significant innovation, through the use of which several other technological and organizational innovations can be generated (Morgan, 2019). Such emergent innovations are supported by an architecture of supporting technologies residing in the *sensors and equipment* layer. One example of supporting technology is embedded sensors, which can facilitate real time status monitoring on any part of an asset during construction and/or operations, which can help construction managers and engineers with (remote) quality control and improved efficiency (Gerbert, Castagnino, Rothballer, Renz, & Filitz, 2016). Another example of an advanced equipment, which also contributes to the *digital/physical integration* layer, is robotics. Through additive manufacturing techniques such as 3D printing, advanced robotic equipment can convert data to physical action to fabricate construction components or even entire structures. Furthermore, through unmanned aerial vehicles (drones), engineers are now able to remotely survey the sites and even couple them with 3D scanners to create digital models of the geography or complex structures, which provides lots of benefits to construction, renovation and/or operation of assets (Gerbert, Castagnino, Rothballer, Renz, & Filitz, 2016).

Another whole world of digital innovations resides within Big Data and Analytics, in which data is collected using various sensors and equipment, processed using analytical methods and exploited to enhance asset design, facilitate decision making and increase the accuracy of assumptions and predictions. Through BIM and data analytics, it is thus possible to improve design processes through data-driven designing, simulations, and iterative design and engineering (generative design). Along these lines is the concept of Internet of Things (IoT), in which equipment and assets become 'intelligent' by connecting them with one another using sensors and wireless technologies, thereby allowing equipment and assets to communicate critical performance parameters with a central platform (Agarwal, Chandrasekaran, & Sridhar, 2015). This will help in equipment/asset monitoring and preventive maintenance, inventory management, quality assessment, energy efficiency, and safety, all which ultimately contributes to improve the overall efficiency and risk management of construction projects. This idea and application are also encompassed in the concept of Digital Twins (DT), a virtual model that simulates the existing real-life situations in the actual asset (Khudhair, Li, Ren, & Liu, 2021). These are also supported by virtual and augmented reality technologies, which helps to place the user in a virtual world or augment a virtual content in the real world respectively, allowing users to compare as-in design and as-in site models. Such technologies reside in the *user interfaces and applications* layer, as can be seen in Figure 2.

As can be understood, the opportunities provided by digital innovations are enormous and it is only possible to barely scratch the surface of the wide opportunities through this empirically grounded review. The foundation of it all is data which can be collected throughout the asset's lifecycle, centralized data management and inter-disciplinary collaboration. In addition, as can be seen in the above examples, most individual technologies have huge potentials to be combinatorial innovations as well. Combinatorial innovations are formed when two or more technologies combine in a right mix, thus allowing firms to create novel innovations tailor-made to their needs and resources. Technologies discussed above have abilities to ‘mutate’ and ‘evolve’ as they spread (Merschbrock & Munkvold, 2015), thus giving the power for the users to exploit it based on their needs. Furthermore, with the advent of Industry 4.0, the concept of Construction 4.0 is also gathering pace, which is along the lines of automation and digitization of design and construction processes using various individual and combinatorial innovations, to optimize time and costs, quality control and worker safety (Rivera, Mora-Serrano, Valero, & Oñate, 2020). According to Gerbert, et al., (2016), adoption of right digital technologies (in the right way) can result in an engineering and construction cost reduction of 15-25% and potential savings of 8-13% in the operations phase, which, given the productivity concerns of the industry, are significant numbers.

2.2. Understanding the term ‘Digital Innovation’

The most used and understood definition of the term innovation is from Rogers’ (2003), for whom innovation is “an idea, practice or project that is perceived as new by an individual or other unit of adoption.” Along these lines, the most important characteristic of an innovation is that it is ‘perceived as new’ by a potential adopter. This means that even if the ‘idea, practice or project’ has been invented or has been in the market for a longer time, if the adopters perceive it as new, it is an ‘innovation’ for that particular adoption unit. The ‘idea, practice or project’ is no longer an ‘innovation’ when the individual gets enough knowledge about it and when it is put into use as “the innovation loses its distinctive quality as the separate identity of the new idea disappears” (Rogers, 2003, p. 180). As much of the diffusion research involves technological innovations, Rogers (2003) mostly used the terms “technology” and “innovation” as synonyms (Sahin, 2006). Rogers (2003) defines ‘technology’ as “a design for instrumental action that reduces the uncertainty in the cause-effect relationships involved in achieving a desired outcome”. He further explains the components of a technology: hardware and/or software, where hardware is “the tool that embodies the technology in the form of a material or physical object” and software is “the information base for the tool” (Rogers, 2003, p. 259).

Along these lines, we can draw up the definition of ‘digital innovation’ for this research: *“a technological idea, practice or tool that is perceived as new by an individual or other unit of adoption and reduces the uncertainty in the cause-effect relationships involved in achieving a desired outcome”*, in which the technology can be hardware, software or related to exploitation of data. Such novel technological ideas, practices or tools might come about as a result of R&D activities within the organization or comes out of practice as a means for problem solving in individual projects or can be from the market. Following the definition, the general implication is that digital innovations usually have some degree of benefits and advantages for the potential adopters, but most of the times these benefits are not clear-cut and obvious for many of the intended adopters (Rogers, 2003, p.13). Thus, the characteristics of an innovation, as perceived by the potential adopters, determine its rate of adoption.

Another factor which needs to be pointed out is the nature and scope of change brought about by digital innovations. Following the definition above, digital innovation is a ‘new’ idea, practice or tool which brings about certain changes to the work practices of the adopters and the social system. According to Lindgren & Widén (2019), the impacts brought about by such changes affects the innovation diffusion. The scope and nature of these changes can be different for different digital innovations. Along these lines Harty (2005) classified innovations into two modes: ‘bounded’ and ‘unbounded’ innovations. Bounded innovations are the innovations in which the implications of the innovation are restricted within a single sphere of influence while for unbounded innovations, the implications of the innovation spills beyond a single sphere of influence (Harty, 2005). Such spheres of influences can be of multiple types within which a key type is the discipline of the innovation. Some digital innovations might only affect a particular individual or a particular discipline, and the adopters will not have to depend on anyone else to use the particular digital innovation. An example for such a digital innovation can be the use of drones for site inspections in construction sites. Site engineers have to control and inspect construction sites time to time. Doing it manually in busy sites, which is the current practice, can be sometimes complicated and time consuming. To improve this process, site engineers can make use of drones to carry out visual inspections, which improves the efficiency of their work, as drones can capture birds eye vision much beyond human capabilities and reduce the time needed for site inspections. This innovation, however, concerns an individual or a single discipline improving their work practices, for which they are not dependent on anyone else. Such innovations will be called *'intra-disciplinary innovations'* in this research.

On the flip side, there are other digital innovations, which affects multiple disciplines or the whole network, making potential adopters of a particular discipline dependent on other adopters from a different discipline (or the same) for the successful implementation of the innovation. One such example, again in the same perspective of site engineers, is augmented reality. Augmented Reality (AR) allows site engineers to improve their site inspection and site works by giving them the ability to compare as-built situations with as-designed models by simply walking around the site with AR technologies. This can be done by superimposing BIM models precisely to the actual physical environment in AR (Dudhee & Vukovic, 2020), for which the site engineers are dependent on the designers. If the BIM models are not capable of being superimposed to the actual physical environment (or if there is no BIM model), AR cannot be used to compare as-designed and as-built situations, restricting site engineers from using that specific innovation. Such innovations, which requires close collaboration and coordination between various disciplines, are defined as *'inter-disciplinary innovations'* in this research. As such, the nature and scope of change brought about by the digital innovation will also influence its rate of adoption.

As per the definition of 'digital innovations' for this research, the technologies discussed in section 2.1 might or might not be digital innovations, depending on the novelty it brings about to the potential adopters. As it is a subjective term, technologies will be synonymously referred to as innovations in this report.

2.3. Diffusion of Digital Innovations in Construction

Several organizational and project related barriers have impeded the diffusion of digital innovations in the construction industry despite its apparent advantages in paper (Gledson & Greenwood, 2017). Such barriers can be directly related to the innovation itself or can be a result of the complex social system of the construction industry. One key factor which can obstruct the diffusion of digital innovations is the misunderstandings by planners or practitioners about specific innovations. According to Li et al., (2008), such misunderstandings can play a major role in negatively affecting the adoption decisions of potential adopters. The misunderstandings can be around the perceived advantages, or the risks related to the specific innovation. Along these lines, Gambatese & Hallowell (2011) also noted that the perceived risk of failure, along with the fear of change and lack of recognition from clients, acts as major barriers against the diffusion of technical innovations in the construction industry.

According to Rogers (2003, p.413), structural characteristics of organizations, such as low centralization, high complexity and low formalization may make it difficult for them to implement innovations. Several literatures have noted that the construction industry is a complex social system with such intricate structural characteristics, and several diffusion studies have pointed out that this characteristic of the industry makes the diffusion of innovations difficult. For instance, Shibeika & Harty (2015) noted that the social system and context into which digital innovations are introduced is "neither stable nor static". Furthermore, following the findings of Dubois & Gadde (2002), Shibeika & Harty (2015) argued that there are multiple social systems within large construction firms, mainly because of the project-based nature of the industry. Along these lines, Lundberg et al., (2019) also argued that the structural characteristics of the social system and of the sub-systems within the social system may hamper innovation diffusion in the construction industry. As such, any innovation diffusion process in the construction industry must take into consideration the nature and characteristics of the social system, within which the diffusion will be taking place.

2.4. Rogers Diffusion of Innovation (DoI) Theory

Rogers Diffusion of Innovation (DoI) theory seeks to explain how innovations are adopted by members of a social system. Rogers (2003, p.11) defined diffusion as "the process by which an innovation is communicated through certain channels over time among the members of a social system". Along these lines, Rogers points out four main elements that influences the adoption of innovations; (1) the attributes of innovation, (2) communication channels, (3) time and (4) the characteristics of the social system, where adoption is defined as "full use of the innovation as the best course of action available" (Rogers, 2003, p.177).

2.4.1. Attributes of Innovation

Rogers (2003, p.232) defined innovation diffusion as an "uncertainty reduction process" and pointed out that it is the attributes of innovation which helps to reduce the uncertainty about the innovation. According to DoI, potential adopter's perception of these attributes determines the rate of adoption of innovations. Rogers defined five key attributes that determines the success of any innovation. They are.

1. *Relative Advantage*: Rogers (2003) defined Relative Advantage as "the degree to which an innovation is perceived as better than the idea that it supersedes". The point to stress here is that the relative advantage should be measured in terms that are relevant for the particular adopter. For instance, for a project manager this term can be cost and/or time advantage while for a design engineer it could be ease of use. So, the relative advantage should be measured for such aspects that matters to the particular adopter. As such, what constitutes the term 'relative advantage' depends on the needs of the particular adopter. According to Rogers, greater the perceived advantages of the innovation, greater its rate of adoption.
2. *Compatibility*: It is the degree to which an innovation is perceived to be consistent towards the values, experiences and needs of the potential adopters. According to DoI, innovations which are not compatible with existing norms will not diffuse rapidly in comparison to the innovations which are compatible to the existing infrastructure and needs within the social system.

3. *Complexity*: It is the degree to which an innovation is perceived as difficult to understand and use. According to DoI, innovations which are easier to understand are adopted rapidly than the innovations which requires adopters to develop new skills and understandings.
4. *Trialability*: Trialability is the degree to which an innovation can be experimented on a limited basis. DoI holds that when the innovations are trailed, it will represent less uncertainty to the potential adopters and hence can be rapidly adopted, given that the adopters are convinced about the other 3 attributes discussed above.
5. *Observability*: It is the degree to which the results of the innovation are visible to the potential adopters. Visible results lower the uncertainty and stimulates conversations around the innovation, which can improve its rate of adoption.

According to Rogers, 49-87% of the variance in the rate of adoption of innovations in a social system can be explained using the five aforementioned attributes of innovation. As such, Rogers stressed the importance of understanding how potential adopters perceive these attributes to determine the nature of the diffusion process in a social system.

2.4.2. Communication Channels and Diffusion Networks

Following the definition of Rogers, diffusion is the process through which an innovation is communicated to a receiver by a source. The means through which the source (change agents) communicates with the receiver (adopters) are defined in DoI as communication channels. Such channels can be either *mass media* or *interpersonal channels* in nature and could originate either from *local* or *cosmopolite sources*. Rogers explains that while mass media channels and cosmopolite sources are more effective in creating knowledge about the innovation, interpersonal channels and local sources are more effective in forming and shaping the attitude towards the innovation.

As diffusion is a “very social process” which involves a high degree of “interpersonal communication relationships” (Rogers, 2003, p.19), interpersonal networks and communication channels are powerful to create or change attitudes held by an individual towards the innovation. Such interpersonal networks which have a strong influence on the individual’s adoption decisions are called *Diffusion Networks*. Within diffusion networks, some individuals can informally influence other individuals’ attitudes or overt behaviour in a desirable way and hence influence other’s opinions. Such individuals are called *Opinion Leaders* (Rogers, 2003, p.271). Opinion leaders play an important role in the diffusion networks and Rogers suggests that opinion leaders should be identified and utilized in diffusion programs. Another characteristic of the diffusion network which have an influence on the diffusion process is the diversity of the members within the network. Rogers used the term *‘Heterophily’* for this characteristic and defined it as the degree to which individuals who interact within a network are different in certain attributes. Rogers explains that if the only interactions are between similar people in socially horizontal patterns, new ideas (and opinions) will be prevented from trickling down from people who have more education and greater technical expertise to people who have lower education and expertise. As such, for the successful diffusion of innovations, diffusion networks should have at least some degrees of heterophily.

2.4.3. Time

Rogers considers time as an important element in the diffusion process and argued that most behavioural science research ignores the dimension of time. As time cannot be attributed implicitly and independently, Rogers incorporates the time aspect within the concepts of (1) innovation decision process of individuals, (2) innovativeness of individuals or adopter categories and (3) rate of adoption. While the rate of adoption is simply the number of members in the system who adopts the innovation during a particular period of time, the other 2 concepts require detailed explanations.

The Innovation Decision Process

Rogers (2003, p.20) defines the innovation decision process as “an information-seeking and information-processing activity”, where the individual is motivated to reduce the uncertainty around the innovation. It involves five steps, which typically follow each other chronologically as depicted in Figure 3. The process begins with the *(1) knowledge stage*, during which the individual tries to determine what the innovation is and how and why it works. As such, the individual seeks for three types of knowledge in this stage: awareness knowledge, how-to knowledge, and principles-knowledge. Awareness knowledge is related to the ‘what’ understanding, during which the individual generates knowledge about the existence of the innovation. It is followed by the how-to knowledge, which contains information about how to use the innovation correctly. This includes skills and expertise the individual should have to start using the innovation. The individual then seeks principles-knowledge, which includes the functioning principles describing how and why an innovation works, such as key understanding about the attributes of the innovation.

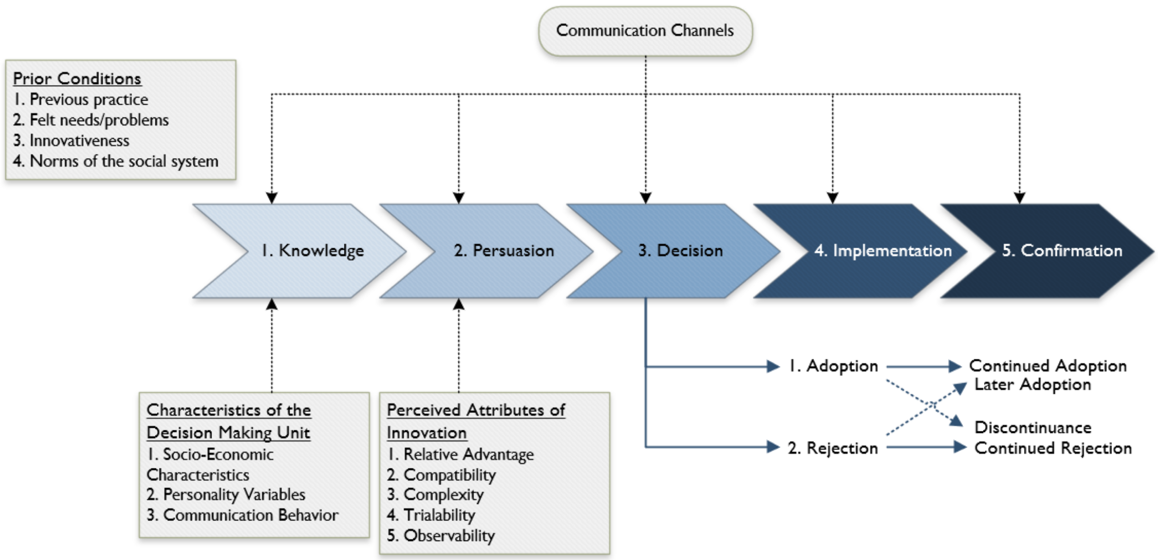

Figure 3 Innovation Decision Process, Rogers (2003)

An individual may gain all this knowledge by the end of the knowledge stage, but this does not mean that the individual will adopt the innovation. This decision is influenced by the attitude of the individual, which is shaped predominantly during the next stage of the innovation decision process, the *(2) persuasion stage.* During the persuasion stage, the individual forms a favourable or unfavourable attitude towards the innovation. Rogers explains that while the knowledge stage is more cognitive (or knowing) centred, the persuasion stage is more affective (or feeling) centred. As such, the individual’s interpersonal networks (diffusion networks) play a huge role in this stage, as they consider subjective evaluations of their close peers’ more credible. Hence social reinforcements from members of their interpersonal networks affects the beliefs and opinions of the individual about the innovation.

The individual then engages in activities that lead to a choice to adopt or reject the innovation in the next stage of the innovation decision process, the *(3) decision stage.* The trialability of the innovation can be key in this stage as most individuals wants to first try the innovation within their own situations before arriving at a decision. If the individual decides to adopt the innovation, they put it into use in the *(4) implementation stage.* As they do that, the consequences of the innovation bring about uncertainties which can still be a problem in the innovation decision process. During this stage, it is key that the adopters receive adequate (technical) assistance to reduce the degree of uncertainties and thereby reduce the chances of the adoption decision being reversed. The last stage of the innovation decision process is the *(5) confirmation stage*, during which the individual seeks reinforcement for an adoption decision already made by them. Attitude of the individual is key at this stage as the individual might reverse their decision if they are exposed to conflicting messages about the innovation, which usually arises from within their interpersonal networks.

Innovativeness and Adopter Categories

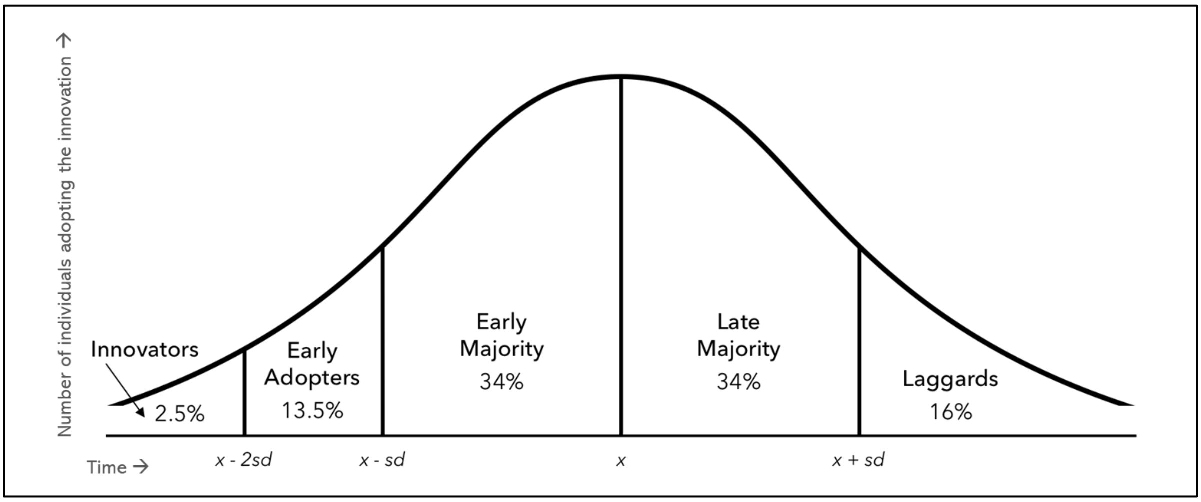

Figure 4 Adopter categorization based on innovativeness, Rogers (2003)

Rogers (2003, p.23) defines *innovativeness* as “the degree to which an individual or other unit of adoption is relatively earlier in adopting new ideas than other members of a system” and *adopter categories* as “the classification of members of a social system on the basis of innovativeness”. This classification is to bring about the notion that some individuals of the social system, who are resistant towards innovations, are not “less innovative that than the average member of a social system”, but rather adopts the innovation in a later stage than the average member. This definition avoids jumping into conclusions and helps diffusion scholars to focus on exact issues which restricts the individuals of each category towards adopting innovations. The five adopter categories defined by Rogers are (1) innovators, (2) early adopters, (3) early majority, (4) late majority and (5) laggards. Rogers further called innovators and early adopters as *‘earlier adopters’* and the rest as *‘later adopters.’* This innovative dimension, measured as the time at which an individual adopts the innovation, follows a continuous curve, which is then categorized into the 5 adopter categories. This normal distribution of adopter categories is illustrated in the Figure 4.

The *Innovators* are the technology enthusiasts of the social system. They are the part of the population who are willing to experience new ideas and are thus venturesome and risk takers by nature. Rogers calls such innovators as ‘gatekeepers’ who imports the innovation from outside of the social system's boundaries. Innovators are followed by the more respectable members and the visionaries of the population, the *Early Adopters.* They are the opinion leaders of the social system with a natural desire to be trend setters, who are always in a lookout for a strategic leap forward in lives or businesses. As such, they are quick to make connections between the innovations and their personal or corporate needs. The early adopters have a key role in diffusion processes. Being the opinion leaders and being respected by their peers, they can play the role of local missionaries for speeding up the diffusion process. Thus, they can reduce the uncertainties around the innovations by adopting it and by conveying subjective evaluations, which is valued by the other members of the social system.

The pragmatists of the population, *Early Majority*, is the next adopter category. They only adopt innovations after deliberate considerations, as they are open to progressive ideas but will not act without solid proof of benefits. Early majority plays a key role through their unique position in the system. They link the 'earlier adopters' to the 'later adopters' and thus provide interconnectedness in the systems' networks. They are followed by the conservatives of the population, the *Late Majority*. Being sceptical towards changes, they adopt ideas just after the average members of the social system. As such, almost all uncertainties about the innovation should be removed for the late majority to be convinced about the idea of adopting it, which can be, however, be influenced by peer pressure and/or economic necessity. At the very end are the *Laggards*, who are the very traditional members of the population. The point of reference of laggards is the past and thus they decide to adopt or reject the innovation by considering whether the innovation is successfully adopted by other members of the social system in the past.

Rogers explains that while designing a diffusion project, it is very important to consider one vital fact which is the percentage who have already taken up the innovation. This figure can help the change agents to determine which section they are addressing next and how they should proceed further in the diffusion process.

2.4.4. Social System

The last key component in the DoI theory is the social system. Rogers (2003, p.23) defines social system as a "set of interrelated unites engaged in joint problem solving to accomplish a common goal". As all the diffusion process happens within a social system, it is influenced heavily by the norms and nature of the social system, as it affects the individual's innovativeness. Much of the innovation research in construction industry is focused on such characteristics of the social system, with the most important being the findings of (Dubois & Gadde, 2002), in which they characterized construction industry as a 'loosely coupled system', with several subsystems within the overarching social system.

2.4.5. Innovation Process in Organizations

Rogers identifies three types of innovation adoption decisions in DoI. These are *(1) Optional-innovation decisions*, in which choices to adopt or reject innovations are made by individuals irrespective of the decisions of rest of the social system, *(2) Collective-innovation decisions*, in which choice to adopt or reject innovation are made by the members of the social system in consensus and *(3) Authority innovation-decisions*, in which choices to adopt or reject innovations are made by elite individuals, the individuals in a position of power in the organization (Rogers, 2003, p.347). So far, we have discussed the factors mainly contributing to the optional-innovation decisions. Along the definition of digital innovations for this research, Optional-Innovation decisions are relevant for intra-disciplinary innovations while collective and authority innovation decisions are relevant for inter-disciplinary innovations. Along these lines, Rogers (2003) also discusses the innovation process of organizations, in which collective and authority innovation decisions are more relevant in the bigger picture. Following that, Rogers developed a model for innovation process in organizations, consisting of two stages and five steps, as depicted in the Figure 5.

Stage I, *Initiation*, is concerned with all the activities leading up to the decision to adopt. This includes information gathering, conceptualizing, and planning for the adoption of the innovation. This stage includes two steps, *(1) Agenda-setting* and *(2) Matching*. *Agenda setting* is concerned with recognition of general organizational problem which creates a perceived need for an innovation. This defined problem with the perceived need for solution is then matched and considered together with an innovation in the second step, *Matching*. In this step, the goal is to analyse the feasibility of the selected innovation in solving the organizational problem recognized in the agenda-setting step. Stage I leads up to the decision to adopt or reject the innovation by the organization (or by the collective members).

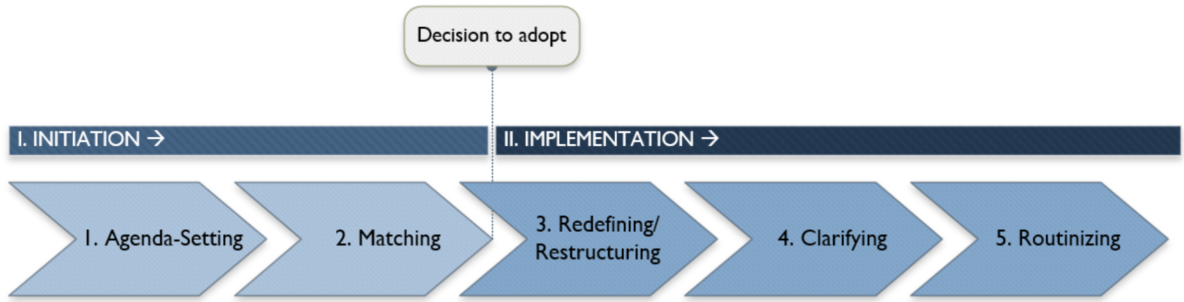

Figure 5 Innovation process in organizations, Rogers (2003)

After the decision to adopt, Stage II, *Implementation*, begins. Implementation stage includes all the activities and events concerned with putting the innovation into use. There are three steps in this stage. The first step of implementation stage and the third step of the innovation process in organization is *(3) Redefining/Restructuring*. In this step, the innovation is modified or sometimes 'reinvented' to fit into the organization. Meanwhile, sometimes the structure of the organization might have to be altered to accommodate the innovation. Thus, in this stage, changes are made to the innovation and/or the organizational structure to accommodate the innovation. The process then moves on to the next step, *(4) Clarifying*, in which the relationship between the organization and the innovation is clearly defined and the innovation is put into full use. This happens as the idea of the innovation becomes clearer to the members of the organization. The process ends with *(5) Routinizing* in which innovation is completely incorporated into the organizational processes, losing its separate identity as a 'new' idea.

2.4.6. Use of Rogers Diffusion of Innovation Theory by Construction Scholars

Many construction scholars have applied Rogers DoI theory for assessing innovations in construction. For instance, Gledson (2016) used innovation-decision process model from DoI to analyse adoption decision of BIM by individuals of a construction firm to gauge the perceptions of the employees about organizational BIM adoption. Gledson & Greenwood (2017) adopted a theoretical framework entailing the concepts of attributes of innovation, types of innovation decisions and communication channels from DoI to assess the adoption 4D BIM in the UK construction industry. Furthermore, Lundberg et al., (2019) used DoI concepts to assess the diffusion of innovation in a Swedish contractor company by studying the social systems implications in the implementation processes, and Kyriakou et al., (2020) used the attributes of innovations to gauge the factors affecting the adoption of cloud computing by Greek municipalities. As such, the validity of using DoI to analyse and learn about digital innovations in the construction industry is well established.

2.5. Research Gap

The characteristics of the social system have received much attention from scholars studying diffusion of innovations in the construction industry. A key factor which has not received considerable attention is the influence of interpersonal networks (diffusion networks) of the adopters on their innovation adoption decisions, and the innovativeness of individuals. Citing Rogers (2003), Greg Orr (2003) stated that understanding and utilizing the diffusion networks can aid strategies aimed at system wide change. Along these lines, Gledson & Greenwood (2017) and Lundberg et al., (2019) proposed future studies directed towards exploiting the diffusion networks in the social system where the innovation is being diffused. Accordingly, Crespin-Mazet et al., (2021) suggested further studies to capture the formal and informal ways of diffusion processes and organizational learning, and to analyse intermediatory structures and networks which connects the formal and informal organization of firms. The review of literature in this field confirms the need for future research into the exploitation of diffusion networks for positive innovation adoption decisions. Furthermore, all the DoI research in the construction industry (discussed in Section 2.4.6), recommended using the DoI concepts in different problem contexts to gauge how innovations are perceived by different populations, in order to shed more light on how generalizations can be made for the construction industry.

2.6. Theoretical Constructs

Based on the literature review about diffusion of innovation in construction and DoI, priori specification of constructs can be defined, which can potentially explain the diffusion and adoption of digital innovation in construction. Priori constructs refers to concepts or ideas which are relevant for the study area, and which proceeds from theoretical deduction rather than from observation or experience. According to Eisenhardt (1989), specifying priori constructs can be valuable as it can help researchers to shape and guide the research. If the defined constructs prove important during the research, then the researchers will have a firmer empirical grounding for the emergent findings (Eisenhardt, 1989). Rogers DoI theory is one of the most important and enduring social science theories, which seeks to explain how, why, and when new ideas and technologies spread. As such, for this research, the priori constructs defined are grounded on Rogers DoI. Based on DoI, attempt has been made to define the factors affecting the rate of adoption of innovation, and a model of diffusion of innovation in firms.

2.6.1. Priori Construct A- Factors Affecting Rate of Adoption of Innovations

Based on Rogers DoI, four key factors which affects the rate of adoption of innovations are identified. These factors are illustrated in Figure 6. The first key factor is the *characteristics of the social system*, which includes the structural characteristics and the established norms of the social system, and the organization of communication channels in the system. These affect the rate of adoption of innovations in two ways. First, the prior conditions of the social system determine the diffusion process and time which is required for diffusion of innovations. For instance, if the structure of the social system is complex and divided into sub-systems with numerous couplings, then the diffusion process might prove to be difficult and extensive. In addition, the established norms and the communication channels also determine the adoption of innovation by individuals. As such, the characteristics of the social system affects the diffusion process and individual's adoption decisions which in turn affects the rate of adoption. As more individuals adopt the innovation, higher the rate of adoption and vice versa. The next key factors which determine the rate of adoption through adoption decision by individuals is the *innovativeness of individuals*. As per DoI, the adopter categorization of an individual determines how sooner or later does that individual adopts an innovation. While 'earlier adopters' play a role of gatekeepers of technology in the organization and brings the idea of the innovations into the social system, 'later adopters' determine the pace of diffusion process and rate of adoption as they make up the majority of the population.

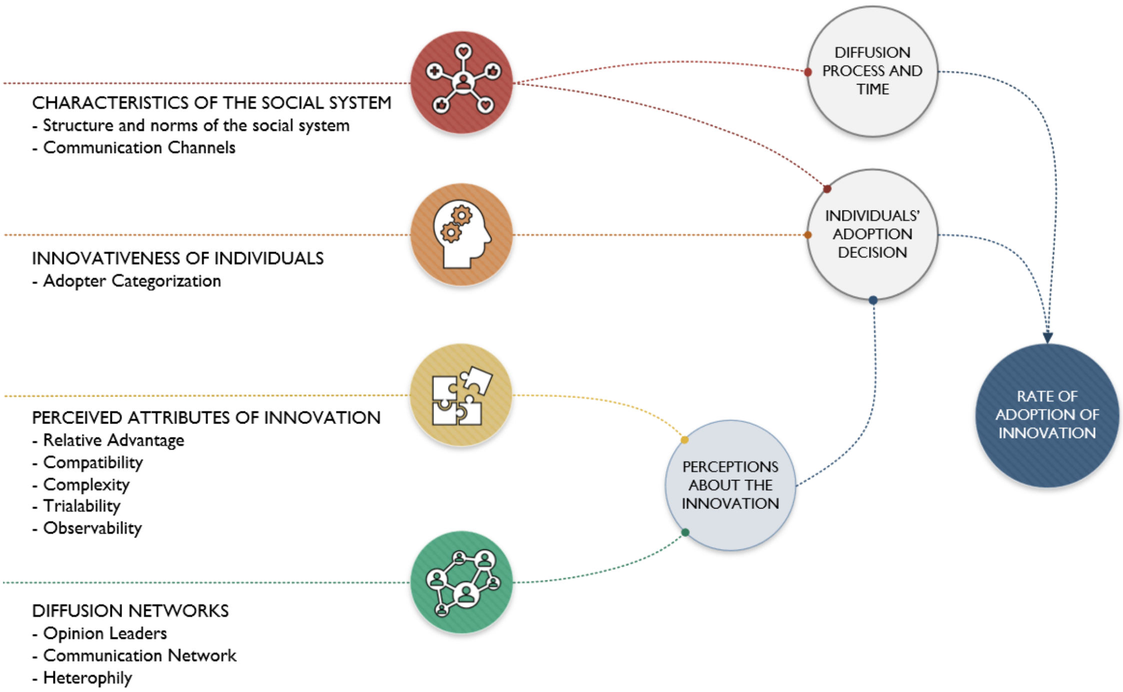

Figure 6 Factors affecting rate of adoption of innovations.

The innovativeness of individuals is followed by, and closely related to the *perceived attributes of innovation*. Perceived attributes of innovation shape the adoption decisions of individuals. According to Rogers, 49-87% of variance in the rate of adoption of innovations can be explained using the attributes of innovation. Attributes of innovation shapes the individuals' perceptions about the innovations, which in turn influences their adoption decisions. Another key factor which can shape an individual's perception about the innovation is the characteristics of the *diffusion networks*. Individuals tends to seek reassurance from their close peers when they are making their adoption decisions and they value the subjective evaluations of their peers more than the theoretical evidence. Hence, diffusion networks also play a key role in influencing the rate of adoption of innovations.

2.6.2. Priori Construct B- Model of Innovation Diffusion Process

Based on DoI, a model of innovation diffusion process is developed, which considers optional, collective and authority innovation-decisions. The model is illustrated in Figure 7. The role of the factors affecting the rate of adoption of innovation, defined in priori construct A, are also identified in this model as can be seen in the figure. Two perspectives are stressed in the model: organisations' diffusion process and the individuals' decision process. Intra-disciplinary innovations are mostly concerned only with the individual's decision process, while the whole model is relevant for inter-disciplinary innovations. To explain the model better, organizational perspective is referred as ‘steps’, and the individual perspective is referred to as ‘stages’ in the following paragraphs.

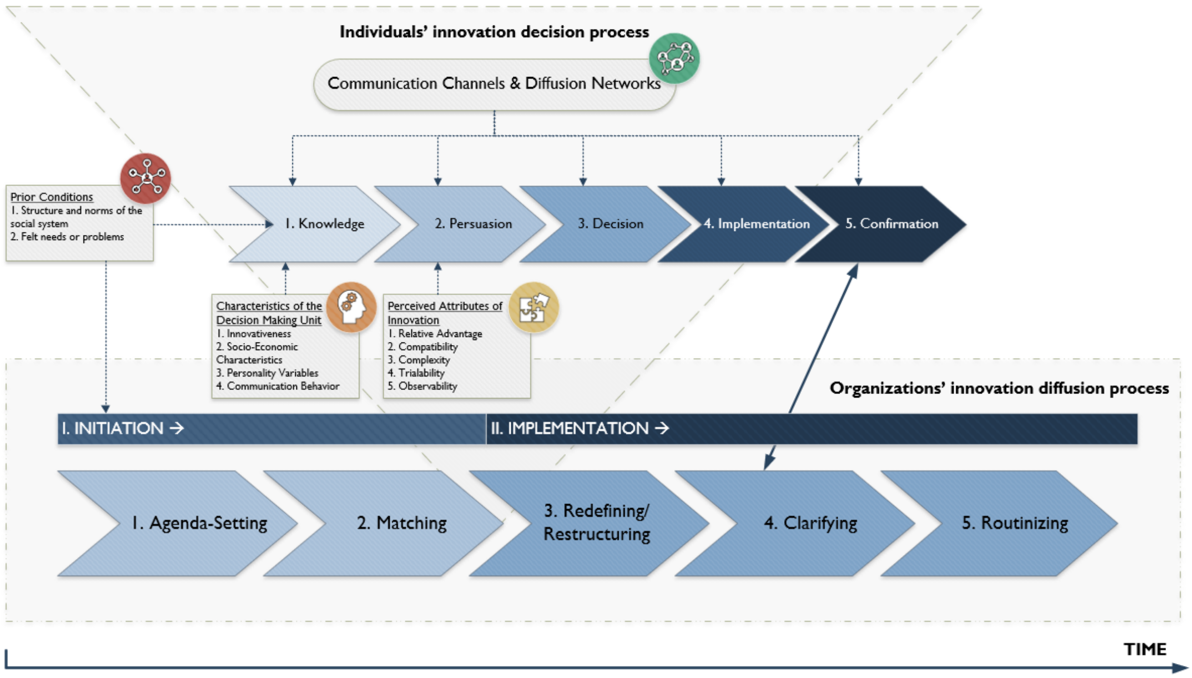

Figure 7 Model of innovation diffusion process

In the organizational perspective, the process starts with the initiation phase. The first step in initiation phase is *agenda-setting*, in which the need for innovation is recognized through a perceived organizational problem. The factor characteristics of the social system plays a key role here. The perceived need is then matched with an innovation in the next step, *matching*, after which a decision to adopt or reject the innovation is taken. This decision can be collective or authority. In both scenarios, after the decision to adopt, the diffusion process then move into the implementation phase, which involves individuals’ decisions to adopt or reject the innovation.

An individual’s innovation decision process involves five stages, as discussed in Section 2.4.3. This starts with the *knowledge stage*, during which the individual tries to determine what the innovation is and how and why it works. The innovativeness of individuals is very key in this stage as it defines how keen the individual will seek knowledge about the innovation. In the *persuasion stage*, the individual forms a favourable or unfavourable attitude towards the innovation. The attributes of innovation shape the perception about the innovation and thus influences the attitude of the individual in this stage. Even though communication channels and diffusion networks play a key role in all the stages of the innovation decision process, they are of extreme influence during the persuasion stage. The individual then makes the decision to adopt or reject the innovation in the *decision stage*, and in case of a positive decision, adopts the innovation in the *implementation stage*.

The *redefining/restructuring* step in the organizational perspective influences the individual’s decision process, especially in the persuasion and decision stages. In this step, the innovation and/or the organization is readjusted to accommodate the innovation. If it is done as per the convenience of the individuals, then it is more likely for the individuals to develop a favourable attitude towards the innovation in the persuasion stage. The redefining/restructuring step is followed by the next step, *clarifying*, in which the relationship between the organization and the innovation is more clearly defined and the innovation is put into full use. The clarifying step is very closely related to the *confirmation stage* of an individual's innovation decision. In the confirmation stage, individual seeks reinforcement for an adoption decision already made by them. There is still a chance that the individual might reverse their decision if they receive conflicting messages about the innovation, because of which the clarification step in the organizational perspective might be affected. If clarification step is successful, the process then moves to the last step, *routinizing*, in which innovation is completely incorporated into the organizational processes, losing its separate identity as a 'new idea'.

The priori constructs defined will act as a backbone for the rest of this research. However, it is important to note that the specified constructs are tentative for this research. The constructs might or might not be relevant for the recommendations, and the relationships defined between might or might not be consistent. Thus, this research will use the specified constructs as a foundation, and the actual relationship between the constructs and study case will be identified during the research.

2.7. Overview of Theoretical Background

This section explored the literature related to digital technologies in construction, technology diffusion in construction, and innovation diffusion theories to establish a theoretical background for this research. First, the digital technologies in the construction industry were discussed to underline the enormous opportunities and benefits posed by the various digital technologies. It was followed by an exploration into the term *'digital innovations'* to derive a definition for the term in the context of this research, which is: *"a technological idea, practice or tool that is perceived as new by an individual or other unit of adoption and reduces the uncertainty in the cause-effect relationships involved in achieving a desired outcome"*, in which the technology can be hardware, software or related to exploitation of data. Furthermore, we also defined *'intra-disciplinary'* and '*inter-disciplinary'* innovations, which is related to the sphere of influence of the innovations in terms of discipline. Intra-disciplinary innovations are related to a single discipline and the decision to adopt/reject an innovation solely depends on the members of that discipline, whereas the adoption decisions of inter-disciplinary innovations depend on collaboration and coordination between two or more disciplines. After establishing the definition of digital innovations, we further explored the status of the diffusion of digital innovations in the construction industry to identify some of the major barriers restricting the same. Following this, various concepts of Rogers (2003) Diffusion of Innovation theory were explored to identify relevant concepts for this research.

Using all the knowledge gathered through the literature review, two priori constructs were defined, which will act as a foundation for the rest of this research. *Priori construct A* (Figure 6) is related to the factors affecting the rate of adoption of innovations, and defines four key factors, them being characteristics of the social system, innovativeness of individuals, perceived attributes of innovation and diffusion networks. *Priori construct B* (Figure 7) presents an innovation diffusion model, consisting of the innovation process in organizations and an individual's innovation decision process. The model also emphasises the influence of the factors affecting the rate of adoption across the diffusion process. These priori constructs will act as the backbone of this research, upon which the reminder of the research will be based on.

3. Research Design

To be able to develop the strategic framework for enhancing technology adoption, priori constructs has been established using a literature review. These constructs were then compared with the current state in the firm, the method used for which is explained in this section. Research questions are discussed, followed by the methodology which was used to conduct the research. Strategies undertaken to ensure the quality of the research are also discussed.

3.1. Research Questions

To achieve the research objective explained in Section 1.4, following research questions were defined using the theoretical foundation established in the previous chapter and the priori constructs specified using it. The main research question is as follows:

What factors affect the adoption of digital innovations in the firm as perceived by their personnel and how can the rate of adoption be increased in a sustainable manner?

The main research question aims to unearth the 'factors' affecting the adoption of innovation by the employees of the firm with respect to their innovativeness and responsibilities. By 'factors', following the priori constructs, the focus are the attributes of innovation, characteristics of the diffusion process and the role of diffusion networks. To stress on these points, the main research question is broken down and dealt with the following sub-questions:

1. *How are digital innovations currently diffused in the firm and how is the current diffusion and progression of digital innovations perceived by different adopter categories? How does this differ for intra-disciplinary and inter-disciplinary innovations?*

Through this question, the research aims to explore the perceptions of individuals about the current diffusion process of digital innovations in the firm with respect to their innovativeness and responsibilities. This is to understand how innovations are currently diffused in the firm, what are the opinions of individuals about the diffusion of digital innovations and what factors aids or restricts the same. It is also key for the research to differentiate such perceptions between intra-disciplinary and inter-disciplinary innovations, as both might have subtle specific factors contributing towards the diffusion processes.

2. *What attributes of innovation enables or restricts the diffusion of digital innovations for each adopter category? How does this differ for intra-disciplinary and inter-disciplinary innovations?*

While the previous question aims to capture the perceptions about the diffusion process, this question aims to capture the perceptions about the innovations themselves. As such, the aim is to identify the factors or the attributes of the innovation which enables or restricts its diffusion, in the perspective of different adopter categories. Again, the intra or inter disciplinary aspect of the innovation is also considered in this question.

3. *What is the role of diffusion networks in the diffusion process of digital innovations as perceived by different adopter categories?*

We have argued that the diffusion networks generally play a key role in diffusion processes. Through this sub-question, the research tries to assess the role of diffusion networks within the firm in shaping the adoption decisions of different individuals and how such diffusion networks can be exploited to improve the rate of adoption of digital innovations.

4. *What should a strategy which aims to improve the rate of adoption of digital innovation comprise of?*

Based on the results of all the above sub-questions, this question aims to develop a strategic framework, which can aid firms to enhance their rate of adoption of digital innovations.

3.2. Research Scope

Adoption of digital innovations is a very broad topic as there are multiple innovations with very different scope and goals. Hence, it was important to focus this research on a feasible scope to avoid being overwhelmed by concepts, perceptions, and complexities. As explained in Section 1.2, the business operations of W+B is divided into four sectors, with a set of Product Market Combinations (PMCs) within each sector. This research was focused on the Infrastructure Sector of W+B and the scope of the research was the design and planning of infrastructure. As such, the research covered certain PMCs, whose focus is the design and planning of infrastructure, them being Infrastructural Engineering PMC, Underground Infrastructure PMC, Traffic and Roads PMC, Smart Infra Systems PMC and Construction Management PMC. Another consideration is the type of digital innovations. We defined digital innovations as 'technological ideas, practices or projects' which are perceived as new by the individuals. However, the scope of this research will be radical technologies (or technological ideas), whose adoption poses profound organizational and/or technical challenges. By this, the goal is to differentiate between the innovations whose adoption is not challenging even if it is perceived as new, with such innovations which are difficult to diffuse because of its radicality (in terms way of working).

3.3. Research Strategy

To answer the research questions, and thereby achieve the research objective, an explanatory multiple case-study research approach with solution-oriented design was adopted. This research aims to understand how innovations are currently diffused in the firm and why the rate of adoption is not at a desired level. Multiple-case study approach was selected for this purpose as it enables us to understand the complex diffusion process in specific contexts, respecting the reasonings of Eisenhardt (1989) and Yin (2003). In addition, explanatory case-study approach allows in-depth and multi-faceted analysis of complex problems in their context (Crowe, et al., 2011). The adoption of digital innovations is such a multi-faceted topic, and the problem context requires an in-depth analysis rather than breadth, as the breadth of the topic is rather expanding and arguably endless. Next to it, solution-oriented research is designed in a way to directly recommend solutions for the identified problem. As such, the research method captures the objective of the research by first exploring the problem within the problem context using case studies and then directly recommending solutions towards it. Further in this section, the cases selected for this research and the research method are discussed.

3.3.1. Case Descriptions

Collective or multiple case studies allows comparisons across several cases, thereby giving the researcher more insights into the problem (Crowe, et al., 2011). Thus, for this research, three cases were carefully selected for analysis. Selected cases differ on important characteristics, thereby providing in depth analysis of the research problem. The cases selected were (1) 3D BIM, (2) Scripting & Programming of design calculations and (3) 5D BIM. The important aspect considered while choosing these cases were the nature and scope of change brought about by the innovation. As discussed in the definition of digital innovations in Section 2.2, whether an innovation is intra-disciplinary or inter-disciplinary may also affect its rate of adoption, and the key factors affecting its adoption might be different for one another. To explore the same, cases for the research were selected considerately. While the first case, 3D BIM, is a successful diffusion, the Scripting & Programming and 5D BIM are intra-disciplinary and inter-disciplinary innovations respectively. The cases selected are briefly discussed below.

Case 1: 3D BIM- Successful Diffusion

The first case selected is three-dimensional Building Information Modelling (3D BIM). 3D BIM is an extension to the conventional CAD models with an additional Z-axis and information about the components. As such, 3D BIM allows collaboration between different disciplines, namely architectural, structural and MEP (Mechanical Electrical and Plumbing) within the same central model. Thus, 3D BIM models brings together all the information about all the components of the asset in one central model, allowing efficient and seamless collaboration and coordination between different disciplines.

3D BIM was selected as one of the cases as it is successfully diffused in the firm. As such, the intent was to study the diffusion process of 3D BIM in the firm and to explore how the then innovation moved from earlier adopters to the later adopters. The barriers involved and how these barriers were dealt with were analysed so that the best practices can be learned and re-applied to other diffusion processes.

Case 2: Scripting & Programming- Intra-disciplinary innovation

Programming and scripting languages that can automate and perform many technically intensive and repetitive tasks can provide valuable advantages for construction firms ((Miller, Hersberger, & Jones, 2013). Having personnel skilled at programming is a huge advantage for firms as they can use various programming languages for design calculations and process automations, thereby making processes more efficient and facilitating reuse of successful solutions instead of re-inventing the wheel every time (Sandberg, et al., 2016). This skill can then be utilized for various other applications as well, such as generative design, machine learning etc.

The motive for selecting this case for the analysis was twofold. First, W+B have initiated the diffusion process of this digital innovation and identified its adoption by the earlier adopters. This innovation is yet to diffuse into the later adopters and thus it is yet to 'cross the chasm' (Moore, 2014) between earlier adopters and later adopters. As such, it was an interesting case to analyse the 'chasm' in the context of W+B and what is restricting the diffusion of innovations from earlier adopters to later adopters. Second, modelling design calculation is an intra-disciplinary innovation; it does not require coordination or collaboration between different disciplines. Hence the analysis of this case gave insights into the diffusion characteristics of intra-disciplinary innovations, which is a question posed for this research.

Case 3: 5D BIM- Inter-disciplinary innovation

Five-dimensional Building Information Modelling involves the extension of 3D BIM model with functional characteristics in addition to the physical characteristics. As such, 5D BIM involves the modelling of project cost and schedule in addition to the standard spatial design parameters in 3D BIM ((Agarwal, Chandrasekaran, & Sridhar, 2015). This allows users to identify and assess the impact of changes in the design model on the project schedule and costs. As such, cost and schedule can be dynamically tracked and updated throughout the course of the project development, thus improving efficiency of construction management by allowing more control over the functional characteristics of the project.

5D BIM was selected for analysis as it is an inter-disciplinary innovation. BIM on itself is an inter-disciplinary innovation. 5D BIM extends the number of disciplines involved in the innovation. As such, close collaboration is required between the design, planning and cost estimation disciplines. In the context of the infrastructure sector of W+B, planning and cost estimations are handled by a separate PMC, the Construction Management PMC, while design is handled by four different PMCs, depending on the type of the design. Thus, different PMCs and disciplines must communicate and coordinate closely to pull off the successful diffusion of 5D BIM. Furthermore, W+B was already attempting to diffuse 5D BIM, but its adoption was not at a desired rate. Thus, it was an interesting case to study what factors are affecting the diffusion of inter-disciplinary innovations.

3.3.2. Research Method

As discussed earlier, a solution-oriented research design was adopted for this research. Solution oriented research begins with understanding the problem and then directly recommending solutions towards it. In this direction, this research was divided into three phases: (1) Preparation, (2) Case studies and (3) strategy development. Figure 8 illustrates a graphical representation of the research design. The research started with the *preparation phase* in which the focus was to first understand the problem context and then explore the theoretical background of the research problem and select an appropriate theoretical framework. For this, an extensive literature review was done. This phase acted as the foundation for the rest of the phases and to build up the whole research. Based on the theoretical foundation and results developed in phase 1, the research then moved into the crucial part of major data collection through three case studies in phase 2. The data gathered in phase 2 was then interpreted and recommendations were developed in the form of a strategic framework in the last phase.

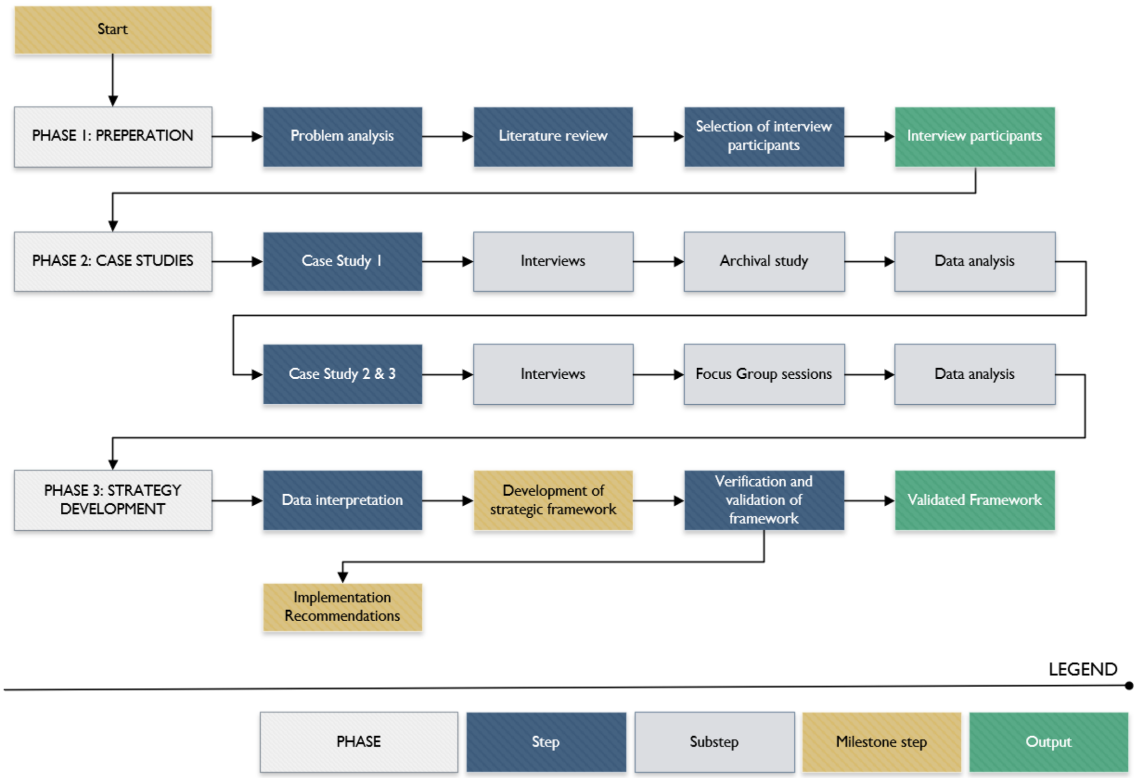

Figure 8 Research Method

Data Collection

After the preparation phase, the key data for this research was collected in the *Phase 2, Case Studies.* The focus of this phase was to explore the perceptions of the personnel towards the diffusion process, the key attributes of innovations enabling or restricting this process, and the role of diffusion networks in this process. As described in Section 3.4.1, three cases were selected for this purpose. Case 1, 3D BIM, was an already diffused innovation and hence the data collection was retrospective. As such, the approach for case 1 is different from case 2 and 3, the data collection of which was done simultaneously.

The focus on case 1 was to understand how 3D BIM was successfully diffused, what factors contributed to its diffusion and how was the factors restricting its diffusion were dealt with. For this purpose, the data collection included interviews with relevant personnel and an archival document study, as can be seen in Figure 8. The archival study was to understand the general motives behind the diffusion and progression of 3D BIM. It contributed to understanding the context within which digital innovations were diffused. It was backed by seven semi-structural, online face-to-face interviews with relevant personnel. Maximum attention was paid to achieve a good deal of diversity in the personnel interviewed, so that all angles of the problem area could be analysed. The personnel interviewed were carefully selected based on two considerations. One, their adopter categorization and two, their roles and responsibilities in the firm. Appendix E provides an overview of the interviewees who were part of the data collection.

Semi-structured interviews consist of key questions aimed at the data required for the problem being studied, but at the same time provides room for the interviewer or interviewee to diverge and explore more in depth out of the question area if required (Gill, Stewart, Treasure, & Chadwick, 2008). As such, it allows potential discovery of new information which might not have been previously considered by the researcher, thus opening rooms for deeper inputs (Gill, Stewart, Treasure, & Chadwick, 2008). The interviews for this research included two sections, the first one discussing the diffusion process and the second section discussing the individual's decision process. The Priori Constructs developed were used as an outline for the interview questions, with some additional questions such as *"what is 3D BIM?"* to explore the consistency of understanding about 3D BIM. The questionnaire used for the data collection interviews for Case 1 is provided in Appendix B. Using such semi-structured interviews helped the researcher to unearth innate barriers and/or enablers towards diffusion processes very characteristic of the firm, thereby contributing to the exploration of depths of the topic.

Data for Case 2 and 3 were collected simultaneously using mainly two data collection methods, semi-structured interviews, and focus groups, as is illustrated in Figure 8. The first part of the data collection included eight semi-structured online face-to-face interviews, selection of personnel for which followed the same criteria as explained for Case 1. Appendix E provides an overview of the interviewees who were part of the data collection for Case 2 and 3. As such, the interviews contributed towards collecting data concerned with how the diffusion process was perceived by the personnel, with respect to their adopter categorization and their roles and responsibilities within the firm. Again, the Priory Constructs were used as an outline and the interviews followed similar characteristics as explained for Case 1. The questionnaire used for the semi-structured interviews of case 2 and 3 can be found in Appendix C.

As can be seen in Figure 8, the data collection for Case 2 and 3 through interviews were followed by two Focus Group sessions. Focus Group is a qualitative data collection method in which a group discussion is organized on the problem area for research purposes, in which the discussion is facilitated, monitored, and recorded by the researcher (Gill, Stewart, Treasure, & Chadwick, 2008). Focus groups are particularly useful to identify information regarding collective views and enhance deeper understanding of the meanings behind those views by triggering discussions on participants experiences and perspectives (Gill, Stewart, Treasure, & Chadwick, 2008). Focus groups can provide depth and insights, much necessary for the research objective of this research as well, as it is important to have deeper insights regarding the low adoption rate of innovations in the firm. The focus groups also ensured data triangulation for this research, by focussing on non-elite individuals with daily responsibility in the firm. As such, the participants for each focus group were selected predominantly based on their innovativeness, roles and responsibilities, age, and their PMC, in order to ensure maximum diversity. The discussions were guided by three main topics developed based on the Priory Constructs, them being the attributes of innovation, type of innovation adoption decision and communication channels. The detailed plan of approach of the focus group sessions can be found in Appendix D and the overview of participants can be found in Appendix E.

Interview Participants

The participants for the interviews for all the cases in Phase 2 were carefully selected using two main criterions, the roles and responsibilities of the participant and their adopter categorization. To do the same, an online questionnaire contributed towards the identification of earlier and later adopters in the population. The questionnaire was sent out to the personnel of the firm to determine their innovativeness. The questionnaire and the subsequent categorization were based on Rogers DoI theory. The questionnaire used was the Individual Innovativeness (II) scale developed by Hurt et al., (1977), which consists of 20 questions, each with a 5-point Likert scale. As such, each question carried options (strongly agree to strongly disagree) for 5 points, making the total questionnaire comprise of questions for a 'score' of 100 points. Based on the respondents' total score out of 100, they were categorized into Earlier Adopters or Later Adopters. The questionnaire used and the categorization procedure can be found in Appendix A.

Based on the results of the categorization and the responsibility of individuals, appropriate participants were selected also in consultation with representatives from W+B. Following the definitions of Gledson et al., (2016), the responsibilities of personnel for this research were divided into three: (1) Strategic Responsibility (upper management), (2) Tactical Responsibility (middle management) and (3) Daily Responsibility (Day to day running). The corresponding role of the personnel with respect to the aforementioned responsibilities within the context of W+B is given in Table 1. Because of the project-based nature of the firm, the innovations are most often diffused in the project level rather than the organizational level. Being at the summit of the social system of projects, the project managers in the firm often have full authority to make the final decisions on matters of their projects. Thus, in the context of innovation diffusion in W+B, the strategic role is carried out by project managers, supported by tactical and daily responsibility personnel, as is shown in Table 1. Detailed overview of the participants, including their adopter categorization, responsibility, role, and PMC can be found in Appendix E.

Table 1 Responsibilities and corresponding roles within the context of W+B

Responsibility	Role
Strategic Responsibility	Project Managers
Tactical Responsibility	Line Managers, Group Leaders, PMC Leaders
Daily Responsibility	Designers, Structural Engineers, Cost Engineers etc

Data Analysis

The data gathered was analysed at the end of each case study. The analysis included two stages, (1) analysis of the diffusion process and (2) analysis of the factors affecting diffusion, corresponding to different responsibility and adopter categorization. For the semi-structured interviews and focus group sessions, the analysis method used was Abductive Reasoning. Abductive reasoning was selected for analysis to avoid the rigidity of deductive reasoning and the complexity of inductive reasoning. Abductive reasoning is advantageous to make room for irregular or surprising observations arising during the data analysis that does not fit in the existing theory, thus allowing the researcher to accommodate these observations in a new theory (Tavory & Timmermans , 2014). In the abductive approach, the developed theory is reasoned with the interview data like in deductive research, and the theory is updated using the relevant surprising observations from the data (Bamberger, 2018). Abductive reasoning is best suited for this research as the theory developed (priori constructs) are developed from marketing perspectives and it needs to be updated in order to accommodate the complex characteristics of the construction industry.

Strategy Development

Based on the theoretical foundation developed in phase 1 and extensive data collection in phase 2, recommendations were developed for the firm to improve their rate of adoption of digital innovations in a sustainable manner in the phase 3 *Strategy Development*. This step involved interpretation of the analysed data to arrive at relevant recommendations, as is illustrated in Figure 8. A strategic framework for digital innovation adoption was developed based on the results, which can act as a guide for the firms to improve their rate of adoption of digital innovations. The proposed framework was then validated using expert validation. The framework was evaluated by experts in the field and domain experts in the firm to determine if it can provide the desired results.

3.4. Quality Assessment

This section aims to discuss the strategies undertaken to ensure the quality of the research and its results. Careful considerations were made during the development of the research strategy to ensure the internal and external validity of the research. The very first point to stress here regarding the internal validity is concerned with data collection. Very often, innovation studies in construction tend to revolve around 'elite' individuals and data sources. An 'elite' individual is someone who holds positions of power or influence in the social system (Natow, 2020). In construction, elite individuals include mainly project managers and/or decision makers. As such, they can provide researchers with key information about the study area. However, the information that elites provide might be biased or inaccurate and the researcher must be aware of that (Natow, 2020). For the study area of this research, elite interviews are indubitably of extreme importance. However, to develop strategies intended at shaping the perceptions of the employees, gauging their perspectives are of equal importance as well. To do that, data triangulation was adopted for this research, illustrated in Figure 9.

Data triangulation refers to the use of multiple data sources or collection methods in qualitative research to develop a deeper understanding of the study area (Carter, Bryant-Lukosius, DiCenso, Blythe, & Neville, 2014). In research that involves elite interviews, triangulation is of particular importance in order to obtain the complete picture of the situation being investigated (Natow, 2020). To ensure data triangulation and thereby internal validity of this research, data source triangulation (multiple data sources) and method triangulation (multiple data collection methods) were adopted. For data source triangulation, employees interviewed were carefully selected after consultation with the supervisors, thereby ensuring that all sort of perspectives can be gauged. Thus, the research conducted both elite interviews and non-elite interviews within the firm, by also considering the individual's adopter categorization. In addition, multiple data collection methods were also adopted. Interviews, focus groups, and document analysis, even though were meant for different purposes, converged, and complemented each other, thereby reinforcing the data set. Triangulation also ensured the internal validity of the research by gauging all perspectives from different dimensions.

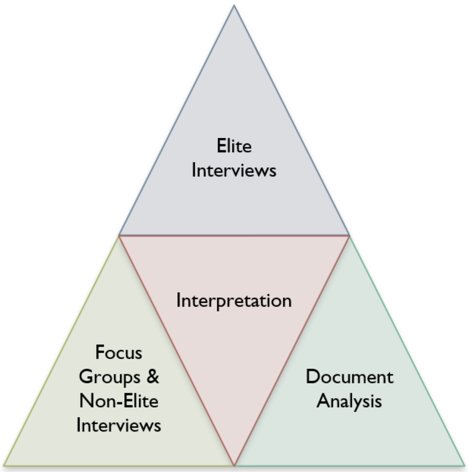

Figure 9 Internal validation through data triangulation for the research

Using the interpreted data, the goal was to develop a strategic framework to enhance digital innovation adoption. Thus, it was also essential to ensure the validity of the proposed strategic framework. To ensure the external validity of the research, the proposed framework was subjected to assessment by experts in the field and the experts in the firm. While expert in the field provided scientific validity for the framework, experts in the firm provided corporate validity for the proposed strategy. Based on the inputs from experts, sufficient changes were made to the framework to ensure that the results of this research have scientific validity and is of upmost quality so that firms can adopt the proposed framework for its intended purpose.

3.5. Overview of Research Design

The client for this research, W+B, wants to develop a strategy to enhance the adoption of innovations in the firm by investigating the factors which contributes to the adoption decisions with respect to the responsibilities of the personnel and their innovativeness, underlying reasons behind those factors, and the influence that their decisions will have on the rest of the network. After careful analysis of the research problem, research objective was defined. The research objective is *"to develop a strategic framework for enhancing digital innovation adoption, which can aid firms in construction to improve their rate of adoption of digital innovations in a sustainable manner".* An extensive literature review was then conducted to create a theoretical background for the research objective, using which two priori constructs were specified. Based on the defined constructs, main and sub research questions were formulated. The main research question is *"what factors affect the adoption of digital innovations in the firm as perceived by their personnel with respect to their innovativeness, and how can the rate of adoption be increased in a sustainable manner?".* To answer the research question, an explanatory case-study research approach with solution-oriented design was developed. To ensure the validity of the research, data triangulation was adopted.

4. FINDINGS

The results of the case studies are discussed in this section. As the aim of the research is to develop a strategic framework, the goal of the case studies is to assess the current situation in the firm. Thus, using the case studies, a general overview of the current process of diffusion and the factors affecting the diffusion process are defined.

4.1. The Current Innovation Diffusion Processes

This section explains the perceived innovation diffusion processes for the three cases analysed. The processes were analysed with respect to the Priori Construct B. The first case, 3D BIM, portrays the process of a completed diffusion in the firm and discusses how the (then) digital innovation was successfully routinized in the firm. Case 2 and 3, Scripting and 5D BIM, shows the current practices (and perceptions) of diffusion of intra and inter disciplinary innovations in the firm. While Scripting has been partially diffused in the firm, 5D BIM is at the very early stages of diffusion. Table 2 provides an overview of the progress of diffusion process, corresponding to the various stages as defined in Priory Construct B.

Table 2 Progress of diffusion of the three cases

No.	Process ↓ I Case →	3D BIM	Scripting	5D BIM
-	Consistent understanding	Yes	Yes	No
1(a)	Agenda Setting	Yes	Yes	In progress
1(b)	Matching	Partial	Partial	No
2(a)	Redefining/Restructuring	Yes	In progress	No
2(b)	Clarifying	Yes	No	No
2(c)	Routinizing	Yes	No	No

4.1.1. Case 1: 3D BIM- A Completed Diffusion

The diffusion process of 3D BIM in W+B started on a project level and then gradually over the years the innovation was routinized to the organization. Here, earlier adopters played the role of 'gatekeepers' and brought the awareness and knowledge about BIM from outside of the social system's boundaries. The early adopters used the success of BIM outside of the organization as triggers to implement the (then) innovation in the projects they were part of. Specifically, the most important role was played by a handful of project managers (strategic responsibility) and design leaders (tactical responsibility) personnel, who took the initiative and used their influential powers to implement 3D BIM in certain projects. One of them noted:

"What I felt the most important thing, and it's probably what you hear a lot from your colleagues too, […], is that to make a step you need a design manager or project manager to do this. Otherwise, it becomes complicated, so I enforced the use of 3D BIM even beyond the boundaries of our company in the project." (Strategic responsibility, Earlier Adopter)

The findings underline the existence and importance of *authority decision-making* in project level for the diffusion of 3D BIM. The two phases of innovation diffusion process were identified to happen on a project level in every project in which 3D BIM was implemented, with some steps disappearing or dissolving as the innovation moved closer towards routinizing. Each step of 3D BIM diffusion process is explained in the following sections.

1(a). Initiation Stage: Agenda Setting

The exact starting point of 3D BIM implementation is hard to pin down precisely as there were numerous scattered implementations across different projects, especially from 2007-2008.

However, the first project to completely adopt 3D BIM and the one which widely triggered the BIM diffusion across the firm, is a large infrastructure connection project in 2013. The interviews show that since that point, there has been a clear agenda setting in the projects across the firm towards the implementation of 3D BIM. The main triggering agenda was indeed the increasing complexity of the projects as clearly explained by tactical responsibility personnel:

"I think within many disciplines the main reason (to adopt 3D BIM) is that we work in more and bigger integral projects. So, with a lot of disciplines, we work together. And we have to finish in quite short times. We have to come up with an integrated design. Yeah, and BIM enables actually to work together, to understand every discipline and also look visually how it fits together. So, we can work efficiently to create a design together." (Tactical Responsibility, Earlier Adopter)

(We adopted 3D BIM) because we had complex projects with severe phasing steps. Actually the phasing was a big issue and we could make the model correct with all aspects with BIM. (Tactical Responsibility, Later Adopter)

The earlier later adopters, irrespective of their responsibilities, were found to share the same agenda towards 3D BIM, which is the integration of disciplines especially in complex projects, which in turn results in a more optimized design. It was complemented with the difficulties in information exchange and the complexities related to managing a single source of truth as noted by the respondents:

"The project (name) was my first large infrastructure project and I noticed how difficult it is to have everybody use the same or the latest data and how difficult it is to organize a good exchange of information between all the disciplines." (Strategic Responsibility, Later adopter)

"Especially in the role of project leader or design leader, I saw that there was a lot of miscommunication within the disciplines, and we started to work 3D and BIM." (Tactical Responsibility, Earlier Adopter)

1(b). Initiation Stage: Matching

There is no clear evidence in our data to prove the existence of an internal procedure to 'Match' 3D BIM with the agenda setting in the firm/projects. Matching is concerned with the feasibility of the selected innovation in solving the agenda. No evidence proves that the feasibility of 3D BIM for a project were assessed with respect to that project context and situation. This feasibility, in the case of earlier adopters, was assessed using success stories and information about 3D BIM from projects outside of the organizational boundaries. In one project, the project manager along with the design leaders chose to use 3D BIM because they saw that *"in England it was used for several big projects […]. So, we then started to implement BIM in the (our) project" (Strategic Responsibility, Earlier Adopter).* Unsurprisingly, the innovation in the case of later adopters was matched using success stories and information about 3D BIM from projects inside of the organizational boundaries, as noted by a team leader:

"I think (we decided to adopt) when it was used at our other projects and then we learn from it. Then based on that we thought it could be useful for us (in our projects) also." (Tactical Responsibility, Later Adopter)

When the diffusion slowed down, the early adopters moved with a clear analysis of what the firm have and what they need to develop and formed a group of BIM enthusiastic individuals to do the same. This 'matching' process was identified on an organizational level rather than project level. However, the formation of BIM group accelerated the diffusion of BIM in various projects across the organization.

"[...] we started as a group of specialists across the company who wants to bring it (BIM) further. We exchanged knowledge about it at points. But that in the end, it doesn't work too much because we had

to do a lot of development, I think 2013 indeed, something there, we were not able to develop and indicate everyone. So, it died a little bit or did not make big steps. Then we created like one BIM group, we started with another team leader, and there we made plans and were able to actually focus on really on BIM" (Tactical Responsibility, Early Adopter)

The two stages of initiation process, agenda setting and matching, were identified in every project, for different levels of the innovation. It is concerned with the fact that *"within 3D BIM there are different directions" (Tactical Responsibility, Earlier Adopter)* with the different applications of 3D BIM and the level of detail to which it will be developed and implemented within the project. It is at this stage in which the most important roadblock to 3D BIM implementation rose and dealt with, the involvement of external parties. In construction projects, being the engineering consultants, W+B is *"not alone as a company" (Strategic Responsibility, Earlier Adopter)* but are collaborating with several other firms (e.g., Contractors) and the client itself, all of whom have decision making authorities. Results show that such strong agenda setting, and matching analysis is required to convince the external parties about the adoption decision. Even though there was no internal procedure for matching the innovation with the agenda, the findings underline the importance of properly assessing the feasibility of the innovation in the project context for a smoother diffusion.

2(a). Implementation Stage: Redefining/Restructuring

Evidence from the interviews suggests that the innovation was customised in several scenarios to fit to the project needs, mainly through development *of "lots of different tools for different projects" (Tactical Responsibility, Earlier Adopter).* The BIM group indulged in extensive development of tools, which was crucial for an accelerated diffusion of 3D BIM. Such development was spearheaded by tactical responsibility personnel with the BIM group.

"(With the BIM Group) It was a lot of development there. There was also a lot of development in tools and automating scripts, so it was quite broad as well and the tools were used in projects." (Tactical Responsibility, Earlier adopter)

There is no evidence of the presence of any active organizational restructuring to accommodate 3D BIM. A slight restructuring can be attributed to the addition of the BIM group into the organizational structure. This however was rather passive than active. The BIM group was formed as an informal group of enthusiastic individuals, which with time was formalised in the organization to support the diffusion process.

In addition, strong restructuring is evident in the project processes to accommodate 3D BIM. Previously, the design process in the concept phase usually included just the project managers and design leaders/line managers (strategic and tactical responsibility personnel), and the concept developed is then translated to design by designers in later stages. With BIM, the designers are involved in the process from the very beginning, and the process itself starts with modelling and the models are used for further analysis and decisions. This need for restructuring was identified by the earlier adopters and was carried out in their respective projects.

"So, we changed the way of working. We said, OK, we put the Revit designer on the platform, he's on a higher level and we got to be quick, so senior structural engineers like myself, together with the (Revit) designer, we will start in the early stages of design along with the Revit designers" (Strategic Responsibility, Earlier Adopter)

The later adopters gauge this restructuring from projects in which 3D BIM is successfully diffused and replicated it in their projects, usually with the help of personnel who already have experience with 3D BIM in prior projects.

"Earlier the process was, (the) project leader thinks of an idea and the calculations (are) made and at the end of the process drawings (are) made. Now it's more, there's a problem and the designer, the BIM engineer, starts modelling, conceptual modelling, and out of the modelling and new ideas arise. So it's a very different approach." (Later Responsibility, Tactical Responsibility)

The results show that the redesigning/restructuring step was extremely important for the diffusion of 3D BIM in projects. The restructuring of the process continued in subsequent projects until the new structure became a routine, along with 3D BIM in the firm.

2(b). Implementation Stage: Clarifying

For 3D BIM, clarifying is identified more on the project level rather than the organizational level. In most cases, the relationships between the project and 3D BIM were reinforced after several iterations with the redesigning/restructuring stage, in which more tools were developed, and the (design) process was adjusted until the idea was clearer to the members of the social system of project and until the complexities of implementation were managed. One example of this is noted by a project manager:

"So, sometimes the scope change, and the software change […] BIM 360 came up and so on, so everything had to be done again. Also, organisations grow, so many people are added to contractors and then you have to make decisions on how to work together. The contractor has his way of designing, we have ours and our partner company had their way which was on a very parametric basis. However, we felt this parametrisation wasn't applicable because the tunnels were very complicated. If you have a standard cross section, you can easily do that, but the tunnels were very complicated. So, we felt you have to put too much effort into the parametrisation before you can really start designing. So, we then decided to change it again and agreed together on working the way of the contractor." (Strategic Responsibility, Earlier Adopter)

This has to do with the fact that 3D BIM, like most innovations in construction, does not have a certain fixed scope or applications. Also, as they were in a learning process during diffusion in this stage, they encounter many unanticipated issues, surprises, or sometimes further potentials. Thus, there need to be iterations to find the best fit for the project. The clarifying stage is also increasingly dependent on the external parties involved, as the idea of innovation becomes clearer, more concerns are raised about the same by the external parties, as noted by a respondent:

"(When you advance with 3D BIM) that's where problems start because in the early stages of the project, you're only doing the design. But later on, you get a contractor on board and there's another party coming in who has his own way of working. So, contractors in the meanwhile were also developing their BIM approach. There's a lot of debate and discussion going on within these companies. In fact, it was a contractor's consortium of eight or nine contractors. So, you can imagine they had their own debates and they still have and then you need to try to bring things together which became rather complicated." (Strategic Responsibility, Earlier Adopter)

The results suggest that the clarifying stage is one of the most difficult in the diffusion process. The key to unlocking this stage is indeed conversations and agreements, built on the basis of the results of a strong agenda setting and matching.

2(c) Implementation Stage: Routinizing

The interviews provided enough information to indicate that 3D BIM has been routinized and is a standard practice now in the company, especially when it comes to complex projects, as the most benefit of BIM lies there. The routinization is also very evident in the personnel's understanding of the concept of 3D BIM. However, the common opinion, especially within the earlier adopters is that the firm took a long time to routinize 3D BIM. This was related to some senior project manager's (strategic responsibility) lack of awareness of BIM on an organizational level. Even though they were convinced of the advantageous and uses of BIM, the implementation stumbled on roadblocks especially during the redesigning/restructuring and clarifying stage, as the project leaders did not possess enough awareness about how to set up BIM. This was clearly identified by one of the respondents:

"Project leaders may be convinced of the advantages if he (they) said OK, I want to do BIM. Then he (they) says to the project team, yeah, just arrange BIM model, but he (they) doesn't know himself (themselves) what is his (their) role in it or what he (they) has to arrange for the team. And then the design team say OK, I need this software, I need to this kind of appointments made with the client or with other parties who delivering information, and that's the role of the project leader (to arrange). […] the project leader thinks that design team can do everything, but he (they) has a role in there as well." (Tactical Responsibility, Earlier Adopter)

The routinizing process cannot be pinpointed to a *"certain moment in time" (Tactical Responsibility, Later Adopter)* but rather can be identified as a process over time (or over projects), during which the organization *"sort of grew into it (3D BIM)" (Tactical Responsibility, Later Adopter).*

4.1.2. Case 2: Scripting & Programming- A Half-Way-Through Diffusion

Scripting and Programming essentially take two directions in the firm: automation of repetitive tasks (such as documentation, report generation etc) and scripting for parametric modelling and modular design calculations. Although Scripting & Programming was termed as an intra-disciplinary innovation for the research, results from interviews show that when it comes to Scripting for modelling and design calculations, the innovation is rather inter-disciplinary in the sub system of projects, as noted by one of the respondents:

"It's not easy for these modular scripts because we mainly (work on) multidisciplinary projects with the same clients for different business units (and) we are really interdependent on each other. (Tactical Responsibility, Earlier Adopter)

A lot of PMCs have been using automation of repetitive tasks, with cost engineers leading the adoption. Most PMCs program several tasks they repeat over projects, such as model checks, generation of reports from database etc. Most of these are initiated by enthusiastic individuals, who, with their teammates try to automate *the "boring, tedious tasks" (Daily Responsibility, Earlier Adopter)* and thereby complete the work more efficiently with less errors. Results show the existence of *optional or collective decision making* in such cases, as is clear from the responses below.

"[…] basically, it was cost engineers like me trying to improve our work." (Tactical Responsibility, Earlier Adopter)

"(The decision) was by team or just by person who's good in scripting and then they think so I can make a script for this and then they make it and then other people look at it and then we all think well it's a good idea. Let's use it from now on. So that's not really from the top that they say you have to do that, but you know there are the opportunities are there." (Daily Responsibility, Later Adopter)

For the Scripting of modelling and design calculations however, even though the initial adoption decision is optional or collective, the final decision is always *authority decision* (by strategic responsibility). This is because scripting of designing is always (or most cases) associated with projects and hence any decision influences the whole project.

"It's (adopting scripting for modelling and design calculations) not a decision just up to me and my team, but we're dependent on what do the other teams (of different discipline) do as well with the same client and in the same project." (Tactical Responsibility, Earlier Adopter)

However, such decisions are strongly associated with collective or optional considerations of the innovation, as in almost all cases, individuals first create a sample of the script they want to use, and exhibit it to the project leaders, who then gets convinced of the results and make the decision to adopt it in the project.

"It's just all starting from our own ideas and then it's always good to have some certain what's called proven steps or let's say every minimal viable product as other things to show project leaders. Because then they see that it's already capable and you're capable of doing it. […] He (project leader) then makes a favourable decision." (Daily Responsibility, Earlier Adopter)

1(a). Initiation Stage: Agenda Setting

There were scattered agendas for the adoption of scripting in the early stages of diffusion but what really inspired the widespread awareness of scripting was the firm's 'innovation program', where innovative ideas of personnel are presented in a competition format. The automation of harbour quay wall design, presented in the program, inspired the whole firm to look into the possibilities of scripting in their own processes.

"The innovation program really made each other enthusiastic. I saw the automated quay wall design and I thought I knew a bit about programming and scripting and ICT issues, but I was with open eyes and excited about it, the way it was done with python. So of course, you can make each other enthusiastic about what is possible." (Tactical Responsibility, Earlier Adopter)

Since then, there existed a strong realisation that there are a lot of tasks that the PMCs can automate and that the scripting of designing is very efficient in specific cases. There is a very good awareness about the agenda behind scripting of both repetitive tasks and designing for both later and earlier adopters as can be seen from the responses below:

"(This new project) are about 200 kilometres of canal walls that has to be restored, and there we can make use of those scripting models because it's (the walls) all the time the same." (Strategic Responsibility, Earlier Adopter)

"Earlier we thought everything is different, each construction is different. But they are different, but within certain limits. And you can categorize say, type of constructions. They maybe a little bit shorter or longer, little bit higher, but the principle calculation scheme or load scheme will be the same. So, I think it's very good to script these kinds of things." (Strategic Responsibility, Later Adopter)

Another strong agenda when it comes to scripting of designing is the advantage of comparing the effect of several scenarios before a final design decision is made. Scripting allows the project team to *"calculate several scenarios"* even when *"some conditions are not known, (by) using a certain bandwidth", (Strategic Responsibility, Earlier Adopter)* which can save time in the design process. Hence it can be stated that scripting is past the agenda setting stage.

1(b). Initiation Stage: Matching

For intra-disciplinary scripting for automation, evidence suggest that a matching process is carried out by the individual (or the team) who make the decision to adopt it. They identify the opportunity, assess it and if feasible, implement it to a larger scale. During the matching stage, several criteria are assessed, including the time required to develop the script and the time available, the resources required and are available to them, and the opportunities for scaling up.

"My personal threshold to use it (scripting) or to make use of scripting or programming is if something is whether repetitive or not, whether we can apply it for multiple purposes or not." (Daily Responsibility, Earlier Adopter)

When it comes to the inter-disciplinary scripting, there are no evidence to prove the existence of a clear procedure to match the agenda and the innovation, and conclusion is usually drawn using examples from previous successful projects. Since every project context is different, sometimes the assessment is not entirely correct, leading to discontinuance of the innovation in that particular project.

"I felt quite positive in the beginning because it looked, yeah it (scripting) has potential. But later, I found out that if you start with scripting the calculations and it's also connected to the drawing models, that is still a little bit, Now, how do you call it? […] too difficult and maybe rough. So halfway the project we needed to do it the old-fashioned way and we had to do start again." (Strategic Responsibility, Earlier Adopter)

The above quote indicates the lack of a proper matching procedure which determines the feasibility of scripting in fulfilling the agenda in the project context. However, there are other projects in which scripting have been partially implemented successfully. Hence it can be stated that scripting is partially past the matching stage in the organizational context.

2(a) Implementation Stage: Redefining/Restructuring

For scripting and programming, implementing the innovation requires redesigning, as not all scripts can be used cross PMCs. Even though some make use of the scripts developed by other PMCs, this is not a usual scenario. Hence evidence of redefining the innovation is clearly visible for this case. This is the same for inter-disciplinary scripting for designing, there are both self-developed scripts and the use of scripts already developed in other projects. However, in most cases, the diffusion process tends to slow down at this stage in projects. During the redesigning stage, the time required to generate and validate scripts are often regarded as barrier for the diffusion, and it is often associated with the lack of awareness of feasibility, in terms of resources and time required.

"We later realised that we have (only a) limited number of people that can work with scripts. That is, that is a one of the main topics. So, we started with scripting in the project, we wanted to make some more speed and then we had a problem that we didn't have the personnel that can work with the scripts. […] and then we do not have time to finish that." (Strategic Responsibility, Earlier Adopter)

The results show that the innovation in most cases is presently in the redesigning/restructuring stage during the time of data collection. It can be identified from the various developments of scripts and programs across PMCs and in projects which is being carried out.

2(b) and 2(c) Implementation Stage: Clarifying and Routinizing

Since the innovation is not one single development but rather continuous, it is difficult to identify the extend of clarification. However, it can be seen that the (already) developed automation scripts are widely accepted by personnel of various PMCs, including later adopters.

"A colleague of mine designed a program (to automate a certain task) […] so that everybody can now use it. I myself and my colleagues make use of it now." (Daily Responsibility, Later Adopter)

In projects, partial implementation of scripting of design calculations are seen to be successfully clarified in many cases, an example is given below.

"We also just did a project where we had to calculate road capacities and we have to do that for 10-15 locations. So we scripted calculations so we do not didn't have to do with 15 times but just once." (Daily Responsibility, Later Adopter)

In both cases, there is a strong will to exploit the opportunities presented by scripting, shared mostly by strategic responsibility personnel. As discussed before, barriers are encountered mainly in the redefining/restructuring stage, because of which the attempts of diffusion are mostly discontinued. This has hindered the routinizing of the innovation in the firm. Results shows that when it comes to scaling up the adoption of scripting, *"constant issues are with respect to knowledge" (Tactical Responsibility, Earlier Adopter)*. The limited resources also means that the teams have to first assess what should be done and where they should focus, as noted by a respondent.

"I think that everyone is getting the awareness (about the possibilities of automation) throughout the whole company. Then the next roadblock is that you have to determine where to start. Because you have limited resources to automate, you cannot do everything, so you have to start with the most helpful thing. Most times, we don't know where to start. (Tactical Responsibility, Earlier Adopter)

Another reason for the lack of routinizing is the lack of resources to scale up the generation of scripts. Even though there is no significant resistance in making use of the generated scripts, not everyone is capable of and enthusiastic about taking up the skills to generate scripts themselves, the reason for which will be discussed in the later sections.

4.1.3. Case 3: 5D BIM- Early Stages of Diffusion

The result from the interviews indicates that *"5D BIM is seldom used in W+B" (Daily Responsibility, Earlier Adopter).* There is a lack of consistent awareness about the innovation, with more than half of the respondents not having a clear and concise answer to the question "What is 5D BIM?". 5D BIM is rarely or never used in the firm and questions are raised about both the agenda and the feasibility of the innovation in the project context. This has to do with the fact that W+B, being an engineering consultancy, does not always have the complete planning or budgeting in their scope, which constitutes the 4^{th} and 5^{th} dimension of BIM. Usually in projects, W+B only must develop a rough estimate of a project, for which 5D BIM is not relevant. Again, in the cases where cost estimation is included in the scope, in order to implement 5D BIM to a larger extend, the cost information have to be shared between the construction contractor and engineering consultants. This is always difficult as the construction contractors does not share their cost information, which is their competitive advantage.

"[…] the contractor is responsible for the money and it's not connected to the design teams, but that's also because the contractor doesn't want to share the information about the cost level. Because it's a competition." (Strategic Responsibility, Earlier Adopter)

Initiation Stage: 1(a) Agenda setting and 1(b) Matching

In the context of an engineering consultancy like W+B, the aspect of 5D BIM is more related to key quantities instead of actually having cost elements in the model according to a respondent.

"We should be careful with using the word cost because it is not our scope. We should use the word key quantities." (Strategic Responsibility, Earlier Adopter)

The focus is now more on integrating designing and cost estimation. That is, instead of cost estimators deriving quantities from drawings, these quantities can now be extracted from the BIM models of the design. Hence, the diffusion process of 5D BIM can be identified still to be in the Agenda Setting stage, and the personnel are still not convinced of the opportunities provided by 5D BIM. However, the second aspect, integration of designing and cost estimation, have gathered pace in recent years.

"The closest to 5D BIM is that we extract some quantity take offs from the models and give to the cost estimator at the end but still like very separated processes too" (Daily Responsibility, Earlier Adopter)

Implementation stage: 2(a) Redefining/Restructuring

The remaining stages of diffusion process are not identified at the time of data collection. In some cases, the integration of designing and cost estimation have showed a proper agenda setting and matching but failing to proceed due to a need of restructuring of the process.

"Currently, it's (designing and cost estimation) completely separate processes, like the planners don't talk with the designers or the cost estimation don't talk with the design and also the way around. So, like we have the BIM people working like in their things the planning and cost people working in their things, not communicating at all. There's no integration, and when you talk about the other dimensions of BIM, this integration of disciplines is very important." (Daily Responsibility, Earlier Adopter)

This need of restructuring of the process is strongly gauged throughout the company and the lack of restructuring has to do with incomplete or inconsistent agenda setting and matching in the initiation process.

4.2. Factors Affecting the Rate of Adoption

In this section of the interview, the focus was on the factors which affect the adoption decisions of the individual with respect to the Priori Construct A. Two most important stages of the individual decision process were focussed during the interviews, the knowledge stage and the persuasion stage. The three main elements within the knowledge stage which we explored during the interviews were (1) the individual's motivation to study or know about the innovation, (2) the type of source from which they received most information from (either cosmopolite- outside of organizational boundaries or local- within organizational boundaries), and (3) the communication channels through which they received information from. For the persuasion stage, the attributes of innovation for each case, and how it affected their decision making were analysed. The results of the analysis can be seen in Table 3. A 'Positive' influence means that the specific attribute positively influenced the personnel's decision making, 'Neutral' influence indicates that the specific attribute did not play a noticeable role in the individual's decision making, and a 'Negative' influence means that the specific attribute negatively influenced the personnel's decision making. All these findings are segregated for earlier and later adopters within strategic, tactical, and daily responsibility.

4.2.1. The Knowledge Stage

When discussing the knowledge stage, the respondents showed good awareness of both 3D BIM and Scripting, but the awareness about 5D BIM was generally very low. Perhaps because of this, the responses for the case of 5D BIM in the knowledge stage were minimal.

For tactical responsibility and daily responsibility, the responses for the knowledge stage were similar for both earlier and later adopters as can be seen in Table 3. Earlier adopters of both responsibilities were motivated by their *self-interest and curiosity* towards 3D BIM and Scripting to learn about the possibilities of and to study about the (then) innovations. Later adopters learned about 3D BIM and (some of them) about Scripting because of *peer pressure*.

"One time you get the project and then it is used and then you're involved with it. That's not really a decision, you follow the decision of team." (Daily Responsibility, Later Adopter)

Table 3 indicates that while earlier adopters of tactical and daily responsibility used *cosmopolite sources and mass media channels* to seek information about 3D BIM and Scripting, later adopters preferred *local sources and interpersonal channels*. There are also evidences of some later adopters using local mass media channels, such as instruction manuals, to learn about 3D BIM. For Scripting however, this part of information seeking for later adopters is more concerned with how to use the developed scripts or programs rather than how to develops the scripts or programs themselves. Almost all the later adopters and many earlier adopters did not have the knowledge about developing scripts themselves, and this is related to the attributes of innovation explained in the following paragraphs. The personnel who had responses for questions on information about 5D BIM had similar answers for motivation, source, and channel.

Table 3 Factors affecting the diffusion process

Case	Responsibility →	Strategic Responsibility		Tactical Responsibility		Daily Responsibility	
	Factors ↓ I Innovativeness →	EA	LA	EA	LA	EA	LA
3D BIM	Knowledge:						
	Motivation to study	Project needs/ Self interest	Peer pressure	Self interest	Peer pressure	Self interest	Peer pressure
	Information source type	Cosmopolite	Local	Cosmopolite	Local	Cosmopolite	Local
	Information channel	Mass media	Interpersonal	Mass media	Interpersonal	Mass media	Mass media/ Interpersonal
	Persuasion (Attributes):						
	Relative advantage	Positive	Positive	Positive	Positive	Positive	Positive
	Compatibility	Neutral	Negative	Neutral	Negative	Neutral	Negative
	Complexity	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Observability	Positive	Positive	Positive	Positive	Positive	Positive
	Trialability	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
5D BIM	Knowledge:						
	Motivation to study	NA	NA	Self interest	NA	Self interest	NA
	Information source type	NA	NA	Cosmopolite	NA	Cosmopolite	NA
	Information channel	NA	NA	Mass media	NA	Mass Media	NA
	Persuasion (Attributes):						
	Relative advantage	Negative	Negative	Negative	Negative	Positive	Positive
	Compatibility	Negative	Negative	Neutral	Neutral	Negative	Negative
	Complexity	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Observability	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Trialability	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
SCRIP-TING	Knowledge:						
	Motivation to study	Project needs/ Peer pressure	Peer pressure	Self interest	Peer pressure	Self interest	NA
	Information source type	Local	Local	Cosmopolite	Local	Cosmopolite	Local
	Information channel	Interpersonal	Interpersonal	Mass media	Interpersonal	Mass media	Interpersonal
	Persuasion (Attributes):						
	Relative advantage	Positive	Positive	Positive	Positive	Positive	Positive
	Compatibility	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Complexity	Neutral	Neutral	Neutral	Neutral	Neutral/Negative	Negative
	Affinity	Neutral	Neutral	Positive	Positive	Negative	Negative
	Observability	Positive	Positive	Positive	Positive	Positive	Positive
	Trialability	Negative	Negative	Positive	Positive	Positive	Neutral

The responses of strategic responsibility personnel did not follow a similar pattern. Their responses tend to be concerned more about their responsibilities than their innovativeness trait. Table 3 indicates that their motivation to learn about both 3D BIM and Scripting has been either the *project needs or peer pressure*, specifically from tactical responsibility peers. However, once they are aware of the possibilities, strategic responsibility followed the same trend as tactical and daily responsibilities. Earlier adopters used *cosmopolite sources and* *mass media channels* to dig deeper into 3D BIM, while later adopters preferred *local sources and interpersonal channels*. For scripting however, strategic responsibility earlier and later adopters tend to focus on the how to facilitate scripting rather than how to create scripts on their own. This is however justifiable given their role in the diffusion process, which in the words of a respondent is to *"create an environment and facilitate the diffusion".* (Strategic Responsibility, Earlier Adopter)

For strategic responsibility, it was noted that persuasion stage tends to dominate over the knowledge stage and not vice versa as it is for both tactical and daily responsibility. Since they are more concerned with the how to facilitate rather than how to use the innovations, they prefer to first be persuaded about the innovations and then learn about it. This is clear from the quotes of a strategic responsibility respondent given below.

"I'm not an early adopter, as being the BIM user myself. But what I felt the most important thing is that […], in order to make a push in innovation, you need a design manager or project manager to step up and create the environment for it and facilitate it. I make (that) possible if these guys convince me that this is the best solution. In that regard, I'm an early adopter." (Strategic Responsibility, Earlier Adopter)

4.2.2. The Persuasion Stage

3D BIM

Table 3 indicates that for all categories in the case of 3D BIM, *Relative Advantag*e played a positive role in persuading the individuals to adopt the innovation. The advantages of 3D BIM with respect to what it was superseding was very clear to the individuals, hence acting as a major factor motivating them to adopt it. *Compatibility* however, played a neutral role for earlier adopters and a negative role for later adopters of all responsibilities. Respondents indicated that this compatibility issue demotivated the adoption in the early stages. However, the development of BIM resources (tools, instructions), restructuring of the processes, and the understanding of relative advantage of 3D BIM eventually led to the individuals gradually adopting the innovation. *Complexity* of 3D BIM also played a neutral role for all respondents as everyone considered the basic concepts of 3D BIM easy to understand. As relative advantage, another important attribute as mentioned by the respondents is *Observability*. The respondents of all categories had a positive impact from the observable results of 3D BIM, both from within and beyond the boundaries of the project sub-system.

As for *Trialability*, most of the respondents indicated that trialability attribute did not play a big role in the adoption decisions. Rather than having an opportunity to 'trial' the innovation, the respondents preferred taking 'small steps' in projects. As discussed earlier, since 3D BIM is not a definite innovation and since its level of detail depends on the project, the respondents preferred to take smaller steps and built upon it project by project, based on the needs and requirements of that specific project. 3D BIM have different trajectories and selection of those trajectories depended on the agenda setting of that specific project, usually building upon what has already been adopted and clarified in a previous project.

"(Introduction of 3D BIM) it was not like Pilot project, we did it just in a first project at a more basic level maybe. What I was sure of that it was working. […] In the next project we use this (what we previously adopted) and something else. So, every project you can make new step." (Tactical Responsibility, Earlier Adopter)

The *Trialability* is however important for the developers of BIM tools as for them it is crucial to validate the results before introducing it to the project context. As such, the earlier adopters mentioned that trialability is very important to validate the outputs, whereas later adopters did not consider trialability as crucial in shaping their adoption decisions because the outputs were already validated by earlier adopters in prior projects. Taking small steps in projects as mentioned earlier was important because of the same aspect, as smaller steps means requiring lesser time in projects to validate the outputs of 3D BIM aspects.

Scripting

Table 3 indicates that the *Relative Advantage* and *Observability* of scripting played a positive role in the shaping the attitude towards the innovation for all respondents, irrespective of their category. *Compatibility* however, played a neutral role in the case of Scripting for all categories, The most important attribute for the case of scripting as mentioned by the respondents is the *Complexity*. Here, the interesting part is that the strategic responsibility and tactical responsibility personnel who did not have the know-how of Scripting, irrespective of their adopter category, indicated that the level of understanding they would prefer to acquire is to understand how to facilitate the adoption and use of Scripting and not how to make scripts themselves. This, and the negatively influencing complexities for daily responsibility earlier and later adopters, have to deal with a new attribute, *Affinity*.

Affinity is concerned with an individual's liking or disliking of the expertise required to use the innovation. For Scripting, the individuals are required to learn programming languages. This is very different from the profile of civil engineers and most of them must start from zero when they have to take themselves to a good level in order to do Scripting on their own. If the field of expertise is not interesting to the individual, even earlier adopters find it hard to acquire the skill, as it is very different from their profile. For Scripting, respondents indicated that the complexity is very much related to their affinity towards programming. Those who knows programming seems to have a positive affinity towards it and those who do not wish to acquire the skill seem to have a negative affinity towards it, irrespective of their adopter categorization. Hence, affinity can be considered as a new attribute, closely in relation with the complexity of the innovation. The responses below illustrate this:

"I think it (scripting) is complex. It depends on the profile of the people of course. If you talk to more technical people like people that like the designers who have more technical experience, maybe they don't find it difficult, but if you hold more on the management side, the curve of knowledge of scripting goes down. (Daily Responsibility, Earlier Adopter)"

"I used to take computer programming at school, it was my worst subject. I had computer programming at university for two years. And it was my worst subject. I was able to do any all the engineering stuff but programming I'm not good at it. […] It will cost me three times as long as someone else to do it. That's basically the math behind it, and the cost value perspective that someone else can do it better." (Daily Responsibility, Earlier Adopter)

The *Trialability* of Scripting played a positive role in the adoption decision of tactical and daily responsibility personnel (Neutral for individuals without the skill). Trialability however, played a negative role for strategic responsibility individuals, because *"it takes a long time to test and validate scripts and in projects we are in limited time frame" (Strategic Responsibility, Earlier Adopter).*

5D BIM

For the persuasion of 5D BIM, both earlier and later adopters with strategic and tactical responsibilities indicated that *Relative Advantage* played a negative role in their adoption decisions. This was also strongly related to *Compatibility*, as the respondents indicated that the relative advantage and the benefits does not overweigh the relative disadvantages and compatibility issues of 5D BIM. Because of this, the strategic and tactical responsibility individuals are not concerned about the rest of the attributes, and indicated that *Complexity*, *Observability* and *Trialability* played a neutral role in the adoption decision.

"At this moment the advantages are not worth the risk, no it isn't. But I expect in the future it will, and it's one of the main things that drives us to try and make the idea more clear" (Tactical Responsibility, Earlier Adopter)

As Table 3 indicates, the daily responsibility personnel however, seems to be motivated by the *Relative Advantage* of 5D BIM. At their role and level of responsibilities, the advantages of 5D BIM are playing a positive role in shaping their decision. However, they agree that with the current way of working, they cannot integrate 5D BIM into their processes, hence indicating that *Compatibility* played (or is playing) a negative role in shaping their attitude towards the innovation. The earlier adopters with daily responsibility call for a restructuring of the process, specifically more integration between the designing and cost estimation processes, for a smoother diffusion of 5D BIM.

4.3. The Role of Diffusion Networks

Data from interviews shows that the interpersonal networks within and beyond the boundaries of the social system and sub-systems played an important role in the diffusion of 3D BIM and in enhancing the awareness of other innovations in general. The responses below clearly indicate this.

"Yeah, I think it's (interpersonal networks) quite important, especially within Witteveen+Bos. But also outside actually. Yeah, and it (had) different roles" (Tactical Responsibility, Earlier Adopter)

"I think it's (interpersonal networks) very important. Especially like I said before, I rely heavily on information that comes to me via discussions with colleagues." (Strategic Responsibility, Later Adopter)

The interpersonal networks are *"important to share knowledge" (Daily Responsibility, Earlier Adopter)* and for resource investigation and sharing as noted by Tactical Responsibility respondents:

"[…] in my role as team leader, it helps as well that people ask me for help and then I say OK, I'm myself I'm too busy but I have some teammates that can help. So, then you are able grow the use of BIM that way." (Tactical Responsibility, Earlier Adopter)

"So, through these (interpersonal) networks, you have more references, and you have better knowledge of available expertise and resources." (Tactical Responsibility, Later Adopter)

While later adopters tend to rely on internal interpersonal networks, earlier adopters also value their external interpersonal networks. Earlier adopters noted that external interpersonal networks have *"a lot of roles, because I (they) have a lot of people also outside of W+B who I (they) can approach" (Daily Responsibility, Earlier Adopter).*

"External(ly), I'm also discussing these topics with my clients and also with their innovation managers, and other institutions sometimes. […] These are fresh perspectives which helps." (Strategic Responsibility, Earlier Adopter)

4.3.1. Heterophily in Interpersonal Networks

Earlier and later adopters indicated alike that heterophily (in terms of disciplines or PMCs) in their interpersonal and diffusion networks helps to make each other enthusiastic and open ways for new ideas which is very helpful for their own disciplines.

"When you have these different disciplines yeah, you can make each other enthusiastic. […] You make each other you know, (make aware of) what is possible and what can be achieved and what can we do together." (Tactical Responsibility, Earlier Adopter)

"There is always a combination of ideas that works for another part (discipline) and can be sometimes translated to another (discipline), and it also the way they're thinking and how they're thinking, and that helps tremendously. So having connections with the many PMCs and their tech people is yeah, helpful." (Tactical Responsibility, Later Adopter)

At the same time, some earlier adopters with daily responsibility share the view that the level of heterophily in their networks is not good and that there is much more to gain by expanding and exploiting the heterophily in their networks.

"I think it's still too small the multidisciplinary part of the network because if I listen to (a technology issue) I'm like why are we not working on that already between the road designers and structural engineers." (Daily Responsibility, Earlier Adopter)

"I think in our intra discipline the connection is fine. It can also be better. For interdisciplinary, I think there's so much more to gain." (Daily Responsibility, Earlier Adopter)

4.3.2. Opinion Leaders

Respondents indicated that they think opinion leaders *"play an important role" (Strategic Responsibility, Later Adopter)* in the diffusion of innovations *"because they are often (the) people (who) are very enthusiastic about something" (Strategic Responsibility, Later Adopter)* in such a way that they *"can make others enthusiastic" (Strategic Responsibility, Earlier Adopter)* as well. Respondents indicated that they *"can think of a couple of persons who were front runners say of BIM and that helped a lot in later on projects" (Tactical Responsibility, Earlier Adopter).* At the same time, there has also been sceptical opinion leaders who negatively influenced the adoption decisions. While earlier adopters mentioned that how they get influenced by the sceptical opinion leaders *"also depends a little bit on yourself (themselves)" (Tactical Responsibility, Earlier Adopter),* some later adopters *"opted against the use of BIM, because we (they) relied mostly on the advice of the technical manager, saying that if we (they) just use the other (conventional) platform, we'd (they will) be able to deliver the promised quality anyway" (Strategic Responsibility, Later Adopter)*.

One respondent indicated that the company should *"give them (opinion leaders) the opportunity and the space to really dive into it (the innovations) and see what it can mean for (the) company" (Strategic Responsibility, Later Adopter),* thereby also *"take(ing) everyone else along in the bus" (Strategic Responsibility, Earlier Adopter).*

4.3.3. Internal Companions

Earlier adopter daily responsibility personnel indicated the importance of Internal Companions to motivate them and to help each other to search for and develop innovations. This was mainly seen for the case of Scripting, where individuals pushed and motivated each other to develop scripts and programs, which they later promoted to their line managers. The following quote nicely shows how innovation could be developed by an individual with their internal companion.

"You always find a counterpart in your company to challenge each other and to say, hey, this is nice, and it then always starts as a joke. Then from the joke part you take off and develop it to a pretty good example product. (For instance) We did the driving simulator and it all started as a joke because we modelled in 3D (and we thought) it would also be nice if we can play a game in our own 3D model. So, let's play, let's make a first-person shooter. And so now OK, but we can also make a driving simulator so I can drive on my own highway, which I still need to design. And so, we then played around with

some tutorials and some sources, and we developed (the simulator). We thought, hey, that's nice. Then we showed it to our project leader, and he says this is useful, lets develop it further." (Daily Responsibility, Earlier Adopter)

4.4. Progress of Innovations

The diffusion of innovations in the firm progressed as a result of combinations of the diffusion process and the factors which affected the diffusion as discussed in the previous two sections. This section provides a general overview of how this progress happened over time for all three cases. The section also gives an overview of the important barriers of the diffusion processes for the three cases.

4.4.1. Progress of 3D BIM

Figure 10 shows a graphical representation of the diffusion process of 3D BIM in the firm. The diffusion process of 3D BIM started with the *agenda setting* stage, which itself was triggered by the awareness of opportunities provided by technological advancements within and beyond the boundaries of the social system. Thus, the awareness of BIM from either external or internal projects, for earlier adopters or later adopters respectively, triggered agenda setting, which was then followed by the *matching* stage in some cases. However, in most cases, a proper feasibility analysis of 3D BIM in the project context is not visible and hence the *matching* stage was in most cases not complete. The strategic responsibility personnel (project manager) and tactical responsibility personnel (team leaders/line managers) took initiatives and pushed the implementation of the (then) innovation by convincing the clients and external parties about the *relative advantage* of 3D BIM within the project contexts.

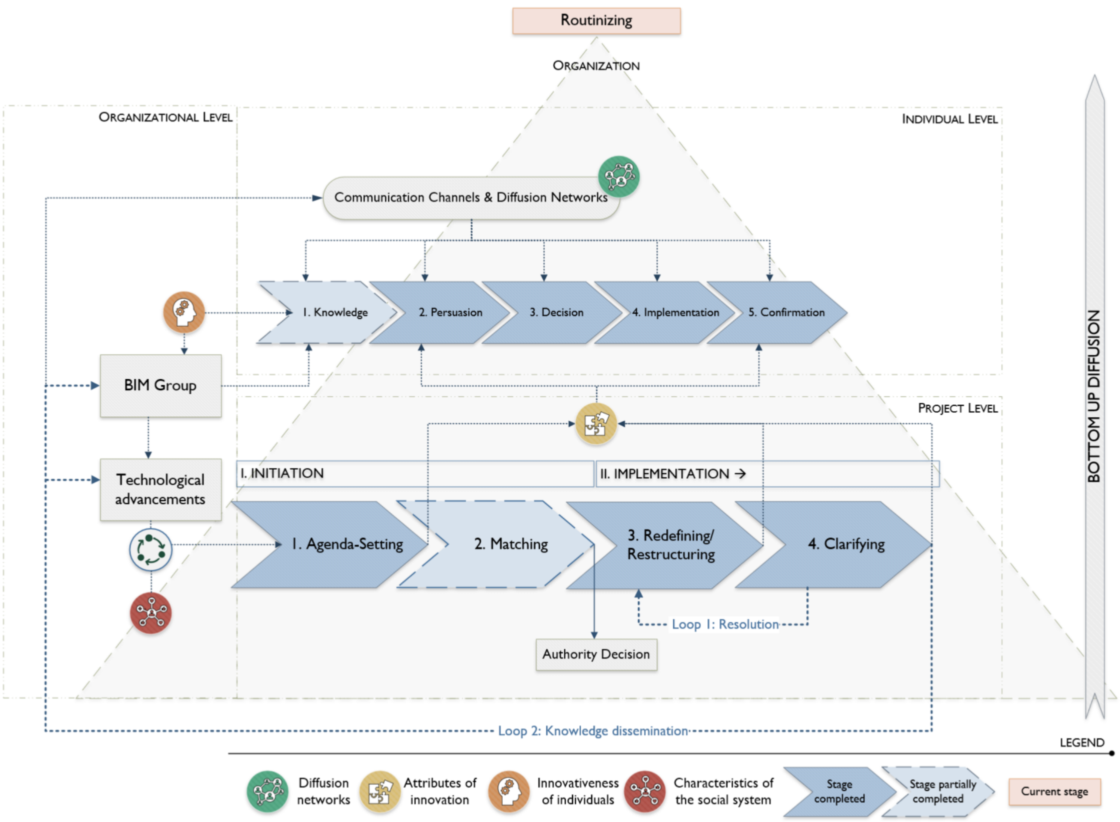

Figure 10 Diffusion Process of Case 1 3D BIM

The content of agenda setting, and matching varies from project to project, depending on the various directions, applications, and level of detail of 3D BIM. Results show that, at this stage the personnel of the firm were clear of the *relative advantage* of 3D BIM and the earlier adopters pushed for its diffusion, claiming that the advantages are bigger than the disadvantages poised by the *compatibility* and *complexity* attributes of the (then) innovation. To gather knowledge and information about 3D BIM, *earlier adopters* sought information from *cosmopolite sources* and *mass media channels*, which was then conveyed to the *later adopters* through *local sources* and *interpersonal channels*.

In some cases, necessary requirements to implement 3D BIM were identified and arranged within and beyond boundaries of the project during the *matching* stage. The most support at this stage came from an *interdisciplinary BIM group*, in which lots of developments of tools, protocols, object libraries, templates and instructions took place. This overlapped with the *redefining/restructuring* stage in the implementation process, during which developments of BIM tools (within and beyond project boundaries) and restructuring of design process (within project boundaries) took place in order to meet the specific project needs. Because of these stages, some barriers poised by *daily responsibility* and *(most) tactical responsibility later adopters* regarding *compatibility* and *complexity* attributes of the innovation were eased and they started using 3D BIM, which was also influenced by peer pressure. *Strategic responsibility (project managers) later adopters* were then also influenced by peers (especially *tactical responsibility (line managers) earlier adopters*) after some successful implementations of 3D BIM in projects across the firm.

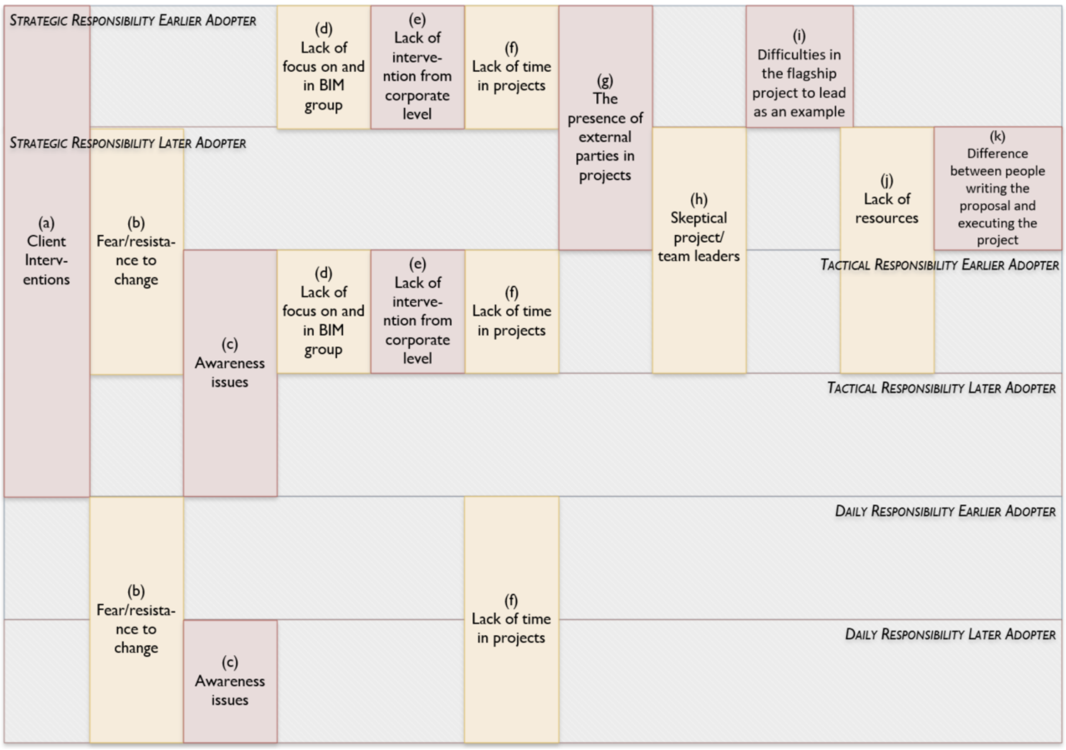

Figure 11 Barriers of 3D BIM diffusion

The redefined 3D BIM and restructured process went through the *clarification stage* in the projects, during which further redefining/restructuring had to be done, especially because of the involvement of external parties such as contractors or clients. For instance, during the diffusion of 3D BIM in the first project, conversations were held with the contractors and details about the innovations were agreed on, which took time but at the same time reduced roadblocks in the later stages. Support and increased enthusiasm from the clients, even though came to action a bit later in the process, were crucial for successful clarification of 3D BIM in several projects. Based on the agreements made up on clarification, 3D BIM, in some cases, had to go through another iteration of redefining/restructuring. An example for this is the change in software package one of the projects had to undergo because of new agreements with the external parties and the clients during the clarifying stage. In addition, during clarification stage, when (different elements of) 3D BIM was put into more and more usage, the members of the social system started to clearly observe the results (*observability attribute*), hence getting more convinced about the idea of the innovation.

Table 4 Resolution of barriers of 3D BIM

Barriers during diffusion	*Stages*	*Resolutions*
a) Client interventions	Matching, Clarifying	i) Initiative and push from strategic responsibility
		ii) Extended support and interest from clients after gauging the benefits
b) Fear/resistance to change	Redefining/Restructuring, Clarifying	iii) Creating an environment for implementation of innovation (by Strategic & Tactical Responsibility)
		iv) Helping each other to learn and use 3D BIM
		v) Extended awareness of 3D BIM in the firm
c) Awareness issues	Agenda setting, Matching, Routinizing	vi) Knowledge dissemination in the firm using knowledge gained from projects and advertising the success stories
		iv) Helping each other to learn and use 3D BIM
		viii) Availability of resources like introductions, instruction manuals
		ix) Presence of an interdisciplinary BIM group for knowledge dissemination and BIM resource development
d) Lack of focus on and in BIM group	Redefining/Restructuring	x) Restructuring of BIM group and redefining BIM diffusion strategy
e) Lack of intervention from corporate level	Routinizing	xii) Extended support and appreciation from the board after successful implementations
f) Lack of time in projects	Redefining/Restructuring, Clarifying	ix) Presence of an interdisciplinary BIM group for knowledge dissemination and BIM resource development
g) The presence of external parties in projects	Matching, Clarifying	i) Initiative and push from strategic responsibility
		xiii) Having conversations and making agreements on (certain) terms with the external parties
h) Sceptical project/team leaders	Agenda setting, Routinizing	xiv) Initiative and push from tactical responsibility
		xv) Advertising successful implementation in projects throughout the firm
		v) Extended awareness of 3D BIM in the firm
i) Difficulties in the flagship project to lead as an example	Routinizing	(No direct resolutions)
j) Lack of resources	Redefining/Restructuring, Clarifying, Routinizing	xvi) Acquisition of skills and expertise
		iv) Helping each other to learn and use 3D BIM
		ix) Presence of an interdisciplinary BIM group for knowledge dissemination and BIM resource development
k) Difference between people writing the proposal and executing the project	Matching	v) Extended awareness of 3D BIM in the firm
		xii) Extended support and appreciation from the board after successful implementations

Iteration of all these stages across different projects resulted in the *routinization* of 3D BIM within the organization. This can be identified with the consistent understanding about 3D BIM, a clear understanding of the agenda setting behind the adoption decisions, lack of resistance towards the implementation of 3D BIM and the loss of perception of 3D BIM as a 'new' idea towards a standard procedure. Figure 11 illustrates the key barriers faced during the diffusion of 3D BIM, plotted against different adopter categories of different responsibilities. Table 4 explains the stage(s) in which these challenges affected the most and how they were dealt with according to the respondents of the interviews. Detailed data analysis can be found in Appendix F.

The diffusion process of 3D BIM can be generalised as a partial success formula for an innovation implementation in the firm. Although the process could have been faster, the slow pace was because of the lack of understanding of the process itself and a failure of recognizing which stage of implementation the organization is in. Moreover, a more corporate approach towards the diffusion process was deemed necessary by the respondents, especially earlier adopters, to accelerate the diffusion process. Even though a bottom-up structure for diffusion of 3D BIM was perceived as the best approach, respondents identified the lack of a top-down support in terms of resource allocation and tools development to reinforce the bottom-up diffusion as a reason for the slow pace of diffusion.

4.4.2. Progress of Scripting

Even though scripting was termed as an intra-disciplinary innovation, results shows that the innovation essentially takes two directions in the firm: *automation of repetitive tasks at PMC level (intra-disciplinary)* and *scripting for modelling and modular design calculations at project level (inter-disciplinary)*. Again, enthusiastic earlier adopters, specifically of tactical and daily responsibility, played the role of 'gatekeepers' of the innovation by bringing the awareness about the innovation from outside of the social system boundaries. Figure 12 illustrates the diffusion process and progress of scripting & programming in the firm.

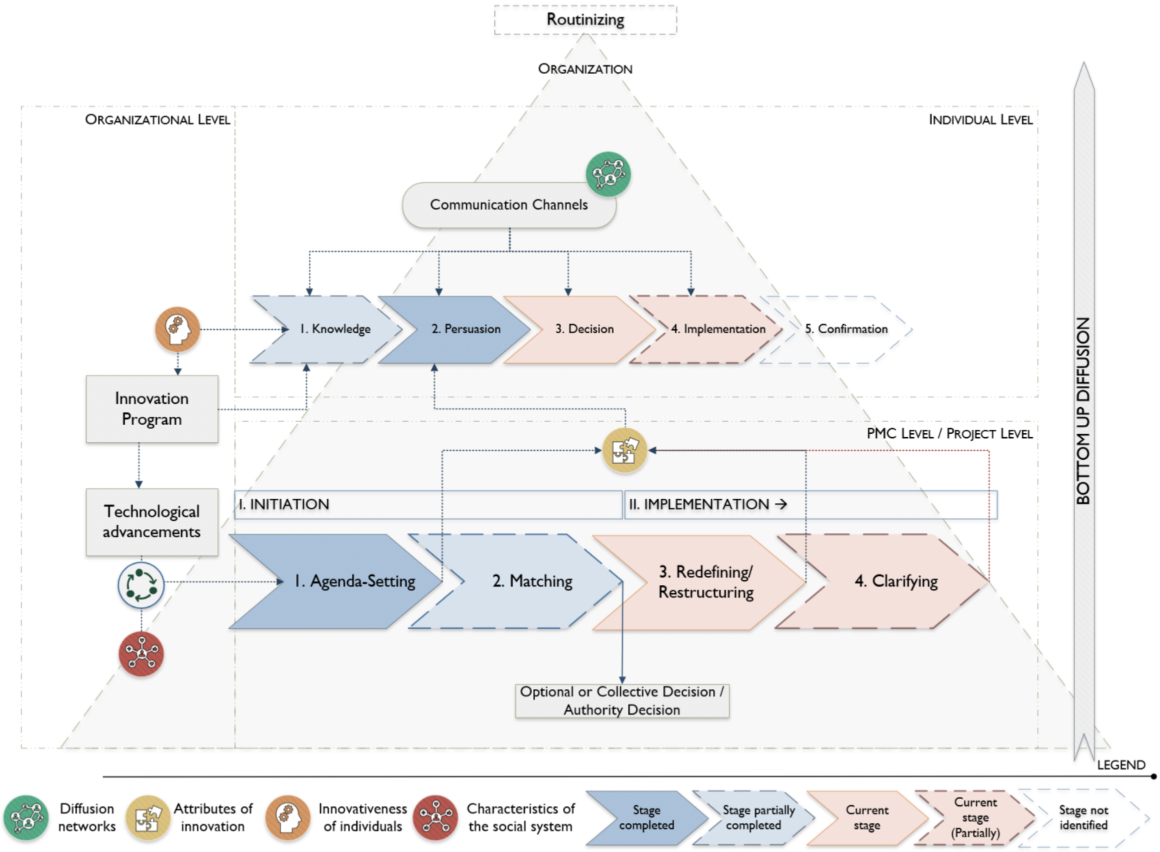

Figure 12 Diffusion Process of Case 2 Scripting & Programming

In the case of intra-disciplinary automation of repetitive tasks, after being convinced of the *relative advantage* of the innovation, the earlier adopters of tactical or daily responsibility developed and trialled scripts to automate the repetitive tasks they perform, to be more efficient in their works. Thereby in almost all cases of automation of repetitive tasks, the adoption decision has been *optional or collective decisions*. The *agenda setting* stage is visible in these cases and it is also backed by a *matching* procedure during which the personnel assess the feasibility of automating the task and make the adoption decision based on it. The diffusion then proceeded to the *redefining/restructuring stage*, during which scripts were developed and sometimes processes were restructured.

Intra-disciplinary scripting, on average, can currently be identified in the redefining/ restructuring stage, in which still a lot of developments (of tools, scripts etc) is being done. The lack of widespread diffusion however has to do with the *complexity* of the innovation, which is very closely related to *affinity*. *Affinity* is concerned with the individual's liking or disliking of the expertise required to use the innovation. Since people must learn new skills and knowledge (programming languages) very different from their profile to script or program, it is important that they have the affinity towards the field of expertise. People who have affinity tend to learn scripting even if they perceive the complexity to be hard and people who do not have the affinity are disinterested to learn it.

In the case of *scripting for modelling and modular design calculations at project level (inter-disciplinary),* the innovation can be said to be past the *agenda setting* stage, and it was largely triggered by an innovation program in the firm, in which the automation of harbour quay wall design was presented. This resulted in an increased awareness and understanding of the *relative advantage* that scripting can offer. The *matching* stage is rather vague for inter-disciplinary scripting and the feasibility is assessed more often with information from outside of the project boundaries and rarely within project context. This lack of proper matching sometimes resulted in discontinuance of the innovation implementation.

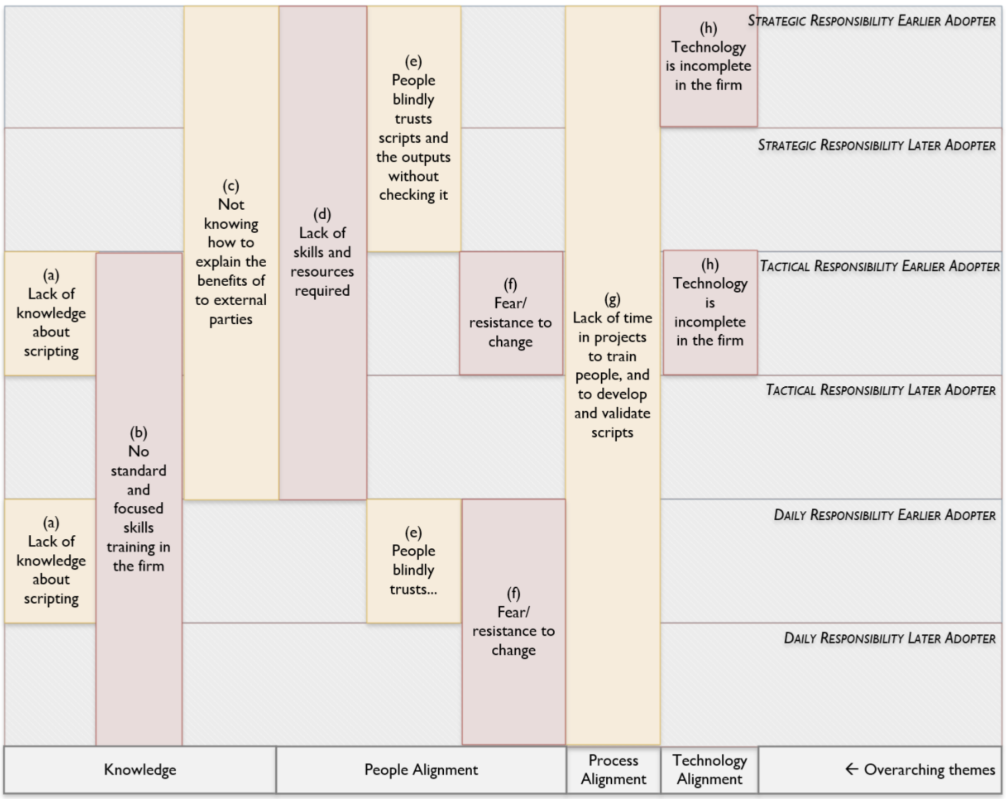

Figure 13 Barriers of Scripting & Programming diffusion

On an average, inter-disciplinary Scripting can also be identified in the *redefining/restructuring* stage, as there are still a lot of developments (of scripts) happening within and beyond project boundaries, coordinated by a knowledge dissemination group. Figure 13 illustrates the barriers and overarching themes affecting the widespread diffusion of inter-disciplinary scripting corresponding to the different adopter categories of different responsibilities. Table 5 shows the stage(s) in which these challenges are affecting the most and some resolutions for the challenges in the perception of the respondents of the interviews. Detailed data analysis can be found in Appendix G.

Table 5 Respondent's resolutions for the barriers of Scripting & Programming

Barriers during diffusion	Stages	Proposed Resolutions
a) Lack of knowledge about scripting	Agenda setting, Matching	i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
		ii) Employing new and enthusiastic individuals who have affinity with programming
		iii) Improved knowledge dissemination in the organization
b) No standard and focussed skills training program in the firm	All stages	i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
		iv) Assigning a balanced team in project in terms of skills and enthusiasm to learn
		v) Project Managers and line managers creating an environment to learn and develop
c) Not knowing how to explain the benefits to external parties	Agenda setting, Matching	vi) Making the crucial (conceptual) structural design decisions before actually scripting
		i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
		vii) Agreeing with contractor that it will not take extra time or money but rather save it
		viii) Having a Plan B and explaining the fall-back scenario to clients and external parties
d) Lack of skills and resources required	Redefining/Restructuring, Clarifying, Routinizing	ii) Employing new and enthusiastic individuals who have affinity with programming
		viii) Making resources like introductions, instruction manuals available to the personnel
		i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
e) People blindly trusts scripts and the outputs without checking it	Redefining/Restructuring, Clarifying	i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
		viii) Making resources like introductions, instruction manuals available to the personnel
f) Fear/resistance to change	Redefining/Restructuring, Clarifying	v) Project Managers and line managers creating an environment to learn and develop
		iv) Assigning a balanced team in project in terms of skills and enthusiasm to learn
g) Lack of time in projects to train people, and to develop and validate scripts	Redefining/Restructuring, Clarifying	ix) Improving people, process, and technology alignment
		vi) Making the crucial (conceptual) structural design decision before actually scripting
		i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
h) Technology incomplete in the firm	Redefining/Restructuring, Clarifying	i) Focussed trainings initiated by the organization, to make scripts and on how to use scripts
		x) Development and validation of more cross-projects/PMC scripts and programs across the organization
		xi) Connecting enthusiastic senior engineers with enthusiastic young engineers to boost up development

As can be seen in Figure 13, even though there is widespread awareness about the possibilities of scripting, tactical responsibility and daily responsibility earlier adopters noted that there is a (*a) lack of knowledge about scripting* in the firm. This lack of knowledge is affecting the matching of the innovation in different project contexts. Tactical and daily responsibility personnel understands that this lack of knowledge could because of *(b) lack of standard and focussed skills training programs in the firm*. Because of the lack of knowledge, *(c) it also hard to exactly explain the benefits to the external parties involved in the project and to convince them*, thus creating consensus for the innovation in the project contexts becomes difficult. These three barriers contribute to the *knowledge* theme of factors restricting the diffusion process and are strongly related to the next theme, *people alignment*. There is a *(d) lack of people who have the adept skills and expertise* to carry out the innovation implementation. Because of the lack of skills and lack of training, people do not understand the process of scripting completely and they sometimes *(e) blindly trust scripts, which leads to errors in the project*. This is because if the results of scripts are not validated properly, it could result in fatal mistakes in projects. In addition, there is always a *(f) fear/resistance to change* expressed by (mostly) later adopters of all responsibilities which also plays a role in slowing down the adoption rate.

There is also an absence of *process alignment* as all the respondents gauged the sheer *(g) lack of time available in projects to train people, and to develop and validate scripts* as a major barrier towards routinizing the innovation. The technology alignment is also a barrier as the project managers and line managers understands that the *(f) technology is incomplete within the firm* and lots of tools, scripts, protocols etc still need to be developed in order to fully implement scripting in projects.

4.4.3. Progress of 5D BIM

The diffusion of 5D BIM in the firm is in its very early stages and there is a lack of consistent and complete awareness about the innovation across the firm (as was discussed in Section 4.1.3). The progress of 5D BIM diffusion is illustrated in Figure 14 There are questions and concerns raised over both the *benefits* and the *feasibility* of the innovation in various project contexts by the respondents, irrespective of their responsibility or adopter categorization. Both earlier and later adopters with strategic and tactical responsibility are of the opinion that the *relative advantages* of 5D BIM are not clear and is having a negative effect on the adoption decisions. Hence, the diffusion process is identified to be in the *agenda setting* stage.

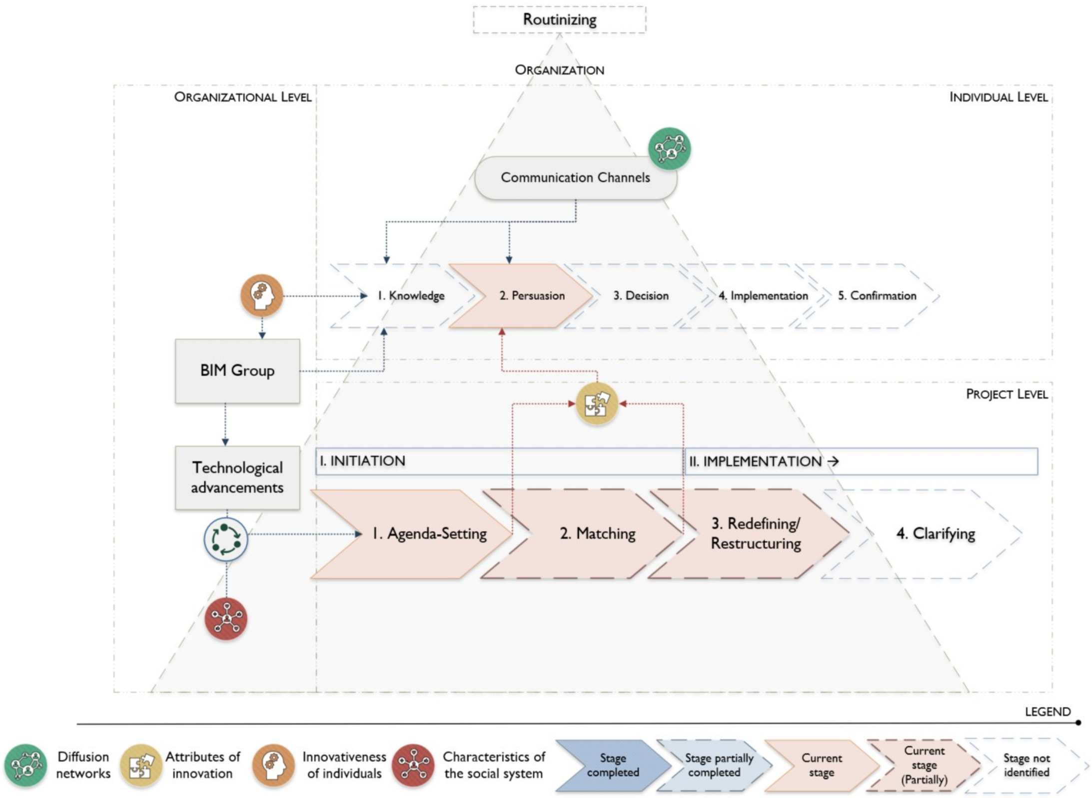

Figure 14 Diffusion process of Case 3 5D BIM

In some projects, the integration of designing and cost estimation have completed the *agenda setting* stage and was partially identified in the *matching* and *redefining/restructuring* stage.

Because of the lack of restructuring of the process, the diffusion was not able to move forward. Figure 15 illustrates the barriers affecting the diffusion of 5D BIM corresponding to the different adopter categories of different levels of responsibilities. Table 6 shows the stage(s) in which these challenges are affecting the most and some resolutions for the challenges in the perception of the interview respondents. Detailed data analysis can be found in Appendix H.

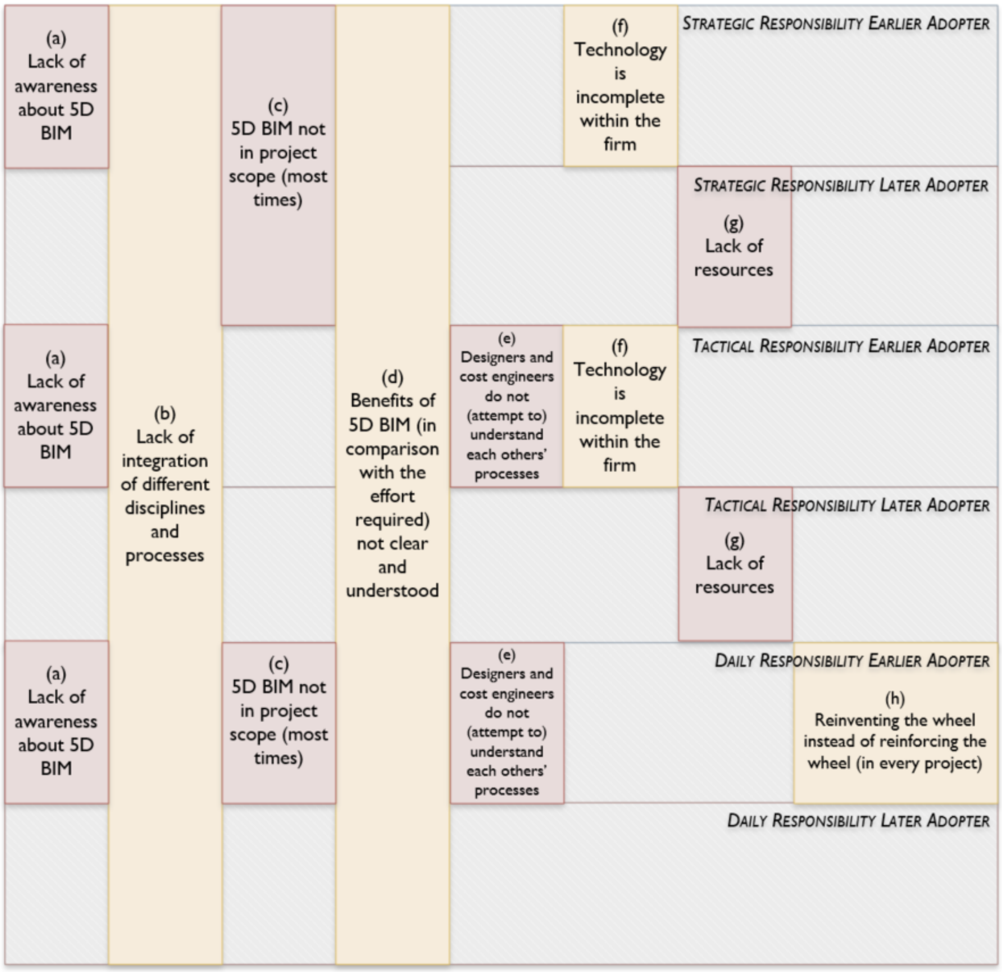

Figure 15 Barriers of 5D BIM diffusion

As can be seen from the figure above, the *(b) lack of integration of different disciplines and processes*, and the *(d) lack of identification of the benefits of 5D BIM* are the two most mentioned barriers affecting the diffusion of 5D BIM. These barriers correspond to the agenda setting stage and redefining/restructuring stage of the diffusion process respectively. Earlier adopters of all categories indicated that there is *(a) lack of awareness about 5D BIM*, which is making the resolution of both the aforementioned barriers difficult.

Since W+B is an engineering consultancy, (*c) 5D BIM is not in the scope of the project* in some cases, because of which the strategic responsibility personnel find it very difficult to initiate or push the diffusion of 5D BIM. This is further complemented with the *(g) lack of resources (skills, time)* and a lack of *(f) technology alignment* within and beyond the project boundaries. Daily responsibility earlier adopters identified that there is a lack of learning from projects, and it is always *(h) reinventing the wheel instead of reinforcing it* when it comes to integration of design and cost estimations. *(e) Designers and cost engineers do not (attempt to) understand each other's processes*, and when they finally do, either the project is completed, or the innovation is dropped, or the team changes, because of which in many cases they had to start all over again.

Table 6 Respondent's resolutions for the barriers of 5D BIM

Barriers during diffusion	Stages	Proposed Resolutions
a) Lack of awareness about 5D BIM	Agenda setting, Matching	i) Exploring the possibilities of 5D BIM in the firm's context and making others aware of the results
		ii) Using it in the best way in one project and then advertising the success stories
		iii) Improved knowledge dissemination in the organization to make people aware of 5D BIM
b) Lack of integration of different disciplines and processes	Redefining/Restructuring, Clarifying	iv) Enhance communication between different disciplines to generate an understanding of each other
		v) Create a common standard language for design and cost estimation, using object libraries, units etc
c) 5D BIM not in project scope	Agenda setting, Matching	X
d) Benefits of 5D BIM (in comparison with the effort required) not clear and understood	Agenda setting, Matching	i) Exploring the possibilities of 5D BIM in the firm's context and making others aware of the results
		vi) Initiatives from project/PMC leaders to explore the possibilities and explaining the benefits
e) Designers and cost engineers do not (attempt to) understand each other	Redefining/Restructuring, Clarifying	iv) Enhance communication between different disciplines to generate an understanding of each other
		v) Create a common standard language for design and cost estimation, using object libraries, units etc
		vii) Involve different disciplines from the beginning of the project to make concrete agreements
f) Technology is incomplete within the firm	Redefining/Restructuring, Clarifying	i) Exploring the possibilities of 5D BIM in the firm's context and making others aware of the results
		viii) Technology alignment with respect to potential of 5D BIM and context of the company
g) Lack of resources	Redefining/Restructuring, Clarifying	iii) Improved knowledge dissemination in the organization to make people aware of 5D BIM
		ix) Actually understanding what resources are needed and arranging it cross PMCs
		x) Focussed trainings initiated by the organization
h) Reinventing the wheel instead of reinforcing it (in every project)	Agenda setting, Routinizing	iii) Improved knowledge dissemination in the organization to make people aware of 5D BIM
		xi) Connecting enthusiastic senior engineers with enthusiastic young engineers to boost up development

4.5. Cross-case Analysis

4.5.1. The Innovation Diffusion Process

The three case studies discussed above underline the importance of earlier adopters in the diffusion of digital innovations in the firm. For both 3D BIM and Scripting, the initiation of diffusion in projects was led by earlier adopters who are of either strategic responsibility (project manager) or tactical responsibility (line managers, PMC leaders). Thus, the results shows that the project teams which includes earlier adopters in either strategic or tactical responsibility or in both is the best environment to initiate innovation diffusion. The success stories from such projects helped to curb the fear and resistance of later adopters in subsequent projects in the cases of 3D BIM and Scripting.

The results also shows that the agenda setting in projects is mostly triggered by technological advancements or organizational agenda. In the case of 3D BIM, technological advancements mostly from outside of the organizational boundaries triggered the agenda, while for Scripting, technological advancements mostly within the organizational boundaries played a triggering role. In both cases, such technological advancements were matched with the needs of and opportunities in the specific project contexts. For 5D BIM however, both the technological advancements and the needs or opportunities are unclear for the personnel. The earlier adopters are aware of the technological advancements in relation to 5D BIM beyond the organizational boundaries, but they cannot match it with the needs and opportunities of specific projects or of the organization. Results from 3D BIM clearly indicated that the environment for innovation created by strategic and tactical responsibility personnel was key for its successful diffusion. While for both 3D BIM and Scripting cases, initiative by some project managers (Strategic Responsibility) and line managers (Tactical Responsibility) was a major factor for accelerated diffusion, such innovation champions for 5D BIM are non-existent during the time of data collection.

Both 3D BIM and Scripting diffusion shows an inexistence of proper procedures in the *Matching* stage and thereby a lack of feasibility analysis rooted in the specific project context. This have resulted in problems during the later stages of diffusion for both cases. Matching in most cases were done by results from other projects instead of detailed analysis within the specific project context. However, it can also be seen as a learning curve, in which the personnel figures out the specifics about the innovations in a trial-and-error manner, but this has proved not to be the best scenario for diffusion. This is because failed diffusion has always led to more fear and resistance against the innovation, which further slowed down the diffusion, as was the case for both 3D BIM and Scripting. Furthermore, all cases underline the importance of Redefining/Restructuring stage for a successful diffusion process. 3D BIM underwent rigorous redefining of the innovation in specific project contexts and restructuring of the project processes, which was then disseminated to other projects by the BIM group. Similarly for Scripting, redefining of the innovation was necessary and is now under progress, and this redefined innovation across projects must be disseminated in the organization to accelerate the diffusion. 5D BIM analysis shows that restructuring of the project processes is extremely important for its diffusion, without which the diffusion will not go through.

A barrier which is affecting the diffusion of both Scripting and 5D BIM is the lack of awareness and knowledge about the innovations. This was also a barrier for the diffusion of 3D BIM, for which the barrier was resolved through extended knowledge dissemination from projects to the organization and through several resources like introductions, instruction manuals etc, all led and coordinated by the BIM group. The BIM group spearheaded the diffusion of 3D BIM by resolving most barriers affecting the diffusion of the innovation. Hence, such innovation acceleration groups can be very influential and can help with many barriers affecting the diffusion of Scripting and 5D BIM. In general, other barriers of diffusion for Scripting and 5D BIM are related to people, process, and technology alignment, all of which indeed played a role during the diffusion of 3D BIM as well. Here also, the accelerator group played an influential role. Beyond that, another element was the board of the organization. Results from 3D BIM shows that enthusiasm and increased support from the corporate level, especially in terms of resource allocations and creating organizational agenda to implement BIM in projects, played a big role in the widespread diffusion of 3D BIM in the firm. This support was initiated after 3D BIM was introduced in some projects and the board became convinced of the benefits of it.

4.5.2. Attributes of Innovation

The cases analysed indicate a sort of sequential importance of the attributes of innovation. The thought process of innovation diffusion starts with awareness of the Relative Advantage of the innovation. When the personnel are convinced with the relative advantage, then they move to the next question, how to make this work, which is related to the compatibility and complexity attribute. For 3D BIM, personnel first got aware of and convinced about the relative advantage of the innovation. They then move on to the next question, how to make it work, which is related to two key aspects, the innovation's feasibility in the project processes (in general and not embedded in project context), and its complexity to learn it themselves and for others to learn. Even though the processes were not compatible, the advantages of 3D BIM were big enough to restructure the process and to implement the innovation. All the respondents also indicated that 3D BIM was not very complex to learn. When the same was assessed for Scripting, all personnel are well aware of and convinced with the relative advantage of the innovation and they are now dealing with the next question, how to make it work. While the compatibility aspect is not a crucial barrier, when it comes to Scripting, complexity is. Scripting is deemed too complex to learn by the majority of the respondents and it is related with the affinity attribute. 3D BIM (and 5D BIM as well) mostly is perceived as not complex to learn also because the profiles of these innovations are not different from the profile of the personnel. That also means that most personnel have a positive affinity towards the profile of 3D/5D BIM (in an assumption that the personnel have a positive affinity towards their roles and responsibilities). Scripting on the other hand, introduces a different profile to the personnel, and most of them do not have a positive affinity towards it. This means when they assess the effort required to learn the innovation, the relative advantage is not valid anymore, as they have to spend way too much time and energy in order to be skilled in it.

When the compatibility and complexity attributes are neutralised, individuals start to use the innovation and they start to observe the results. Results from the case of 3D BIM showed that when personnel start to use the innovation and observe the results, they get more convinced with the idea of the innovation. The lack of widespread diffusion of Scripting can also be attributed to this as most of the personnel are still to observe the results of Scripting in projects they are involved, as the diffusion has in most cases either discontinued or scoped down because of various complications. The trialability attribute of the innovation also becomes important around the same time. It is very important to trial the innovation and verify the results before its widespread implementation in the project. This, for 3D BIM, was carried out cross-projects and did not take a huge amount of time, also because the firm took 'small steps' across projects, thus building up it as an incremental innovation. For Scripting however, trailing the scripts and validating the results takes a lot of time because of the intricacy of the innovation. Every script line must be checked with high accuracy and the results must be validated as well, both of which are time consuming and seen as a barrier for widespread diffusion. A cross-project organizational level approach similar to 3D BIM could be helpful to accelerate the diffusion of Scripting. But again, Scripting is not as direct as 3D BIM, which means its validation in project contexts is much more complex than how it was for 3D BIM. Hence the processes must be aligned by taking into consideration the time and effort required for validation of the scripts and outputs. For both 3D BIM and Scripting, earlier adopters stressed on the importance of trialability more than later adopters. This is because earlier adopters do not have any reference to validate the outputs of the innovation and hence require time and space to do the same in projects or beyond projects, while later adopters mostly have references validated by the earlier adopters.

5. Development of Strategic Framework

Based on the results of the interviews and in line with the two priori constructs defined, a conceptual strategy for diffusion of technological innovations in construct firms is developed. The priori constructs derived from literature were refined and redesigned based on the results from the interviews to develop the strategy, thus combining theory with the best practices and the actual situations in the firm. The strategy has two parts: (1) *Factors* which affect the rate of adoption of innovations, and a (2) model of innovation diffusion *process* that is focussed on using the factors to enhance adoption and to improve diffusion process in general. As such, the strategy is predominantly underpinned by the *Sections 2.6, and 4*. The strategy thus explains a diffusion model and illustrates *what* factors play a role in the adoption of innovations, *when* does these affect the diffusion process and *how* can the adoption of innovations be influenced by the factors. The complete strategy can be found in Appendix I.

5.1. Part 1: Factors Affecting Rate of Adoption

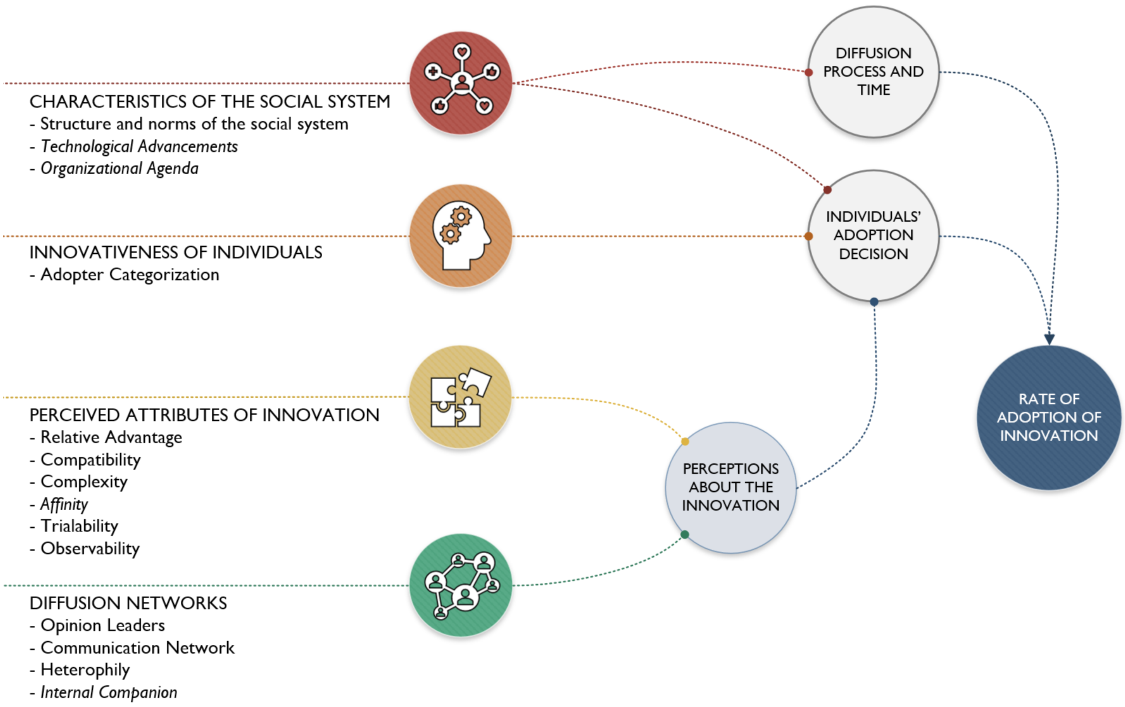

Figure 16 Factors Affecting the Rate of Adoption

Figure 16 illustrates the factors which affect the rate of adoption of technological innovations. These factors are briefly explained below:

1. Characteristics of the Social System

The results of the interviews validated that the characteristics of the social system plays an important role in the adoption decisions. The *structure* of the social system is decentralised autonomous sub-systems (projects), all with its own decision-making authority and in which the members collaborate with different sets of external parties. This decentralisation affects the diffusion process and also the adoption decisions of the members in the firm. The *norm* of the social system also plays a similar role. The nature of the social system (firm) is entrepreneurial and innovative, and this gives room and freedom for the earlier adopters to attempt diffusion of innovations. Another character which plays a role is the *technological advancements*, especially within the firm. Results shows that the technological advancements within (and sometimes beyond) the firm triggers agenda settings in the sub system of projects. Similarly, the *organizational agenda* or felt needs also plays a role in triggering agenda setting and initiating diffusion processes in the sub system of projects.

2. Innovativeness of Individuals

The interviews confirmed that the innovativeness of individuals plays an important role in the diffusion of innovations. While *earlier adopters* play the role of gatekeepers of innovation who brings the idea of the innovation from outside of boundaries of the social system, *later adopters* determine the pace of the diffusion process as they are the majority in the population. Hence it is important to identify the earlier adopters and give them space and support to initiate innovation diffusions, and to identify and manage the later adopters to facilitate the innovation diffusion process.

3. Perceived Attributes of Innovation

Six attributes of innovations are identified to play a role in shaping an individual's perceptions about the innovation. These attributes should be identified, exploited, and explained to the potential adopters to shape their perceptions towards the innovation. These attributes and a brief explanation are given below:

a. *Relative Advantage:* By far the most important attribute, relative advantage is the benefits of the innovation in comparison with the idea it is proposed to supersede. Results shows that the adopters must be convinced about the fact that using the innovation will bring them more advantages than whatever it is supposed to replace. The terms which the adopters measure these advantages with depends on the roles and responsibilities of the personnel. While strategic responsibility personnel are more concerned with the strategic aspects (such as time, money, client satisfaction, implementation efforts etc) of the innovation, tactical responsibility personnel are concerned with the quality of results. Daily responsibility personnel also consider ease of use as a factor to assess relative advantage.

b. Compatibility: Compatibility is the consistency of the innovation towards the values and previous experiences of the individuals. Results show that compatibility plays an important role and incompatible innovations takes far more time to diffuse. To facilitate compatibility, sometimes the innovation needs to be reinvented or the processes need to be restructured, especially for the later adopters to perceive the innovation as acceptable.

c. Complexity: Complexity is concerned with the difficulty in understanding the innovation and learning to use it. More complex innovations are perceived as difficult to adopt and the results show that focused trainings are required, and personnel should 'help each other' to overcome this attribute. Complexity is also strongly related to the next attribute, affinity.

d. Affinity: Results shows that affinity, or the interest of and towards the expertise (or field /knowledge) required to learn the innovation, plays a big role in the adopters' decision to accept or reject an innovation. Affinity is related to the profile and age of people. The older the adopters are, it is unlikelier that they will learn an innovation towards which they perceive to have lower affinity.

e. Trialability: Trialability of the innovation is the opportunity to experiment the innovation. Results shows that trialability is important to validate the use of innovation in project contexts before scaling up its implementation. Respondents also indicated that because of the need to validate, it is important to take ‘small steps’ with the innovation in projects and built up its use eventually.

f. *Observability:* Observability of the innovation is the degree to which the results of the innovation are visible. Our findings shows that observability is crucial to determine the course of diffusion process. While the diffusion process starts with identifying the relative advantage, observability determines the continued adoption or discontinuance of the innovation in the later stages of the diffusion process.

4. Diffusion Networks

The communication networks, which have a strong influence on the innovation adoption decisions of individuals, are called diffusion networks. The results validated the importance of diffusion networks in the diffusion process as these networks play a role in almost every stage of an individual’s decision-making process. Results from interviews shows that individuals prefer different *communication channels* based on their adopter categorization. While earlier adopters prefer mass media channels from cosmopolite sources, later adopters prefer interpersonal channels from local sources. Another important aspect of the diffusion networks is the *opinion leader*; individuals who can informally influence others’ opinions. Results from interviews shows that such opinion leaders play an important role in the diffusion of innovations by shaping positive or negative opinions about the innovation. Opinion leaders who are positive and optimistic about innovations should be identified and utilized in diffusion process while sceptical opinion leaders should be identified and managed to avoid rejection decisions. Results from interviews also indicated that there should be *heterophily* in the diffusion networks to enhance awareness about innovations and to spread new ideas. Similarly, results indicated that the presence of an *internal companion* could be key and highly motivational for (particularly earlier adopter) personnel, to help each other to learn and develop innovative solutions and ideas.

These four key factors should be identified and managed in the diffusion process to enhance the rate of adoption of technological innovations and to ensure a smoother diffusion process.

5.2. Part 2: Model of Innovation Diffusion Process

Figure 17 illustrates the developed model of innovation diffusion process. It incorporates the best practices from theory and industry in one comprehensive model, which illustrates a bottom-up diffusion process, assisted, and sometimes initiated by top-down influence. The model consists of five stages and four loops, which addresses three key levels in the innovation diffusion process. These levels are: (1) organizational level, (2) project level and (3) individual level. These levels, the stages and explanations are described below.

Organizational Level

The organizational level constitutes of mainly four components, which is directly related to, or shapes the characteristics of the social system factor. These components are (1) innovation acceleration groups (A/B/C in diffusion model), (2) centralized knowledge dissemination point, (3) technological advancements and, (4) organizational agenda/needs. These four components are inter-related and strongly influences each other.

a) *Innovation Acceleration Groups*: These are the decentralized groups of enthusiastic individuals, who passionately brings knowledge and information about specific innovations from outside of the organizational boundaries and coordinates its diffusion within the organization. Results show that such groups play an important role in the diffusion process, for instance, the actions of BIM group in the diffusion of 3D BIM. These groups play a role of 'change agents' in the diffusion process and act as a 'guiding coalition' during the diffusion process of the particular innovation. These groups also ensure learning from projects, which is very important in the diffusion process.

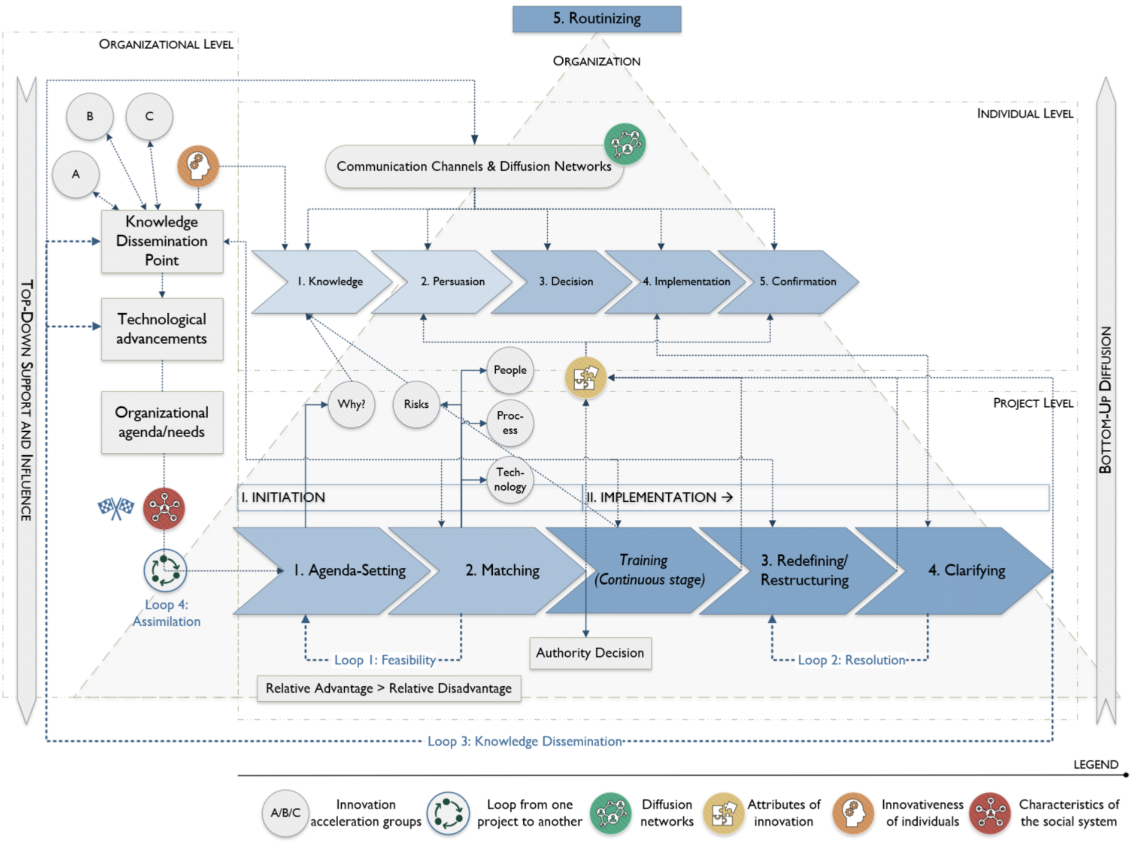

Figure 17 The Innovation Diffusion Model

b) *Knowledge Dissemination Point*: The idea of the knowledge dissemination point is the centralization and coordination of the acceleration groups to enhance the awareness of the different innovations within the firm. This can be a group of people, who have an overview of all developments within the firm or the leaders of the acceleration groups. It should coordinate the connection between acceleration groups and the project sub systems. They play a major role throughout the diffusion process, especially in the implementation phase.

c) *Technological Advancements*: Results from interviews indicate that technological advancements from within or beyond the organizational boundaries triggers agenda setting in the sub-system of projects. These technological advancements are continually updated by the knowledge dissemination point through success stories from projects within the firm in addition to the knowledge from outside of the firm. These advancements should be constantly communicated with the personnel through various mass media and interpersonal communication channels. Such advancements will have a technology push effect in the project sub systems.

d) *Organizational Agenda/Needs*: These are the agenda set by the board of directors of the company, who have a superior influence on the agenda setting in the sub-system of projects. Such organizational agenda are influenced both by felt needs and the technological developments within the firm. Results from interviews shows that such organizational agenda is very important for routinization of innovations in the firm as it can put pressure on later adopters to adopt innovations.

Project Level

The components discussed in the organizational level is related mainly with influencing and coordinating the diffusion of innovations in the firm. Results from interviews indicated that the actual diffusion happens in the sub-system of projects. Successful diffusion is best coordinated through two phases and five stages, with three reinforcing loops. Phase 1, *Initiation* is concerned with all the activities which leads up to the decision to adopt or reject the innovation. These activities are generalised into two stages, *(1) Agenda-Setting* and *(2) Matching*. Initiation phase is followed by Phase 2, *Implementation*, which includes activities and events concerned with putting the innovation into use. Implementation stage consists of one continuous and two other stages: *Training (continuous stage)*, *(3) Redefining/Restructuring* and *(4) Clarifying*. The diffusion process itself is triggered by the structure and characteristics of the social system, which includes technological advancements and the organizational agenda. The different stages are discussed below:

a. *Stage 1: Agenda-Setting:* Agenda Setting is concerned with identifying and assessing the perceived need for an innovation. It involves gathering and analysing information to understand the specific problem or the opportunity to implement the innovation. The key attribute to identify at this stage is the *Relative Advantage* of the innovation and the decision-makers should be able to develop an answer for 'why' the innovation is needed, and what can it deliver to the project. This is important to create a sense of necessity for the innovation and to focus on the problem instead of the solution, which was gauged as a reason for discontinuance of some innovations in the firm by respondents of the interviews. Results also shows that while for earlier adopters, Agenda Setting could be triggered by Technological Advancements beyond the social systems' boundaries, the trigger for later adopters is Technological Advancements within the firm, which itself is fed by developments and success stories from other projects.

b. *Stage 2: Matching:* This stage includes the procedure to assess the feasibility of the innovation in the specific project context to solve the related needs identified in the previous stage. The absence of this stage was identified as a key reason for slowed diffusion of various innovations in the firm during the interviews. During the feasibility assessment, on top of the external factors such as contractual obligations, client involvement etc, at least four key internal aspects need to be assessed: *People* alignment, *Process* alignment, *Technology* alignment and *Risks*.
    - *People* alignment is concerned with identifying the skills, roles and responsibilities required for the innovation and comparing it with the available skills.
    - *Process* alignment is concerned with identifying the processes required to implement the innovation to determine if it is compatible with the previous practices and if not, investigating how it can be aligned.
    - *Technology* alignment is concerned with assessing the technological capabilities required to implement the innovation and comparing it with existing technological capabilities to understand what needs to be acquired, developed, or established.
    - *Risks* is concerned with identifying the technical and nontechnical risks and barriers associated with implementing the innovation and developing mitigation

strategies for the same. Risks should be treated with utmost importance and should be communicated with the members of the social (sub) system.

These aspects should be assessed in order to identify the feasibility of the innovation within the project context and to determine the efforts and risks involved with implementing the innovation. An important role here is for the Innovation Acceleration Groups, who have the role of change agents, as they possess the most inside knowledge and information about the innovation. Thus, the project team should make use of the Innovation Acceleration Groups to coordinate the matching of the innovation within the project context.

c. *Loop 1: Feasibility:* The feasibility loop is associated with critically analysing the aspects identified in the Matching stage with the results of the agenda setting stage to compare the relative advantage and relative disadvantage of the innovation implementation. The agenda needs to be modified if the relative disadvantage is greater than the relative advantage and the new agenda's match needs to be assessed again. A positive adoption decision can be made when the relative advantage of the innovation implementation is greater than its disadvantages. If it is not achievable, it is advised not to implement the innovation within that specific project. This adoption decision needs to be an *Authority Decision*, made by the elite individuals of the project team. Results from interviews shows that authority innovation decisions are required for implementation of innovations in projects. The decision needs to be made in close coordination with the client and the other external parties, for which results of a strong Agenda Setting, Matching and Feasibility loop can play a major role.

d. *Training (Continuous stage)*: This stage is associated with rolling out training to support and empower the personnel to build up the skills required to adopt the innovation. Results from interviews showed that a lack of focussed and standard skills training sometimes acts as a barrier in innovation diffusion. Training is a continuous stage and spans the entire implementation phase, as the skills should be built up in stages and through practice. Personnel should be encouraged to help each other, and teams should be composed in such a way which makes collective learning possible. Again, the Innovation Acceleration Groups can play a crucial role in organizing and coordinating the training. This stage will also address the *Complexity* attribute of the innovation by helping the adopters to understand and use the innovations better.

e. *Stage 3: Redefining/Restructuring:* This stage is concerned with modifying the innovation to fit the project context and needs or restructuring the project processes or project team organization to fit the use of the proposed innovation. Results from interviews shows that this stage is extremely important in building up the *Compatibility* of the innovation with the processes and needs. The Innovation Acceleration Groups can again play a huge role in this step as it concerns various developments in terms of tools, protocols, instructions etc within and beyond the boundaries of the project.

f. *Stage 4: Clarifying:* In this stage, the innovation is gradually put into further use and the meaning of the new idea gets clearer to the members of the project. During this stage, the external parties can play a huge role as they can raise concerns or criticism of the innovation, which needs to be resolved. As such, Clarifying stage also involves identifying the immediate barriers and issues related to the innovation and developing action plans to solve them. The Clarifying stage also contributes to the *Observability* attribute of the innovation as at this stage the results of the innovation start to become more and more visible and clearer.

g. *Loop 2: Resolution:* The barriers and issues identified in the Clarifying stage needs to be resolved with sometimes several iterations with the redefining/restructuring stage. It can include further reinvention of the innovation or restructuring of the process, and the resolution of other barriers. The existence of this loop is important to understand that such need for resolutions are not setbacks, but it rather reinforces the innovation diffusion process. Such iterations are to be continued until the innovation is smoothly associated within the project.

h. *Loop 3: Knowledge dissemination:* It is important to take away crucial learnings from projects and feed it to the organization so that other projects can learn and improve their processes. Such disseminations of knowledge are to be coordinated by the Knowledge Dissemination Point and the Innovation Acceleration Groups. The best practices, tools and resources developed, challenges and resolutions and other important details should be documented and used in following projects.

i. *Loop 4: Assimilation:* Once the innovation is clarified and the success stories and knowledge gained are disseminated in the organization, the Technological Advancements within the organizational level will be updated, which will trigger the Agenda Setting of another project. This loop continues from project to project and in each iteration, the uncertainties related to the innovation and the resistance towards adoption will be reduced because of positive perceptions shaped during it.

j. *Stage 5: Routinizing:* After several Assimilation loops, at the Routinizing stage the innovation becomes incorporated to the organization. The innovation at this point will lose the identity of a 'new idea' and the members of the organization will have a consistent understanding of what the innovation is and how it works, and it will be considered as a standard working practice in projects (if the opportunity exists)

For intra-disciplinary innovations, the diffusion process is almost the same with some minor differences. The innovation diffusion happens in the *PMC Level* rather than Project level and the initial innovation adoption decision (after the matching stage) is *Optional or Collective decision*, rather than Authority decision.

Individual Level

When the stages of diffusion process in the project level is being completed, individual navigates through a decision process which includes five stages. It is important to understand these stages and what factors play a role in it in order to better manage and influence an individual's decision-making process. These stages are: (1) Knowledge, (2) Persuasion, (3) Decision, (4) Implementation and (5) Confirmation.

a. *Knowledge Stage:* During the Knowledge stage, the individual tries to determine what the innovation is, how it works and why it can be useful. The beginning of the Knowledge stage depends on the innovativeness of the individual. Results from the interviews shows that if the individual is an earlier adopter, they might seek information about innovations out of curiosity and explore beyond the boundaries of the organization, while later adopters prefer the information to reach them via internal communication channels. As such, the Training stage in the project level directly plays a role in acquiring knowledge and information about the innovation. The results of the Agenda Setting stage is also important to trigger the Knowledge stage, particularly of the later adopters, as they'll seek information when they understand and are convinced about the benefits of the innovation.

b. *Persuasion Stage:* The individual forms a favourable or unfavourable attitude towards the innovation during the Persuasion stage which leads up to their innovation decision. The Persuasion stage is directly influenced by the attributes of innovation, which is further shaped particularly by the Matching, Training, Redefining/Restructuring, and Clarifying stages of the diffusion process in project level.

c. *Decision Stage:* The individual then decides to adopt or reject an innovation based on the preceding stages. The Decision stage is highly influenced by the Diffusion Networks, particularly by Opinion Leaders. Thus, Diffusion Networks should be exploited to shape positive adoption decisions in the Decision stage.

d. *Implementation Stage:* After the individual makes a positive adoption decision, they put it into full use. As they do that, uncertainties can cause problems and they might require adequate technical assistance and support. Implementation stage is strongly associated with the Clarifying stage of the project level process, as the uncertainties and barriers are to be resolved in the Clarifying stage and Resolution loop, which will help the individual navigate the Implementation stage.

e. *Confirmation Stage:* During the Confirmation stage, the individual seeks reinforcement for the innovation decision already made by them. Such reinforcements are through their own experience with the innovation, visibility of results and the opinions of others. As such, the Diffusion Networks again play a very crucial role in this stage.

5.3. Overview of the Strategic Framework

The innovation diffusion process starts with the Agenda Setting stage in the project level, which itself is triggered by the Characteristics of the Social System, like the Technological Advancements and Organizational Agenda. During the Agenda Setting, the perceived need for the innovation is identified and assessed. The feasibility of the innovation to satisfy the perceived needs in the project context is analysed during the Matching stage, with strong emphasis on People alignment, Process alignment, Technology alignment and Risks involved. The results of the Matching stage are compared with the identified needs in the Agenda Setting stage during the Feasibility loop and an Authority adoption decision is made if the relative advantage is greater than the relative disadvantage. If not, the agenda is modified and the Feasibility loop continuous until a favourable comparison between relative advantage and disadvantage is available. If this is not achievable, the innovation implementation is discontinued. These stages are assisted and coordinated by the Innovation Acceleration Groups and the Knowledge Dissemination Point.

The diffusion process then moves to the Implementation phase, during which Training programs are rolled out to empower personnel to embrace the innovation, which also triggers the Knowledge stage of an individual's decision process. In the next crucial stage, Redefining/Restructuring, the innovation is redefined, or the processes (or project organization) are restructured in the project context, if necessary, in order to make the innovation compatible. As the innovation is put into more use, the idea becomes clearer to the members in the Clarifying stage. At this stage, the (internal/external) members of the project might raise concerns, which are resolved through several iterations with the Redefining/Restructuring stage through the Resolution loop, until the innovation is efficiently put into use in the project. These three stages also influence the Complexity, Compatibility and Trialability attributes of the innovation respectively, which in turn shapes the Persuasion stage of the individual's decision process. As the innovation is put into more use, the members start to observe the results, which further shapes their attitude towards the innovation (*Observability*).

The knowledge gained and lessons learned from the project is then disseminated in the organization through the Dissemination loop. This updates the Technological Advancements in the firm along with the success stories from the projects, which in turn influences the Agenda Setting of another adjacent or subsequent project. Such several assimilation loops result in routinization of the innovation in the firm, during which the innovation loses the separate identity of a new idea. Diffusion Networks play a key role throughout the diffusion process, and it should be managed and exploited to aid and accelerate the process.

5.4. Validation of Strategic Framework

The Strategic Framework discussed in the above sections was validated by experts in the field, the results of which are summarised below. The framework was presented and explained to domain and academic experts to understand both the corporate and academic validity of the proposed strategic framework. The domain experts were a PMC Leader/Project Manager and BIM Group Leader from W+B. Academic expert was a researcher in the field of Construction Process Integration and Information & Communication Technology (ICT).

Validity of Strategic Framework

All respondents indicated that the strategic framework is very comprehensive and covers all important elements of the diffusion process, thus providing *"a very nice overview"* of the diffusion process. The domain experts noted that the focus of the firm's personnel naturally *"is all about projects"* and the model helps them to step out of that focus and *"make a holistic organizational view"*. The domain experts noted that with the model the company can identify which step of the diffusion process an innovation is in and can assess *"where the innovation is stopping in projects"*. Most importantly, they stressed the necessity of the three loops in the model and specified that the Feasibility and Knowledge Dissemination loops are very important. A domain expert pointed out that sometimes in projects, the firm *"skips the 'why' (agenda-setting) and focus on the how"* because of which the innovation *"diffusion stops"*. For this reason, the experts reiterated that the Feasibility loop is *"very important to know.* Furthermore, they noted that the mentality in the firm is *"very linear in the project direction"* because of which most of the times they do not focus on knowledge dissemination. The diffusion of innovations in the organization mostly *"goes one way and stops one way"*, and the learnings are not taken from the one-way diffusions. The domain experts indicated that the *"third loop (knowledge dissemination) is more important than we (they) thought"* and stressed the necessity of making the *"third loop (Knowledge Dissemination) more explicit"* in the organization.

From an academic standpoint, the academic expert noted that three elements must be instrumental in an innovation diffusion strategy in the construction industry: 1) understanding clear benefits, 2) feasibility in the project context and 3) top management support. The respondent noted that these three elements are clearly found in the proposed strategic framework as well, making it a sound diffusion model. The respondent agreed with the importance of the Resolution loop and identified it as an *"important element in the learning process"* during innovation diffusion.

Suggested Improvements

The People, Process and Technology alignment described in the Matching stage were described as "very important and strong elements" by all the respondents. Thus, they suggested making these components more explicit and include it in the diagram itself. The same was suggested for the Risk element, as the academic expert noted that "identifying and managing risks are very important" and hence the element should be illustrated clearly in the diffusion model. These suggestions were considered, and the mentioned four elements, People, Process, Technology, and Risks were illustrated explicitly in the diagram.

Limitations and Next Steps

Some concerns were raised by the domain experts regarding explicit future attention required for some elements of the model for immediate implementation in the organization. The domain experts raised concerns over the structure and formation of the Knowledge Dissemination Point. The Knowledge Dissemination Point, being a very crucial part of the diffusion process, have roles throughout the diffusion process. The respondents shared fears if a "small team can handle everything". However, the Knowledge Dissemination Point's responsibility is mainly coordination and holistic management. The hands-on activities, such as training, is to be managed by the Innovation Acceleration Groups (along with the project teams). Nevertheless, the composition and management of the Innovation Acceleration Groups and Knowledge Dissemination Points requires explicit attention and planning within the organizational context. Similar concerns were raised about the Training stage, where the fears were over how to "organize and manage training in projects". The model stresses the importance of taking small steps in projects with innovations and building it up cross projects, along with balanced team composition with earlier and later adopters to facilitate training and collective learning. However, Training stage does need more explicit attention and future research to plan an effective training strategy within the organizational context.

6. DISCUSSION

The findings of this research portrait the current diffusion processes in the firm and combined the best practices and lessons learned from theory and practice into one comprehensive diffusion model, illustrated in Figure 17. For this, the research explored the grey areas of technology diffusion in construction industry, which exists in the interface of the theoretical benefits of digital innovations and its implementation in the industry. This section compares these results with the existing literature to find the similarities and differences. Furthermore, the implications to practice, research limitations and some directions for future research are also outlined.

6.1. Discussion of Results

6.1.1. Structure and Characteristics of the Social System

This research explored how digital innovations currently diffuse in the firm using three cases. Case 1 3D BIM, Case 2 Scripting & Programming, and Case 3 5D BIM. The diffusion of these digital innovations followed the same trend as most of the innovations in construction do, diffusion in projects. Construction industry is largely a project-based industry with a very high degree of product diversity (Morris & Pinto, 2004). This project-based nature makes diffusion of innovation in construction complex. Yet, it is not just the project-based nature; what makes it more complicated is the level of diversity in each project, including the product diversity but also the diversity in terms collaborating parties.

Projects in the firm acts as autonomous sub systems, each with their own decision-making authority, and their own set of collaborating external parties. This decentralized structure of the firm follows the findings of Dubois & Gadde (2002) who portrayed the construction industry as a 'loosely coupled system', in which firms gets involved in different projects, via different set of resources, and coordinates with different sets of external parties. In addition, many previous studies, for instance Swan et al., (2010) and Eriksson (2013), have also argued that these different construction projects have high autonomy, which is consistent with our findings. As a result, the project members have a short-term perspective and a focus on suboptimization, which hinders innovation and technology developments which usually requires a long-term approach (Dubois & Gadde, 2002). The decentralized decision making, and financial control also means that the decision to adopt an innovation does not lie with just the firm itself, but also with all the other external parties, which itself changes from project to project. This, coupled with the other diversities in projects in terms of final product, components, and materials (to name a few) makes innovation diffusion in the construction industry challenging.

This study confirms that such external factors, which arises due to the complex structural characteristics of the construction industry, and which are not in the direct control of firms, are the major barriers towards diffusion of digital innovations in the industry (Bresnen et al, 2006; Gadde & Dubois, 2010; Shibeika & Harty, 2015; Lundberg et al., 2019). Thus, in the developed strategic framework, the characteristics and structure of the social system is treated as the first factor which affects the rate of adoption of digital innovations. Firms attempting to diffuse digital innovations should step out of the strong focus of projects and take a holistic approach to innovation diffusion by enhancing resource, knowledge, and information sharing across various projects of the firm. In addition, we also identified the importance of norm of the social system as a key factor which can motivate individuals to attempt innovation diffusions. As discussed above, the complex structure of the construction industry means that innovation diffusion within it is challenging and sometimes risky. To innovate in such a social system, there should be an environment which motivates and supports individuals to take on the related challenges and risks. An entrepreneurial and innovative culture and environment provides room and support for enthusiastic individuals to take initiatives and responsibilities towards innovation diffusions. Firms should attempt to create such an environment, where the personnel have space and enough support, to initiate and attempt innovation diffusions.

6.1.2. Individual Innovativeness and Adopter Categorization

Overcoming the barriers posed by the structure and characteristics of the construction industry's social system is indeed the first most important challenge for firms intending to innovate. But once they cross that, the firms are confronted with the next set of internal barriers. While most of the construction management literature focusses on the external factors, the internal barriers have not received similar attention and are usually summarised into perceived failure of the innovation along with fear of change, which the members of the social system possess (Gambatese & Hallowell, 2011). In addition, the literature in this field does not really shed more light on how these barriers should be dealt with. This research explored the internal factors in depth by focussing on the innovativeness of personnel along the lines of Rogers (2003). Thus, this research not just identified the factors affecting the diffusion, but also proposed a strategic framework focussed on overcoming the posed internal barriers. The use of Rogers' (2003) adopter categories is found in construction literature but are more related to categorizing organizations rather than the individuals. This study attempted to categorize personnel of the firm into earlier and later adopters in order to identify the difference in the role of these categories in the diffusion process of digital innovations in the construction industry.

The study found that while earlier adopters play the role of 'gatekeepers' of innovation, later adopters determine the pace of diffusion and the rate of adoption. This validates the findings of Rogers (2003) and Moore (2014) in the context of construction industry as well. As per Rogers's (2003) adopter categorization, earlier adopters include the 'innovators' and 'early adopters' while later adopters include the 'early majority', 'late majority' and 'laggards' of the social system. Rogers (2003, p.248) portrayed 'innovators' as the venturesome members of the social system who are eager to try new ideas and 'early adopters' as the more respected technology enthusiasts in the social system. Together, these groups play the gatekeeping role by bringing the idea of the innovation to the social system and promoting it by playing the role of 'local missionaries' (Rogers, 2003, p.248). Moore (2014) identified the existence of a 'chasm' between the earlier adopters and later adopters. This 'chasm' represents the fear and resistance among other barriers posed by the later adopters towards innovation adoption. The pace with which the innovations 'cross the chasm' determines the pace of the diffusion of digital innovations and rate of adoption (Moore, 2014). Thus, the strategies for enhancing adoption of digital innovations should predominantly focus on the 'chasm' between earlier and later adopters, thereby managing the barriers and challenges posed by the later adopters. The results indicates that to organize an efficient and smoother innovation diffusion, the earlier adopters should be recognized and supported, and the later adopters should be recognized and managed.

Furthermore, the earlier adopters of the firm were found to be more cosmopolite than later adopters, who preferred local sources. Also, earlier adopters were found to prefer and having more exposure to mass media communication channels than later adopters. Both findings corroborate with the communication behaviour generalisations of earlier and later adopters by Rogers (2003). Furthermore, our results also validate Rogers (2003) arguments that there is no direct relationship between age and adopter categorization of individuals. These results indicate that the communication channels used during innovation diffusions should be selected based on the target category of the diffusion process stage. For instance, during the early stages of diffusion information should be gathered from cosmopolite sources and should be communicated to the earlier adopters through mass media channels. Later during the process, when the diffusion is approaching later adopters, the focus should be on local sources and interpersonal channels.

6.1.3. Perceived Attributes of Innovation

Rogers (2003) defined five attributes of innovation which plays a role in shaping the perceptions of the adopters. The five attributes are 1) relative advantage, 2) compatibility, 3) complexity, 4) observability and 5) trialability. These attributes were assessed and validated in the context of the construction industry in this research. We found that all the five attributes of innovation play a significant role in shaping the perceptions of digital innovations in the context of construction. However, while relative advantage was indeed crucial in triggering the innovation diffusion process, compatibility, and complexity was related to the decision to adopt or reject the innovation. Once the innovation is put to use, the observability and trialability attribute plays a big role in shaping the continued adoption or discontinuance decisions of the individual.

The trialability attribute however is related to validating the outputs of the specific digital innovation before its extended adoption and this attribute is particularly important for earlier adopters than later adopters. Later adopters do not necessarily want to trail innovations before they use it if they know that the outputs are validated. These findings are in line with Rogers (2003, p. 231), who argued that earlier adopters perceive trialability as more important than later adopters, because earlier adopters start using the innovation without any pre-set examples to follow while later adopters are surrounded with peers who have already adopted the innovation. Our findings also corroborate the results of the assessment of trialability attribute in the construction context by Gledson & Greenwood (2017), who argued that it is advantagous to trail the innovation in a safe enviornment before implementing it in a live construction project. However, we do not entirely agree with need to have a ‘safe environment’ to trial the innovation before using it in a live project. Our results indicate that both 3D BIM and Scripting were trialled in live projects during its diffusion process. The important aspect here was ‘taking small steps’, thus building the innovation step by step over projects, thereby taking more of a reinforcing the wheel approach.

In addition to the five attributes, we defined a new attribute, *Affinity*, which is closely related to complexity. Affinity is concerned with an individual’s liking or disliking of the profile of the digital innovation. On this regard, literature often stops at the perceived complexity or ease of use, often discussing whether an innovation is easy to learn and use. As such, this new attribute, Affinity, is an important contribution of this research to the well-established attributes of innovation, as it takes the understanding regarding complexity to another level by relating the profile of an individual to the profile of the innovation. If the profile of the innovation is completely new to the individual, then they must start from zero in order to learn the innovation. If they do not have a positive affinity towards the new profile, individuals perceive the innovation to be very complex to learn and use, irrespective of their adopter categorization.

6.1.4. Diffusion Networks

Diffusion Network is the network of information and communication channels which have an influence on the innovation adoption decisions of individuals. Our results indicate that developing a strong diffusion network or identifying and managing the existing ones within the organization is very key in an innovation diffusion process. We found that when it comes to communication channels, earlier adopters prefer mass media channels from cosmopolite sources when they're learning about an innovation while later adopters prefer interpersonal channels from local sources. These findings are slightly contradictory to the generalisations of Rogers (2003) diffusion theory, and results of Gledson & Greenwood (2017) who assessed diffusion theory in construction context. Rogers (2003, p.198) argues that cosmopolite mass media channels are relatively more important than local interpersonal channels in the knowledge stage (Generalizations 5-12/13), while Gledson & Greenwood (2017) found that construction professionals prefer to obtain knowledge from their interpersonal networks. However, our results indicate that the preference of the communication channels and sources depends on the adopter categorization. To gain knowledge about the innovation, earlier adopters consider cosmopolite mass media channels relatively more important than local interpersonal channels and vice versa for later adopters. This again owes to the fact that since earlier adopters are playing the role of gatekeepers of innovation, they require cosmopolite sources to gather information about the innovation and bring it within the social system. This is because knowledge and information about the innovation within the social system is in most cases inexistant when earlier adopters are adopting an innovation. However, for later adopters, the information will be available within the boundaries of the social system (brought in by the earlier adopters) by the time they consider the innovation.

6.1.5. Current Innovation Diffusion Process in the Firm

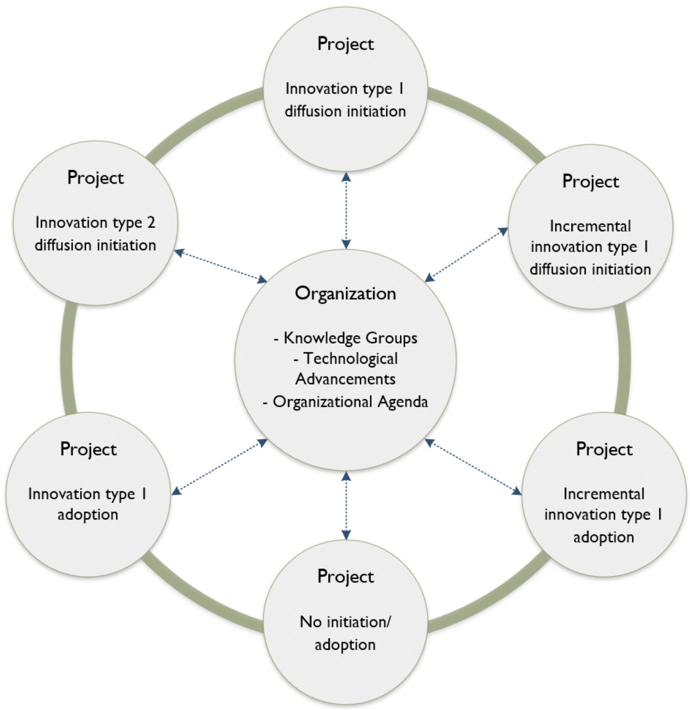

Figure 18 An illustration of the identified innovation diffusion process in the firm

We assessed the current innovation diffusion process in the firm through the lens of Rogers (2003) innovation diffusion model. The findings of this research indicated that in the context of construction industry, initiation and implementation of digital innovations happens in the autonomous subsystems of projects, triggered by certain factors of the overarching social system. This is in line with the findings of Winch (1998), Gambatese et al., (2011) and Lundberg et al., (2019), who argued that in the construction industry, innovations are usually not developed and implemented in the firm, but in projects they are engaged in. Innovation diffusions are initiated in projects of the firm, which are mostly triggered by organizational agenda, and/or technological advancements within or beyond organizational boundaries and are often supported by knowledge groups formed by enthusiastic earlier adopters. After successful diffusion (or partial diffusion) of the specific innovation in one project, sometimes other projects attempt to adopt it, while some initiate a diffusion process of an incremental innovation, depending on the specific needs within the respective project contexts. Such diffusion processes are strongly facilitated by diffusion networks between different projects, and between projects and organization. Lundberg et al., (2019) also identified a similar type of diffusion process in a contractor firm, where products produced in one sub-system is adopted and sometimes modified by other sub-systems, all coordinated by the central organizational unit. Our results further push the understanding of innovation diffusion in the construction industry by bringing the concepts of technological advancements within or beyond the firm, organizational agenda, and knowledge groups to the forefront. Figure 18 shows a generic illustration of the current digital innovation diffusion process in the firm.

6.1.6. Refined Innovation Diffusion Model

Rogers' (2003) organizational innovation diffusion model includes two phases and five stages. Phase 1, Initiation includes activities leading up to the decision to adopt or reject the innovation and have two stages: (a) Agenda Setting and (b) Matching. Phase 2, Implementation, is comprised of activities concerned with putting the innovation into use and includes three stages: (a) Redefining/Restructuring, (b) Clarifying and (c) Routinizing. We assessed the diffusion of 3D BIM, Scripting and 5D BIM using the model and refined the model in the form a strategic framework. The refined model is a comprehensive innovation diffusion model dedicated to the construction industry, which incorporates the characteristics of the industry, the factors which affect the diffusion of innovation, and solutions to manage these factors within it. As such, this model contributes to bridging the apparent gap between the theoretical benefits and the actual implementation of digital innovations in the construction industry. The refined model, in addition to the aforementioned five stages, consists of one continuous stage in the implementation phase, Training, and four reinforcing loops: Loop 1 Feasibility, Loop 2 Resolution, Loop 3 Knowledge Dissemination and Loop 4 Assimilation. While Rogers (2003) organizational innovation diffusion model includes only one level (organizational level), we extended the model by incorporating two more levels, project level and individual level, in order to make the model feasible for the construction industry. In addition, four reinforcing loops are added which captures unique challenges and needs related to innovation diffusion in the construction industry. The various stages and loops, the need for it, and the challenges it addresses are briefly discussed below.

1(a) Agenda Setting

Agenda setting is concerned with identifying and assessing the perceived needs, problems, or performance gaps, which calls for the intervention of an innovation. Our data confirms that agenda setting is important to create an initial consensus for the innovation. The results of this research indicate that agenda setting is usually triggered by the technological advancements in the firm, through some individuals becoming aware of the existence of an innovation and then realising that it perfectly solves a perceived problem or need they have. This is in line with Rogers (2003, p.364) arguments that agenda setting can be 'problem-initiated' or 'technology-initiated', and most frequently it is the latter. Thus, such 'sensemaking' involved in agenda-setting can be triggered by either organizational needs (pull), technological innovations (push) or both (Adriaanse, Dewulf, & Voordijk, 2009). We argued that agenda setting should be carried out in project level instead of organizational level. Even though this finding is different from Rogers (2003) according to whom agenda setting happens in organizational level, it is consistent with the arguments of Gadde & Dubois (2010) and Lundberg et al., 2019, that innovation diffusions efforts in the construction industry are best facilitated by predicating them in local (project) contexts. Swanson and Ramiller (2004) also argued that decision makers (mostly earlier adopters) should not take generalised claims about the benefits of the innovation as the basis of their motivation and should critically assess the validity of the innovation in the local context.

1(b) Matching and Loop 1 Feasibility

Matching stage is concerned with assessing the feasibility of the innovation to solve the perceived agenda within the project context. While Rogers (2003 p.364) describes matching as a step to simply identify whether the innovation can solve the agenda, our findings indicate that the matching stage should have more attention than simply assessing whether the innovation can solve the problem or not. At the end of matching stage, an adoption (or rejection) decision must be made. In the construction industry, project contexts are highly complex as we discussed before, and it includes many stakeholders. This insinuates that every decision made within the project contexts comes of a very high cost (literally), and hence must be scrutinized. As such, the decision makers must assess the feasibility of the innovation in the project context and should evaluate and compare the relative advantage with the relative disadvantages of implementing the innovation. This is in line with the findings of Adriaanse et al., (2009) who argued that construction projects should not use or should limit the scope of digital innovations if the related barriers cannot be eliminated sufficiently and if the risks cannot be mitigated.

In addition to the arguments presented to consider the matching stage seriously, another factor which stresses this point is the incremental nature of digital innovations in construction. The findings of this research indicates that even though most of the digital innovations in construction are radical in nature, once introduced and implemented in a firm, it can also take the shape of incremental innovations with further adaptations. This in line with the findings of Cesnik et al., (2019) and Poirier et al., (2015), who discussed cases where digital innovations were initially perceived as radical, and after implementation, a series of incremental innovations took place to further exploit the possibilities of the innovation. Such potentials of construction innovations, while posing exciting opportunities, sometimes also acts as a hinderance. The results indicated that the earlier adopter developers of such incremental innovations expect to diffuse incrementations to one innovation, which was successfully carried out in one project, in another project context without any major hinderance. In such cases, the earlier adopters often skip the matching stage, thereby avoiding a proper feasibility analysis, and uses the conclusions from successful implementations in previous projects to draw implementation strategies. Owing to the diversity of construction projects, an innovation successful in one project might not be successful in another, as the success is determined by specific characteristics of the respective project context. This happened in the firm during the diffusion of 3D BIM and Scripting & Programming, thus resulting in discontinuance of the innovation use in some cases, which in turn contributed towards more resistance to those innovations in the organization. These findings are in line with the arguments of Harty (2008) that incremental innovations in one project context could still be of radical nature in another project context within the same firm, and hence should be approached cautiously.

To ensure this feasibility assessment, we added the *Feasibility Loop* to the diffusion model, which ensures critical evaluation and comparison of the matching stage results with the results of agenda setting stage. The content of the agenda setting (the scope of innovation adoption) must be adjusted and the loop continues until the relative advantage is greater than the relative disadvantage, after which an adoption decision is made. If relative disadvantages are always greater than the relative advantages, it is advised not to continue with the innovation diffusion within that specific project context.

2(a) Redefining/Restructuring

According to Rogers (2003, p.365) in the redefining/restructuring stage, the innovation is redefined, or the organization is restructured, to accommodate the innovation. Our findings are line with this argument, as for the successful diffusion of 3D BIM, reinventions of the innovation took place and later the organizational structure was altered by the addition of knowledge groups (although started as informal, these groups were later formalised). However, our findings also point out another restructuring: restructuring of the project processes. Sometimes to accommodate innovations, project process needs to undergo deep restructuring, which is very important for its diffusion. Such restructuring allowed diffusion of 3D BIM and the lack of it is hindering the diffusion of 5D BIM in the firm. For instance, in order to accommodate 3D BIM in the projects, conventional design practices, in which designers are not involved in the conceptual phase, were restructured by bringing designers into the conceptual design phase as is required for the use of 3D BIM. Similarly, the designing and cost estimation processes are isolated in the conventional practices, integration of which is required for the diffusion of 5D BIM. Thus, restructuring of project processes related to the respective innovation is important to make the innovation and project processes compatible. Robinson et al., (2016) and Lundberg et al., (2019) also identified redefining and restructuring in the construction industry, who argued that such technological and organizational changes happen simultaneously, in interactive processes, during the diffusion process.

2(b) Clarifying and Loop 2 Resolution

In the Clarifying stage, the innovation is put into wider use and the idea of the innovation becomes clearer to the members of the social (sub) system. Our findings report that during the clarifying stage, the external parties involved could raise concerns about the innovation use as the idea becomes more clearer to them. In addition, there could be other barriers which were not anticipated by the project team (Adriaanse, 2007). In order to overcome these barriers, we introduced the Resolution Loop in the innovation diffusion model. The idea of the resolution loop is not to enforce resolution, but it is to understand that the need for resolutions in later stages of diffusion process is not a setback but rather a reinforcement to the diffusion process. This reasoning is consistent with arguments of Swanson and Ramiller (2004) and Adriaanse et al., (2009), that innovators should expect surprises in the diffusion process, and should be open to the potential for further adaptations of the innovation to address those surprises and/or unanticipated problems.

Loop 3 Knowledge Dissemination, Loop 4 Assimilation and 2(c) Routinizing

Winch (1998), Widén (2006) and Widén & Hansson (2007) argues that, unless an innovation is widely used beyond the boundaries of the project it was introduced in, only minimal organizational gain will be achieved. To facilitate this in project-based industries such as construction industry, organizational learning is necessary. For project-based firms with industry specific challenges, organizational learning is regarded as a core competency (Eken, Bilgin, Dikmen, & Birgonul, 2020). The project-based nature induces a short-term perspective and a focus on suboptimization, which means that the abundant knowledge gained during the projects usually remain tacit with the project members. Such knowledge and ideas which remains tacit in the projects are difficult to be managed into ‘good currency’ for the organization (Winch, 1998). Intrinsically, to maximise organizational gains, sharing and utilizing ideas, information, and knowledge across projects are very important. To facilitate such organizational learnings, our diffusion model incorporated the Knowledge Dissemination Loop, the idea of which is to take learnings from projects and disseminate it in the organization through a centralised knowledge dissemination point. This in turn will modify the technological advancements in the firm, thereby triggering the agenda setting in a new project. This loop of innovation diffusion, continuous learning, and knowledge dissemination, which triggers the agenda setting in simultaneous or sequential projects, is termed as the assimilation loop. These findings are related to the findings of Papadonikolaki (2018), who argued that the sub system's interactions and behaviour in the local contexts triggers the emergence of global structures and behaviours in the social system.

The result of assimilation loop is routinization of the innovation in the firm. The same was identified in the diffusion of 3D BIM, which after several assimilation loops was routinized in the firm. According to Rogers (2003), when an innovation is routinized, it will lose its identity as a 'new idea'. Similarly, Swanson and Ramiller (2004) argued that the innovation will be seen as a normal activity by the members of the social system at this stage. Both observations were identified for the case of 3D BIM diffusion in the firm. In the assimilation loop, the phenomenon which plays a role is the diffusion effect. Rogers (2003, p. 240) defined diffusion effect as the *"cumulatively increasing degree of influence upon an individual to adopt or reject an innovation".* The effect is a result of the increasing peer pressure. Rogers (2003, p.40) further explains that when the awareness about the innovation within the social system cross the threshold of 20-30%, further awareness and thus the adoption rate within that social system accelerates. Each assimilation loop will increase the awareness of the innovation in the firm, thereby triggering increased initiation of diffusion in various projects, gradually resulting in the routinization of the innovation in the firm.

6.2. Implications for Practice

In addition to the developed strategic framework, the findings of this research offer several other implications to practice. First, it is important to have an entrepreneurial and innovative culture in firms who are attempting to innovate in the complex social system of the construction industry. The characteristics of the construction industry makes innovating within it challenging. Hence, firms should provide enough space and support for enthusiastic individuals to take on such challenges affecting diffusion of innovations.

Second, the composition of project teams should respect innovativeness of individuals. The innovativeness of individuals determines their attitude during innovation diffusions. As such, an ideal scenario for innovation diffusion is project teams with earlier adopters in strategic and tactical responsibilities. However, our results also suggest that tactical responsibility personnel have bigger influence on innovations which are related to their role in the project. Thus, project teams with earlier adopter tactical responsibility personnel (related to the innovation) could also be perfect for innovation diffusions.

Third, diffusion networks are crucial elements of a firms' diffusion processes and should be identified (or established) and managed. Furthermore, the communication channels used to share information about the innovation should depend on the target audience (earlier adopters prefers mass media channels and later adopters prefer interpersonal channels) and the information shared should be concrete and specific as possible (particularly for later adopters).

Lastly, a proper matching procedure rooted in the project context is extremely important for successful diffusion of innovations. This is also important for incremental innovations, as incremental innovations in one project context could still be perceived as radical in another project context. Thus, innovators should not draw conclusions from prior successes and should not take generalised claims about the innovation as the basis of their adoption decisions. Adoption decisions should always be backed by a thorough feasibility analysis rooted in the project context. It is also important to note that the lack of feasibility analysis have led to discontinuance of innovations in many cases, and such failed diffusions has always led to increased fear and resistance towards the innovations, which further slows down the rate of adoption.

6.3. Research Limitations and Directions for Further Research

As all research, this research has some limitations that must be touched on, which also opens room for further research. First, even though the strategic framework is meant to be for the whole construction industry, the research client was engineering consultants, and thus the resultant framework is derived from research in the engineering consultancy industry. Even though factors specific to engineering consultancy are not included in the strategic framework or has affected the development of the same, the generalizability of the framework might be influenced. This owes to the fact that the different firms in the AECO industry, Architectural, Engineering, Construction, and Operations, are predominantly involved in different phases of a construction project, which means that the phase-specific characteristics could affect the strategies outlined in the framework. Furthermore, the factors influencing generalizability are also related to the structural characteristics of the firm, which could be very different when compared to other firms. Thus, the validity of the framework could be extended by assessing it across various industry sectors and construction firms.

Second, even though the research considered the external factors affecting the diffusion such as client and external party involvements, further research focussed on the direct effect of such external factors on the strategic framework could contribute towards the validity of the framework. More studies concerning the role and influence of such external parties in the different stages, particularly the agenda setting and matching stages, should be conducted with a focus on how the influences can be managed.

Third, the digital innovations selected for the case studies were all assessed in design and planning of infrastructure projects of the same firm and 'only' three cases were analysed. Albeit rather representative, this might have affected the generalizability of the results, as the digital innovations and the industry sectors are diverse in the construction industry. Furthermore, all the cases were analysed rather holistically in the organization and did not particularly follow a project-by-project pattern. This means that the diffusion of innovations was not followed in one single project to identify the different stages, but rather a holistic approach was taken to assess the existence of different stages because of time constraints. Thus, it is suggested to conduct further long-term (or even longitudinal) research with diverse digital innovations in diverse sectors and firms, which studies diffusion of a specific innovation in a specific project using the strategic framework and analyses the effect of the diffusion on the organization and its other projects. This will significantly contribute towards the validity and generalizability of the proposed strategic framework.

Another limitation is on the data collection for this research when it comes to the attributes of innovation. Even though we paid maximum attention to diversity in the selection of the interview participants, the number of participants interviewed, particularly with day-to-day responsibility, were limited when compared to the proportion of the participants to the actual number in the social system. Hence, an extensive survey which covers all the members in the social system will be very advantageous in gauging substantial and concrete data about the importance of attributes of innovation and the members' perceptions about the diffusion process. Even though a qualitative approach provided in-depth analysis of the research area, quantitative approach can reinforce our findings through more objective results. Same can be said about the validation of the strategic framework. The strategic framework was validated by two domain experts and one academic expert. Thus, further validation with a larger number of diverse participants is recommended to improve the validity of the results.

7. Conclusion and Recommendations

This research was conducted to explore the grey areas of technology diffusion in the construction industry and thereby bridge the gap between the theoretical benefits advocated by various literature and the actual implementation of digital innovations in the industry. The clients of this research, W+B, wanted to scale up their rate of adoption of digital technologies, which is currently not at a desired level because of various known and unknown barriers restricting the diffusion of digital innovations. Thus, the objective of this research was *"to develop a strategic framework for enhancing digital innovation adoption, which can aid firms in construction to improve their rate of adoption of digital innovations in a sustainable manner"*. To establish a theoretical background for the defined research objective, a literature review was conducted, using which two theoretical priori constructs were defined. Priori Construct A explains four key factors which determines the rate of adoption of digital innovations. These factors are 1) characteristics of the social system, 2) innovativeness of individuals, 3) perceived attributes of innovation, and 4) diffusion networks. Priori Construct B illustrates a diffusion model consisting of the innovation process in organizations, the individual's innovation decision process, and the influence of the factors affecting the rate of adoption across the diffusion process. Using these two priori constructs, the research question was derived as *"what factors affect the adoption of digital innovations in the firm as perceived by their personnel and how can the rate of adoption be increased in a sustainable manner?".* The main research question was broken down and dealt with four sub-questions, each one of which will be answered in the reminder of this section.

RQ.1. How are digital innovations currently diffused in the firm and how is the current diffusion and progression of digital innovations perceived by different adopter categories? How does this differ for intra-disciplinary and inter-disciplinary innovations?

The diffusion of digital innovations takes a bottom-up approach in the firm, in which innovations are introduced by enthusiastic earlier adopters in the projects they are part of. The process often starts with the agenda setting stage, in which the perceived need for the innovation is identified. The agenda setting is most often triggered by the awareness of technological advancements beyond the firm boundaries for earlier adopters and within the firm boundaries for later adopters. Here, earlier adopters, mostly of tactical or strategic responsibility (PMC leaders, line managers, project managers), play the role of 'gatekeepers' of the innovations and brings the idea from outside of the organizational boundaries to the projects they are involved in. The feasibility of the specific innovation in the specific project context is often not entirely assessed and the decisions to adopt or reject the innovation is usually grounded in the innovation's prior success, in projects outside of the organizational boundaries for earlier adopters and within the organizational boundaries for later adopters. This inexistence of the matching stage, in which feasibility of the innovation is assessed in the local context, has led to failed diffusions or discontinuance in many cases. A proper matching procedure rooted in the local context is deemed necessary for successful diffusion of digital innovations, also because failed diffusions has always led to more fear and resistance against the innovation, which further slowed down the adoption rate of innovations.

Once the decision to adopt or reject the innovation is made, often a lot of development in terms of tools, protocols etc is carried out. In some cases, the project processes related to the specific innovation is restructured to accommodate the innovation. This step in the innovation diffusion process, the redefining/restructuring, is extremely important for successful diffusion and increased adoption of digital innovations. In some cases, such developments are orchestrated by groups of enthusiastic individuals within or beyond the project boundaries. Such innovation groups act as change agents and often facilitates the innovation diffusion processes. Once the innovation is successfully diffused in a project, the knowledge is disseminated in the organization through various formal and informal communication channels, and the awareness of that innovation is increased in the firm, which triggers the agenda setting of the innovation in a subsequent project.

The diffusion of inter-disciplinary innovations often occurs on a project level, and the final adoption decision is always authority decision, i.e., the final adoption decision is always made by the strategic responsibility personnel. For intra-disciplinary innovations, the innovation diffusion was often observed at the PMC level rather than project level. For such innovations, the adoption decision is often optional or collective decisions, i.e., the innovation adoption decisions are made by either an individual or a group, irrespective of the adoption decisions of the rest of the network. The individual, or the group makes the decision to adopt or reject the innovation after matching it with their existing needs and available resources. By nature, the use of intra-disciplinary innovations is mostly concerned with one discipline only, whereas inter-disciplinary innovation requires alignment and sometimes integration of different disciplines. This difference makes the diffusion of intra-disciplinary innovations a bit less complex than inter-disciplinary innovations. However, when the intra-disciplinary innovations are diffused in project level (rather than PMC level), it might still affect other disciplines, thus taking characteristics of inter-disciplinary innovations. Apart from these differences, both intra and inter disciplinary innovations were identified to follow a similar diffusion process.

RQ. 2. What attributes of innovation enables or restricts the diffusion of digital innovations for each adopter category? How does this differ for intra-disciplinary and inter-disciplinary innovations?

This research assessed attributes of innovation using the priori constructs defined based on Rogers (2003) Diffusion of Innovation theory. The five attributes assessed were relative advantage, compatibility, complexity, observability and trialability. The results indicate that all five attributes are instrumental when it comes to shaping the perceptions of individuals. In addition to these five attributes, an additional attribute was also identified, affinity. The first attribute, relative advantage, is the benefits of the innovation in comparison with whatever it is replacing. Relative advantage was found to be instrumental in triggering the thought process of the individual's innovation decision process and the agenda setting stage. Once the relative advantage of the innovation is clear, the individuals are then concerned with the compatibility and complexity of the innovation. Compatibility is the consistency of the innovation with the individual's previous experiences and values while complexity is the perceived difficulty to learn the innovation. Both compatibility and complexity play a crucial role in enabling or restricting the innovation diffusion process. Incompatible and complex innovations are perceived as hard to be diffused unless and until the innovation or processes are reinvented or restructured respectively to accommodate the innovation and until the adopters possess adequate resources to learn about and use the innovation.

The complexity of the innovation is also closely related to the attribute of affinity. Affinity is an individual's liking and interest towards the profile of the innovation. Individuals who have a positive affinity towards the innovation tends to learn the innovation even if it is complex (given the relative advantage is clear), whereas individuals with a negative affinity prefers not to learn the innovation if it is perceived as complex. Once the individuals make a favourable decision to adopt the innovation and starts using it, the observable results reinforce or inhibits the diffusion process, which is related to the attribute of observability. Also at the same time, the trialability attribute comes into forefront. Trialability is the opportunity to test the innovation before implementing it on a larger scale. The trialability attribute was considered more important by earlier adopters than later adopters. This is because earlier adopters do not have any references within the organizational boundaries when they bring in the innovation, whereas later adopters often have references set by the earlier adopters in prior implementations.

While the relative advantage, affinity and observability were considered equally important by both earlier and later adopters, later adopters consider complexity and compatibility more detrimental than earlier adopters and earlier adopters consider trialability as more detrimental than later adopters. However, no major differences were found between intra and inter disciplinary innovations when it comes to an individual's decision process and attributes of innovation. Furthermore, the way the attributes are assessed by individuals does depend on their roles and responsibilities. This was noted particularly for relative advantage and complexity. For instance, strategic responsibility and daily responsibility personnel have different considerations for the attribute of complexity. When it comes to daily responsibility, the level they have to understand the innovation is deeper than strategic responsibility, as the former has to make use of the innovation in their day-to-day activities, while the latter most often only have to understand the innovation up to a level with which they can facilitate its use.

RQ. 3. What is the role of diffusion networks in the diffusion process of digital innovations as perceived by different adopter categories?

The research indicates that the diffusion networks are instrumental in an innovation diffusion process, and it plays a role in almost every stage of an individual's innovation decision process. The diffusion networks should be managed and exploited to improve the awareness about a digital innovation and to shape a positive attitude towards it. Some key components of the diffusion networks are the communication channels, heterophily, opinion leaders and internal companion. Results indicate that individuals prefer different communication channels based on their innovativeness. While earlier adopters prefer mass media channels from cosmopolite sources, later adopters prefer interpersonal channels from local sources. The interpersonal networks thus play a major role in the diffusion network. Heterophily in these interpersonal networks enhances the personnel's awareness of various innovations across the firm. Opinion leaders, who can informally influence other's opinions also have a major role in the diffusion process. Such opinion leaders can form positive or negative attitude towards an innovation and hence should be identified and exploited/managed. The last aspect identified is the presence of internal companions, who motivates and assists an individual to learn about or develop innovative solutions and ideas. These four aspects of diffusion networks should be managed in the diffusion process in order to enhance the awareness and to shape positive attitudes towards the digital innovation.

RQ. 4. What should a strategy which aims to improve the rate of adoption of digital innovation comprise of?

The strategy to enhance the rate of adoption of digital innovations should comprise of the factors which affects the adoption of digital innovations, and a diffusion model which exploits and manages these factors. As such, the developed strategic framework comprises of two parts, 1) the factors affecting rate of adoption and 2) model of innovation diffusion process. The factors affecting the rate of adoption are the structure and characteristics of the social system, innovativeness of individuals, attributes of innovation and diffusion networks. The diffusion model captures these factors and focusses on three levels, the organizational level, project level and individual level. The organizational level consists of the innovation acceleration groups, which are coordinated by the knowledge dissemination point. These two parties play a key role throughout the diffusion process by assisting the feasibility analysis of the innovation in the project context, training of personnel and developing tools, instructions, and protocols for the digital innovation. Furthermore, the project level consists of six stages and three reinforcing loops, which strongly influences the stages in the individual level. Repeated loops of the stages in the project and organizational level will induce increased diffusion effect in the organization, resulting in the routinization of the innovation.

During the validation of the strategic framework, it was reviewed as a strong model which gives a holistic view to the diffusion process, thereby allowing organizations to understand where the innovation diffusion is stopping in projects and reinforce the diffusion process in the firm through the various loops. However, more attention is required on the composition and functioning of the knowledge dissemination point, and the organization and strategy of the training stage in the innovation diffusion model.

Conclusion

To conclude, diffusion of digital innovations poses multifaceted problems which requires multifaceted solutions. We studied the diffusion process in an engineering consultancy using theoretical constructs defined based on Rogers Diffusion of Innovation theory, and developed a multifaceted strategic framework comprising of a diffusion model addressing three levels of innovation diffusion: the organizational level, project level and individual level. The findings of this research and developed strategic framework for enhancing technology adoption are of a high degree of corporate and scientific relevance. The strategic framework can aid firms in construction to plan their innovation diffusion activities and aid their efforts to enhance the rate of adoption of digital innovations. The framework explains what factors affects the rate of adoption of digital innovations and how these factors can be managed through a comprehensive diffusion model. Thus, the research sheds more light into the grey areas of technology diffusion in the construction industry by recommending solution towards resolving the identified barriers in the form of the strategic framework. It thus contributes towards bridging the gap between theoretical benefits of digital innovations and its actual implementation in the industry.

As digital innovations become routinized in firms through the phenomenon of *diffusion effect*, further effects could be on the industry itself, which slowly (but surely) can lead to successful digital transformation of the construction industry.

7.1. Recommendations

This research was conducted to contribute towards W+B's ambition to become industry leaders in digital engineering and BIM. Following the findings of this research and the resultant strategic framework, few recommendations can be drawn towards this ambition. They are:

Composition of the Knowledge Dissemination Point

The knowledge dissemination point is supposed to be at the summit of the diffusion process, thereby having an overview of all the diffusion processes throughout the organization. It should best be formed as a group consisting of the group leaders of the innovation acceleration groups. As such, the knowledge dissemination point will have easy access to all the developments throughout the organization, thus further cementing their position at the summit of the diffusion processes. In addition, it is best that the group have a fair degree of heterophily, as their diverse interpersonal networks will further enhance the awareness of the innovation in the organization. Furthermore, it is also important to consider personnel with opinion leadership for both innovation acceleration group leadership and the knowledge dissemination point. Opinion leaders can have an instrumental role in shaping the attitude towards the innovation, thus directly influencing the innovation diffusion.

Earlier Adopters for Tactical Responsibility

Even though strategic responsibility individuals have the final say in the adoption decisions of digital innovations, tactical responsibility personnel were found to have a very high influence on these adoption decisions. Thus, for successful initiation for innovations in process, it is recommended to have earlier adopters in strategic or tactical responsibility (or both) in the project teams. Tactical responsibility personnel, being PMC leaders, team leaders, line managers etc, have high influence on both the strategic and daily responsibility personnel, and their sphere of influence should be exploited in the diffusion process. For the same, there should be increased initiatives from the tactical responsibility personnel towards the diffusion of digital innovations and they should create an environment in projects and PMCs for personnel to develop and use digital innovations.

Training Stage

The training stage is a very crucial and complex stage in the innovation diffusion process. There should be more analysis into the organization and management of training within and beyond the projects in the organization. However, the immediate recommendations towards the training stage are to focus on taking small steps in projects with the digital innovations, and a balanced project team composition with respect to the innovativeness, knowledge, and expertise of individuals. Building the innovation step by step in projects gives the time and space for the individuals to learn and adopt the innovation without compromising the project deliverables, while balanced team composition will contribute towards collective learning. In addition, the trainings must be well designed and structured, giving the employees all the necessary information for adopting the innovation. In addition, establishing competence centres in the organization, with a responsibility of designing and implementing focussed training programs, is a promising option. Such competence centres can be charged with R&D as well. However, further studies are required to assess the feasibility and the structure of competence centres.

To wrap up, some questions still pose a risk to the implementation of the developed strategy, with the most important one being where to start with the implementation. Such further barriers should be identified, assessed, and mitigated to ensure a smoother implementation of the strategic framework and thereby a smoother innovation diffusion process in project-based AECO firms.

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8. References

Adriaanse, A. M. (2007). *The use of interorganisational ict in construction projects: a critical perspective.* University of Twente.

Adriaanse, A., Dewulf, G., & Voordijk, H. (2009). The introduction of Building Information Modelling in construction projects: An IT innovation perspective. *9th International Conference on Construction Applications of Virtual Reality.*

Agarwal, R., Chandrasekaran, S., & Sridhar, M. (2015). *Imagining construction's digital future.* New York: McKinsey.

Ali, M. M., & Chileshe, N. (2009). The influence of the project manager on the success of the construction projects. *ICCEM-ICCPM.*

Bamberger, P. A. (2018). AMD- Clarifying what we are about and where we are going. *Academy of Management Discoveries, Vol. 4*, 1-10.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., . . . Brown, S. (2017). *Reinventing Construction: A route to higher productivity.* McKinsey & Company.

Berlak, J., Hafner, S., & Kuppelwieser, V. G. (2020). Digitalization's impacts on productivity: a modelbased approach and evaluation in Germany's building construction industry. *Production Planning & Control, DOI: 10.1080/09537287.2020.1740815*.

Breen, R. L. (2006). A Practical Guide to Focus-Group Research. *Journal of Geography in Higher Education, 30:3*, 463-475.

Bresnen, M., Goussevskaia, A., & Swan, J. (2006). Implementing change in construction project organizations: exploring the interplay between structure and agency. *Building Research and Information, Vol. 33 No. 6*, 547-560.

Burnes, B. (1992). *Managing Change: A Strategic Approach to Organisational Development and Renewal.* Pitman.

Carter, N., Bryant-Lukosius, D., DiCenso, A., Blythe, J., & Neville, A. (2014). he use of triangulation in qualitative research. *Oncol Nurs Forum 41(5)*, 545-7.

Cesnik, J., Zibert, M., Lah, M., & Skalja, M. (2019). Required model content and information workflows enabling proficient BIM usage. *IOP Conf. Series: Materials Science and Engineering* (p. 603). IOP Publishing.

Chandra Y., S. L. (2019). Inductive Coding. In S. L. Chandra Y., *Qualitative Research Using R: A Systematic Approach* (pp. https://doi.org/10.1007/978-981-13-3170-1_8). Singapore: Springer.

Crespin-Mazet, F., Goglio-Primard, K., Havenvid, M. I., & Linné, Å. (2021). The diffusion of innovation in project-based firms – linking the temporary and permanent levels of organisation. *Journal of Business & Industrial Marketing Vol. ahead-of-print*.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., & Sheikh, A. (2011). The case study approach. *BMC Med Res Methodology, 11: 100*, doi: 10.1186/1471-2288-11-100.

Dubois, A., & Gadde, L.-E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction Management & Economics, 20:7*, 621-631.

Dudhee, V., & Vukovic, V. (2020). Superimposing Building Information Models in Augmented Reality. *Proceedings of the 20th International Conference on Construction Applications of Virtual Reality* , (pp. 11-18.). Teesside University.

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *The Academy of Management Review Vol. 14, No. 4*, 532-550.

Eken, G., Bilgin, G., Dikmen, I., & Birgonul, M. T. (2020). A lessons-learned tool for organizational learning in construction. *Automation in Construction, Vol. 10*.

Eriksson, P. (2013). Exploration and exploitation in project-based organizations: development and diffusion of knowledge at different organizational levels in construction companies. *International Journal of Project Management, Vol. 31 No. 3*, 333-341.

Ernstsen, S. N., Whyte, J., Thuesen, C., & Maier, A. (2021). How Innovation Champions Frame the Future: Three Visions for Digital Transformation of Construction. *Journal of Construction Engineering & Management, 147(1)*, 05020022.

Gadde, L., & Dubois, A. (2010). Partnering in the construction industry-problems and opportunities. *Journal of Purchasing and Supply Management, Vol. 16*, 254-263.

Gallestey, J. B. (2020, February 20). *Cluster analysis.* Retrieved from Encyclopedia Britannica: https://www.britannica.com/topic/cluster-analysis

Gambatese, J. A., & Hallowell, M. (2011). Factors that influence the development and diffusion of technical innovations in the construction industry. *Construction Management and Economics 29*, 507–517.

Gerbert, P., Castagnino, S., Rothballer, C., Renz, A., & Filitz, R. (2016). *Digital in Engineering and Construction; The Transformative Power of Building Information Modelling (The Boston Consulting Group).*

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *Br Dent J 204*, 291–295.

Gledson, B. J. (2016). Hybrid project delivery processes observed in constructor BIM innovation adoption. *Construction Innovation Vol. 16 No. 2*, 229-246.

Gledson, B. J., & Greenwood, D. (2017). The adoption of 4D BIM in the UK construction industry: an innovation diffusion approach. *Engineering, Construction and Architectural Management, Vol. 24*, 950-967.

Glen, S. (2021). *Inferential Statistics: Definition, Uses.* Retrieved from StatisticsHowTo.com: Elementary Statistics for the rest of us!: https://www.statisticshowto.com/probability-and-statistics/statistics-definitions/inferential-statistics/

Harty, C. (2005). Innovation in construction: a sociology of technology approach. *Building Research & Information, 33*, 512–522.

Harty, C. (2008). Implementing innovation in construction: contexts, relative boundedness and actor network theory. *Construction Management and Economics, Vol. 26 No. 10*, 1029-1041.

Hurt, H., Joseph, K., & Cook, C. (1977). Scales for the measurement of innovativeness. *Human Communication Research, Vol. 4*, 58-65.

Karimi, S., & Iordanova, I. (2020). Integration of BIM and GIS for Construction Automation, a Systematic . *Archives of Computational Methods in Engineering Literature Review (SLR) Combining Bibliometric and Qualitative Analysis*.

Khudhair, A., Li, H., Ren, G., & Liu, S. (2021). Towards Future BIM Technology Innovations: A Bibliometric Analysis of the Literature. *Applied Sciences, 11, 1232*.

Kotter, J. P., & Schlesinger, L. A. (2008). *Choosing Strategies for Change.* Harvard Business Review.

Koutsogiannis, A. (2020, September). *Escaping the blame game: Enable onsite teams to make decisions quicker and deliver sooner*. Retrieved from Lets Build: https://www.letsbuild.com/blog/blame-culture-in-construction

Kyriakou, N., Euripides, L., & Paraskevi, D. (2020). Factors affecting cloud storage adoption by Greek municipalities. *In Proceedings of the 13th International Conference on Theory and Practice of Electronic Governance (ICEGOV 2020)* (pp. 244–253). New York, NY, USA: Association for Computing Machinery.

Li, H., Huang, T., Kong, C., Guo, H., Baldwin, A., Chan, N., & Wong, J. (2008). Integrating design and construction through virtual prototyping. *Automation in Construction 17*, 915-922.

Linderoth, H. C., Jacobsson, M., & Elbanna, A. (2018). Barriers for Digital Transformation: The Role of Industry. *Australasian Conference on Information Systems.* Sydney.
Lindgren, J., & Widén, K. (2019). Exploring the Dynamics of Supplier Innovation Diffusion. *Emerald Reach Proceedings Series, Vol. 2*, 2516-2853.
Lundberg, M., Engström, S., & Lidelöw, H. (2019). Diffusion of innovation in a contractor company; The impact of the social system structure on the implementation process. *Construction Innovation, Vol. 19 No. 4*, 629-652.
Merschbrock, C., & Munkvold, B. E. (2015). Effective digital collaboration in the construction industry – A case study of BIM deployment in a hospital construction project. *Computers in Industry 73*, 1-7.
Miller, C., Hersberger, C., & Jones, M. (2013). Automation of common building energy simulation workflows using python., (p. DOI: 10.13140/RG.2.1.1999.4087).
Moore, G. A. (2014). *Crossing the chasm: Marketing and selling disruptive products to mainstream customers- 3rd edition.* New York: Harper Collins.
Morgan, B. (2019). Organizing for digitalization through mutual constitution: the case of a design firm. *Construction Management and Economics, 37:7*, 400-417.
Morris, P., & Pinto, J. (2004). Project management in the construction industry. In P. W. Morris, *The Wiley guide to managing projects* (pp. 1350–1367). Hoboken, NJ: John Wiley & Sons.
Natow, R. S. (2020). The use of triangulation in qualitative studies employing elite interviews. *Qualitative Research Vol. 20(2)*, 160–173.
Oloke, D. (2020). Deployment of Building Information Modelling (BIM) for Energy Efficiency in the UK. *Collaboration and Integration in Construction, Engineering, Management and Technology*, (pp. 559-564).
Papadonikolaki, E. (2018). Loosely coupled systems of innovation: aligning BIM adoption with implementation in Dutch construction. *Journal of Management in Engineering, Vol. 34 No. 6.*
Poirier, E., Staub-French, S., & Forgues, D. (2015). BIM adoption and implementation for a specialty contracting SME. *Construction Innovation, Vol. 15 No. 1*, 1471-4175.
Rivera, F. M.-L., Mora-Serrano, J., Valero, I., & Oñate, E. (2020). Methodological-Technological Framework for Construction 4.0. *Archives of Computational Methods in Engineering, 28*, 689–711.
Robinson, W., Chan, P., & Lau, T. (2016). Sensors and sensibility: examining the role of technological features in servitizing construction towards greater sustainability. *Construction Management and Economics, Vol. 34 No. 1*, 4-20.
Rogers, E. (2003). *Diffusion of Innovations, 5th ed.* New York: Free Press.
Sahin, I. (2006). Detailed review of rogers' diffusion of innovations theory and educational technology-related studies based on rogers' theory. *The Turkish Online Journal of Educational Technology, ISSN: 1303-6521, volume 5 Issue 2 Article 3*.
Sandberg, M., Gerth, R., Lu, W., Jansson, G., Mukkavaara, J., & Olofsson, T. (2016). Design automation in construction – an overview . *Proceedings of the 33rd CIB W78 Conference 2016*, (pp. http://ltu.diva-portal.org/smash/get/diva2:1045280/FULLTEXT01.pdf). Brisbane, Australia.
Shibeika, A., & Harty, C. (2015). Diffusion of digital innovation in construction: a case study of a UK engineering firm. *Construction Management and Economics, 33:5-6*, 453-466.
Succar, B. (2009). Building information modelling framework: A research and delivery foundation forindustry stakeholders. *Automation in Construction 18*, 357–375.
Swan, J., Scarbrough, H., & Newell, S. (2010). Why don't (or do) organizations learn from projects? *Management Learning, Vol. 41 No. 3*, 325-344.

Swanson, E., & Ramiller, N. (2004). Innovating mindfully with information technology. *MIS Quarterly, 28(4)*, 553-583.
Taofeeq, D., & Adeleke, A. (2019). Factor's Influencing Contractors Risk Attitude in the Malaysian Construction Industry. *Journal of Construction Business and Management, 3(2)*, 59-67.
Tavory, I., & Timmermans , S. (2014). *Abductive Analysis: Theorizing Qualitative Research.* University of Chicago Press.
Widén, K. (2006). *Innovation diffusion in the construction sector.* Doctoral Thesis, Lund University.
Widén, K., & Hansson, B. (2007). Diffusion characteristics of private sector financed innovation in Sweden. *Construction Management and Economics, Vol. 25 No. 5*, 467-475.
Winch, G. (1998). Zephyrs of creative destruction: understanding the management of innovation in construction. *Building Research & Information, 26:5*, 268-279.
Winch, G. M. (2003). How innovative is construction? Comparing aggregated data on construction innovation and other sectors – a case of apples and pears. *Construction Management and Economics, 21:6*, 651-654.
Yin, R. (2003). *Case Study Research: Design and Methods 3rd Edition.* Thousand Oaks: Sage Publications.

Appendix A- Questionnaire for Adopter Categorization

The questionnaire is based on Individual Innovativeness Scale (II) developed by Hurt et al (1977) and was used for online surveys. The questionnaire:

“Directions: People respond to their environment in different ways. The statements below refer to some of the ways people can respond. Please indicate the degree to which each statement applies to you by marking whether you: Strongly Disagree = 1; Disagree = 2; are Neutral = 3; Agree = 4; Strongly Disagree = 5 Please work quickly, there are no right or wrong answers, just record your first impression.

________ 1. My peers often ask me for advice or information.

________ 2. I enjoy trying new ideas.

________ 3. I seek out new ways to do things.

________ 4. I am generally cautious about accepting new ideas.

________ 5. I frequently improvise methods for solving a problem when an answer is not apparent.

________ 6. I am suspicious of new inventions and new ways of thinking.

________ 7. I rarely trust new ideas until I can see whether the vast majority of people around me accept them.

________ 8. I feel that I am an influential member of my peer group.

________ 9. I consider myself to be creative and original in my thinking and behaviour.

________10. I am aware that I am usually one of the last people in my group to accept something new.

________11. I am an inventive kind of person.

________12. I enjoy taking part in the leadership responsibilities of the group I belong to.

________13. I am reluctant about adopting new ways of doing things until I see them working for people around me.

________14. I find it stimulating to be original in my thinking and behaviour.

________15. I tend to feel that the old way of living and doing things is the best way.

________16. I am challenged by ambiguities and unsolved problems.

________17. I must see other people using new innovations before I will consider them.

________18. I am receptive to new ideas.

________19. I am challenged by unanswered questions.

________20. I often find myself sceptical of new ideas.

Scoring:

- Step 1: Add the scores for items 4, 6, 7, 10, 13, 15, 17, and 20.
- Step 2: Add the scores for items 1, 2, 3, 5, 8, 9, 11, 12, 14, 16, 18, and 19.
- Step 3: Complete the following formula: II = 42 + total score for Step 2 – total score for Step 1.

Categorization:

- Scores above 80 are classified as Innovators.
- Scores between 69 and 80 are classified as Early Adopters.
- Scores between 57 and 68 are classified as Early Majority.
- Scores between 46 and 56 are classified as Late Majority.
- Scores below 46 are classified as Laggards/Traditionalists.

In general people who score above 69 and considered as Earlier Adopters, and people who score below 65 are considered Later Adopters" (Hurt et al, 2003).

Appendix B- Questionnaire for interviews: Case 1

Interview name: 3D BIM
Interview format: *Online face to face.*
Interview structure: *Semi-structured.*
Time: *1 hr.*

The Organizational Diffusion Process

1. In your words, how would you describe 3D BIM? (What is your role in its use?) → *Aim of the question is to assess the consistency of understanding about what 3D BIM is across the organization.*
2. Why was 3D BIM introduced in the firm?
    a. How did the firm decide 3D BIM was the solution (if agenda setting is clear)?

    → *Attempts to understand if 'Agenda setting' and 'matching' stages from Priori construct B happened, and if it did, is the understanding consistent.*
3. Can you describe the process through which 3D BIM was introduced in W+B? → *Understand how 3D BIM was diffused. Stress on structural characteristics of the social system and the project-based nature of the industry.*
4. What factors contributed to the aforementioned process? → *Aims to understand the factors which helped the diffusion process.*
5. What were the roadblocks during the diffusion, how was those roadblocks dealt with? → *Aims to understand the factors which restricted the diffusion and how was it dealt with.*

The individual decision process and attributes of innovation

6. Your awareness about BIM.
    a. When did you decide to know about BIM?
    b. how did you seek information and where did you get most information from?

    → *Aims to understand the 'Knowledge' stage from Priori construct B, and to see when do individuals seeks understanding about an innovation and where do they prefer that information from.*
7. What qualities (attributes) of 3D BIM persuaded you in your decision? → *Aims to understand the key attributes of innovation, without provocations.*
    a. Was 3D BIM better than the idea it supersedes, and how did this affect your decision? → *Relative Advantage*
    b. Was 3D BIM consistent towards your experiences, needs and existing norms how did this affect your decision? → *Compatibility*
    c. Was 3D BIM difficult to understand and how did this affect your decision? → *Complexity*
    d. Was the 3D BIM trailed and did it affect your decision? → *Trialability*
    e. Was the results of 3D BIM apparent, and how did this affect your decision? → *Observability*
8. What was the role of your interpersonal networks in your decision to adopt 3D BIM?
    a. Did any specific individual(s) influence your decision? → *Opinion leaders*
    b. Did your interpersonal networks have personnel of different disciplines and roles, and did it help in your adoption decision? →*Heterophily of interpersonal networks*

Appendix C- Questionnaire for interviews: Case 2 & 3

Interview name: *Scripting & Programming, and 5D BIM*
Interview format: *Online face to face*
Interview structure: *Semi-structured*
Interview time: *1-1.5 hrs.*

Process- Scripting

1. In your words, how would you explain scripting of design calculations?
2. Do you or your team currently Script design calculations in your design processes?
    a. If yes, why did you/your team decide to adopt scripting? → agenda setting/matching
    b. who made the decision to use/adopt scripting? → type of adoption decision
    c. From the decision to adopt to actually using it, can you explain the process through which scripting was introduced within your group or organization?
    d. Uncertainties
3. Why do you think scripting is not being adopted by more individuals/groups?
4. Are you aware of anyone (else) in your organization who currently uses scripting?
    a. Does this influence your decision?

Process- 5D BIM

5. In your words, how would you explain 5D BIM?
6. Do you or your team currently use 5D BIM?
    a. If yes, why did you/your team decide to adopt scripting? → agenda setting/matching
    b. who made the decision to use/adopt scripting? → type of adoption decision
    c. From the decision to adopt to actually using it, can you explain the process through which scripting was introduced within your group or organization?
    d. Uncertainties
7. Why do you think 5D BIM is not being adopted by more individuals/groups?
8. Are you aware of anyone (else)/any project in your organization who currently uses 5D BIM?
    a. Does this influence your decision?

9. Any comparison points between Scripting and 5D BIM?

The Individual Decision Process and Attributes of Innovation- Scripting

10. When did you decide to get knowledge about scripting?
    a. How did you seek information and where did you get it from? → more connection to university
    b. What factors helped you/blocked you from getting knowledge about scripting?
11. (if no knowledge) When will you prefer to know about Scripting?
    a. how and where do you prefer to get the knowledge about Scripting from?
12. What made you like/dislike the use of scripting?
13. What qualities (attributes) of Scripting do you consider as key?
    a. Do you think Scripting is better than the idea it supersedes?
        i. How is this affecting your decision?
    b. Do you think scripting is consistent towards your experiences, needs and existing norms?

        i. How is this affecting your decision?
    c. Is Scripting difficult to understand?
        i. How is this affecting your decision?
    d. Was scripting trailed?
        i. How is this affecting your decision?
        ii. If you have an opportunity to trial, can it change your decision?
    e. Are results of Scripting apparent?
        i. How is this affecting your decision?
14. What is the role of your interpersonal networks in your decision to adopt/reject Scripting? (Positive/Negative)
    a. Did any specific individual(s) influence your decision?
    b. Did your interpersonal networks have personnel of different disciplines and roles, and did it help in your adoption decision?

The Individual Decision Process and Attributes of Innovation- 5D BIM

15. When did you decide to get knowledge about 5D BIM?
    a. How did you seek information and where did you get it from?
    b. What factors helped you/blocked you from getting knowledge about 5D BIM?
16. (if no knowledge) When will you prefer to know about 5D BIM?
    a. how and where do you prefer to get the knowledge about 5D BIM from?
17. What made you like/dislike the use of 5D BIM?
18. What qualities (attributes) of 5D BIM do you consider as key?
    a. Do you think 5D BIM is better than the idea it supersedes?
        i. How is this affecting your decision?
    b. Do you think 5D BIM is consistent towards your experiences, needs and existing norms?
        i. How is this affecting your decision?
    c. Is 5D BIM difficult to understand?
        i. How is this affecting your decision?
    d. Was 5D BIM trailed?
        i. How is this affecting your decision?
        ii. If you have an opportunity to trial, can it change your decision?
    e. Are results of 5D BIM apparent?
        i. How is this affecting your decision?
19. What is the role of your interpersonal networks in your decision to adopt/reject 5D BIM? (Positive/Negative)
    a. Did any specific individual(s) influence your decision?
    b. Did your interpersonal networks have personnel of different disciplines and roles, and did it help in your adoption decision?

Appendix D- Plan of Approach for Focus Group Sessions

a. Goal and Topics to be Discussed

The goal of the focus groups will be to assess the attributes of innovation considered as key by individuals who have day to day responsibilities. In addition to that, the preferred type of innovation adoption decision and communication channels will also be explored, based on Priori Construct A: Factors affecting rate of adoption of innovations. Thus, the topics selected for discussion in focus groups are:

1. Attributes of innovation
    a. Relative advantage
    b. Compatibility
    c. Complexity
    d. Trialability
    e. Observability
2. Innovation adoption decisions
    a. Optional innovation decisions
    b. Collective innovation decisions
    c. Authority innovation decisions
3. Communication channels
    a. Mass media & interpersonal channels
    b. Local & cosmopolite sources
    c. Diffusion network & opinion leaders

b. Potential Participants

Size

Two focus group discussions were conducted, one with Earlier adopters and another one with Later adopters. Each group size was of 4 participants plus the researcher playing the role of moderator.

Composition

Homogeneity and heterogeneity were considered in the selection of participants. The homogeneity was considered in their innovativeness (earlier adopters/later adopters), their type responsibilities in the firm (day to day responsibilities) and age category (25-40). Such homogeneity helps to reduce inhibitions among people and will maximize disclosure amongst participants (Breen, 2006). Heterogeneity was considered on their PMCs. This helped to gather different perspectives based on different expertise of participants, which might fuel further discussions.

Participant Selection

Participants were selected using similar criterion for interviews for the cases. The surveys contributed to the adopter categorization and based on the survey results and aforementioned composition; participants were selected by the researcher in consultation with the company supervisor.

c. Session Design

Each focus group session was of 1 hour. The format was online face to face meetings. The researcher moderated the discussion with the 3 topics previously mentioned and some guiding questions around the same, given below. The focus was on the current diffusion of intradisciplinary and interdisciplinary innovations in the firm, which in this research was assessed using the case studies of Scripting and 5D BIM. As such, each topic was discussed for both cases in a session. This was done per topic, i.e.., the discussion started with topic 1 attributes of innovation for Scripting (Case 2), followed by attributes of innovation for 5D BIM (Case 3), thus opening room for discussions on comparisons between intradisciplinary and interdisciplinary innovations for each topic. Through this, insightful results were gathered which were very valuable for the research, complementing the results from (mainly) elite interviews.

d. Questionnaire for the Sessions

Format: Online face to face
No. of participants: 4 respondents + 1 researcher/moderator
Time: 1 hr.

Case 2: Scripting and Programming

1. Do you currently use scripting or programming in your functions?
2. If yes, why? What attributes of innovation was important?
    a. Relative advantage, do you think:
        i. Scripting & programming improves my productivity and efficiency
        ii. Scripting & programming reduces mistakes
        iii. Scripting & programming provides time/cost advantages to the project
    b. Compatibility, do you think:
        i. Scripting & programming is compatible and consistent with my previous experience
        ii. Scripting & programming is compatible with the culture and mentality of the company
    c. Complexity, do you think:
        i. Scripting & programming is difficult to understand and study
        ii. Implementing Scripting & programming requires more effort
        iii. Scripting & programming is difficult to use in projects
    d. Trialability, do you think:
        i. I require an opportunity to trial Scripting & programming before adopting it completely.
        ii. I need to see results from other projects which used Scripting & programming before adopting it completely.
    e. Observability, do you think:
        i. I see the results of scripting & programming
3. Decision making
    a. How was the decision to adopt scripting & programming made?
    b. How should the decision to adopt scripting be made? Should it be made by yourself, personally, or together by the team you are working with, or should it be made by the project manager/leader?
4. Communication Channels
    a. Where would you like information and knowledge about scripting and programming from? Sources inside of the company or outside?
    b. How would you like to get this information? From mass media like presentations or interpersonal channels like from colleagues

Case 3: 5D BIM

1. Do you currently use 5D BIM in your functions?
2. If yes, why? What attributes of innovation was important?
    a. Relative advantage, do you think:
        i. 5D BIM improves communication and coordination between disciplines
        ii. 5D BIM reduces mistakes in the project
        iii. 5D BIM provides time/cost advantages to the project
    b. Compatibility, do you think:
        i. 5D BIM is compatible and consistent with my previous experience
        ii. 5D BIM is compatible with the culture and mentality of the company
        iii. 5D BIM is compatible with the way of working of the company
    c. Complexity, do you think:
        i. 5D BIM is difficult to understand and study
        ii. Implementing 5D BIM requires more effort
        iii. 5D BIM is difficult to use in projects
    d. Trialability, do you think:
        i. I require an opportunity to trial 5D BIM before adopting it completely.
        ii. I need to see results from other projects which used 5D BIM before adopting it completely.
    e. Observability, do you think:
        i. I see the results of 5D BIM
3. Decision making
    a. How was the decision to adopt 5D BIM made? (if adopted)
    b. How should the decision to adopt 5D BIM be made? Should it be made by yourself, personally, or together by the team you are working with, or should it be made by the project manager/leader?
4. Communication Channels
    a. Where would you like information and knowledge about 5D BIM from? Sources inside of the company or outside?
    b. How would you like to get this information? From mass media like presentations or interpersonal channels like from colleagues

Diffusion Networks

1. What role does/can your interpersonal networks play in shaping your adoption decisions?
2. Can specific individuals shape your adoption decisions?

Appendix E- Overview of Interview and Focus Group Participants

Table a. Overview of Personnel for Data Collection Interviews and Focus Groups					
Case	Interview Type	Participant		Role	PMC
Interview 3D BIM	Retrospective	1	Strategic Responsibility Earlier Adopter	Project Manager	Underground Infrastructure
		2	Strategic Responsibility Later Adopter	Project Manager	Construction Management
		3	Tactical Responsibility Earlier Adopter	Group Leader	Construction management
		4	Tactical Responsibility Later Adopter	Line Manager	Infrastructural Engineering
		5	Daily Responsibility Earlier Adopter	BIM Coordinator	Infrastructural Engineering
		6	Daily Responsibility Earlier Adopter	BIM Coordinator	Infrastructural Engineering
		7	Daily Responsibility Later Adopter	Structural Engineer	Infrastructural Engineering
Interview Scripting and 5D BIM	Current perspective	1	Strategic Responsibility Earlier Adopter	Project Manager	Smart Infra Systems
		2	Strategic Responsibility Earlier Adopter	Project Manager	Infrastructural Engineering
		3	Strategic Responsibility Later Adopter	Project Manager	Underground Infrastructure
		4	Tactical Responsibility Earlier Adopter	PMC Leader	Construction management
		5	Tactical Responsibility Later Adopter	Line Manager	Traffic and Roads
		6	Daily Responsibility Earlier Adopter	4D Planner	Construction management
		7	Daily Responsibility Earlier Adopter	3D Modeller	Infrastructural Engineering
		8	Daily Responsibility Later Adopter	Structural Engineer	Traffic and Roads
All Cases	Focus Groups 1: Earlier Adopters	1	Daily Responsibility Earlier Adopter	3D Modeller	Underground Infrastructure
		2	Daily Responsibility Earlier Adopter	Structural Designer	Infrastructural Engineering
		3	Daily Responsibility Earlier Adopter	Road Designer	Traffic and Roads
		4	Daily Responsibility Earlier Adopter	Geotechnical Engineer	Underground Infrastructure
	Focus Group 2: Later Adopters	1	Daily Responsibility Later Adopter	Cost Engineer	Construction Management
		2	Daily Responsibility Later Adopter	System Engineer	Traffic and Roads
		3	Daily Responsibility Later Adopter	Safety Engineer	Underground Infrastructure
		4	Daily Responsibility Later Adopter	Structural Engineer	Traffic and Roads

Appendix F- Data Analysis- Barriers of 3D BIM Diffusion

Table b. Barriers which affected 3D BIM Diffusion

1st Order Concepts	2nd Order Themes	Overarching Dimension
Convincing the clients	Client interventions	External Barriers
Client intervened		
Client does not know what they want		
Presence of different external parties within projects	The presence of external parties in projects	
Guiding external partners are difficult		
External parties are lagging with BIM		
People are afraid to change	Fear/resistance to change	Internal Barriers
Fear of having more work		
Inconsistent awareness of BIM across the firm	Awareness issues	
Partial awareness of BIM across the firm		
No awareness of BIM		
User friendliness of the software		
Difference between people writing the proposal and executing the project		
Leadership of BIM group could not give full attention	Lack of focus on and in BIM group	
Decentralised BIM development turned out to be slow		
We had no technical support from an organizational point of view	Lack of intervention from the corporate level	
Lack of support from the board		
Some senior leaders are not aware of how to organize 3D BIM	Sceptical senior leaders	
It is hard to convince senior colleagues		
Senior managers could not convince external parties		
Difficulties in explaining the benefits of 3D BIM	Not knowing how to explain the benefits of BIM for different parties	Project Barriers
Difficulties in explaining the return of investment on BIM		
Difficulties in explaining the benefits to the BIM developers		
The scope had to change in flagship project	Difficulties in the flagship project to lead as an example	
Change of team in flagship project		
Setbacks in flagship project		
Lack of time available to develop tools and skills	Lack of time in projects	
The time required to develop BIM models was too big		
Lack of time available to learn new skills		
Lack of people with the required skills	Lack of resources	
The ICT department did not have enough expertise on BIM		

Appendix G- Data Analysis- Barriers of Scripting & Programming Diffusion

<table>
<tr><th colspan="3">Table c. Barriers restricting the diffusion of Scripting & Programming</th></tr>
<tr><th>First Order Concepts</th><th>Second order themes</th><th>Overarching dimensions</th></tr>
<tr><td>For data mining you need other parties (client, contractor) to collaborate and participate as well</td><td rowspan="3">Not knowing to explain to clients</td><td rowspan="8">Knowledge issues</td></tr>
<tr><td>We can't explain to our clients what the values of innovation are</td></tr>
<tr><td>Maybe some trainings are required to understand it better</td></tr>
<tr><td>Not everybody is that enthusiastic about the new developments</td><td rowspan="2">There is no standard way of training skills in the company</td></tr>
<tr><td>In most cases we do not have all the knowledge ourselves</td></tr>
<tr><td>If you do not have complete idea of a specific programming language, then it doesn't work</td><td rowspan="3">Lack of knowledge about scripting</td></tr>
<tr><td>Not knowing where to start</td></tr>
<tr><td>Not knowing what should be automated</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>I think we took quite a long time to check all the scripting files</td><td rowspan="9">Lack of time in projects to train people and to develop and validate scripts</td><td rowspan="10">Lack of Process and Technology Alignment</td></tr>
<tr><td>If you are not familiar with it and must acquire skills, then it takes time</td></tr>
<tr><td>It makes some time to make a script or program</td></tr>
<tr><td>It will take a long time for me to make a very good script</td></tr>
<tr><td>One roadblock is the decision regarding whether we can put additional time for scripting</td></tr>
<tr><td>The basic script file must be checked for a high level of detail to avoid any sort of mistake and we need enough time to do that</td></tr>
<tr><td>The engineers are focussed on making the scripts better while project leaders just want the drawings on time</td></tr>
<tr><td>When we must teach and mobilize other people then development takes more time</td></tr>
<tr><td>When we started, we only had one reference project which was a small tunnel project</td></tr>
<tr><td>We then realised that we haven't developed scripting to the extend to be completely used in the project (from a tech POV)</td><td>Incomplete technology in the firm</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Lacked expertise in the project team</td><td rowspan="5">Lack of skills and resources required</td><td rowspan="9">Lack of people alignment</td></tr>
<tr><td>Limited number of people that can work with scripts was a roadblock</td></tr>
<tr><td>We do not have enough skill (software engineers) within our PMC, so we need other PMCs to help us with that</td></tr>
<tr><td>We have limited resources for scripting which means we need to determine where to start</td></tr>
<tr><td>Sometimes the drawback is that people tend to blindly trust scripts</td></tr>
<tr><td>One disadvantage is that if you are not careful, there are no drawings to check, only codes. So must be careful</td><td rowspan="2">People blindly trusts scripts which can be an issue</td></tr>
<tr><td>Fear of people who do not know how and where to start and if they will understand scripting or not</td></tr>
<tr><td>First question people ask for new innovations is that will it bring more work to me or will it make my work easier</td><td rowspan="2">Fear/resistance to change</td></tr>
<tr><td>They may be scared of the new developments</td></tr>
</table>

Appendix H- Data Analysis- Barriers of 5D BIM Diffusion

Table c. Barriers restricting the diffusion of 5D BIM		
First order Concepts	Second Order Themes	Overarching Dimensions
Many people do not completely understand 5D BIM	Lack of awareness of 5D BIM	Awareness issues
There is still miscommunication and misinterpretation about (3D+) BIM		
There is no single understanding of 5D BIM across the organization		
Even for extracting quantities, it was hard to convince cost estimators	Benefits not clear and understood	
The benefits of 5D BIM are mainly for the clients so if they do not want it we cant do it		
The BIM users understand the benefits of 5D BIM, but it is only a small section of people		
ROI not clear		
Different disciplines are not communicating at all, and it is like different processes	Lack of integration of disciplines and processes	Lack of process alignment
The cost estimators need lot of pre work with the extracted quantity take off because they are not integrated		
The designers and the planners were not aligned		
The cost estimators have little knowledge with BIM	Designers and cost engineers do not (attempt to) understand each other's processes	
We (designers and cost engineers) have different definitions of specific terms (area for ex)		
The cost engineers always had some accuracy issues.		
Reinventing the wheel instead of reinforcing the wheel	Reinventing the wheel instead of reinforcing the wheel	
At this time, we do not have the necessary technology to do it as well	Incomplete technology within the firm	Lack of technology and people alignment
It is difficult to consider costs other than material costs in 5D BIM		
We still do not have a common object library		
Lack of people	Lack of resources	
Lack of standards		
Being a consultancy company, the firm sometimes don't need to deliver detailed cost information	5D BIM not in the project deliverables scope	External factors
What we need to deliver for cost and what is needed for 5D BIM does not match		
Client does not want it	Lack of support from external parties	
The contractor does not want to share the cost details because it is their competitive advantage		

Appendix I- Strategy for Enhancing Technology Adoption