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INVESTIGATING THE IMPACT OF BUILDING INFORMATION MODELING ON COLLABORATION IN THE ARCHITECTURE, ENGINEERING, CONSTRUCTION AND OPERATIONS INDUSTRY

MONTREAL, NOVEMBER 20, 2015

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FOREWORD AND ACKNOWLEDGMENTS

I embarked on this journey four years ago not knowing what I was getting into. At that time I was working full time for an architectural office in Vancouver, work that went on roughly for another year and a half, and I was getting more and more upset with the state of things in our industry. Although I had worked on some major projects over the 5 years that I had been practicing architecture at that point, I never had the chance to work on a project that didn't involve a flurry of accusatory e-mails and awkward meetings. Given my junior status for the first couple of years, I could fly under the radar, keep my head down and do my job, which mainly consisted in drafting and detailing with the occasional opportunity to show my design prowess in laying out washrooms. As I grew into a management and lead role, I started being on the receiving end of those accusatory e-mails and awkward conversations during meetings. After a couple of years of those, all the while bearing witness to some pretty deficient practices and total lack of collaboration in the sense of working towards a shared goal, I took the opportunity that was offered to me to embark on this journey, the result of which is laid out in this thesis.

The subject is collaboration: what does it entail? How can we assess it? The subject is also innovation: there are better ways to do things, some that exist and some that have yet to be invented. The Canadian Architecture, Engineering, Construction and Operations (AECO) industry finds itself at the fork in the road where collaboration and innovation meet. While other countries have whole heartedly gone down the path (especially the UK, Singapore and the Scandinavian countries), it seems as though that we in the Canadian industry are sitting here, looking backwards, wringing our collective hands. Maybe if we better understood what going down that path entailed, we could take a couple of steps. There is increasing evidence that this is happening in a very limited manner. On the other hand, there are many issues with the current state of BIM and collaboration in the global AECO industry. First is the incredible attention that BIM is getting, and with reason, it is an exciting time. However, BIM and collaboration have become some sort of mantra, the core message that we need to improve the value and the performance of the industry is getting lost in the mix. BIM is a means to support

better collaboration. Collaboration is a means to support a better performing industry. We shouldn't lose sight of this. As my principal advisor, Professor Forgues says, BIM acts as a Trojan horse: Once within the walls, they start to come down. Ironically, I believe that this research project would have been impossible without the current state of practice being what it is. As with the analogy to the Trojan horse, the emergence of BIM has allowed a different view of collaboration by bringing to light or exacerbating issues and events that perhaps lay dormant or hidden in the past.

Of course, this research project would have been impossible without the support of many people. First and foremost are my advisors, Professor Forgues and Professor Staub-French. Professor Forgues was the one who convinced me to undertake this journey and for that I will be forever grateful. I am also grateful for all the opportunities he's presented me with over the years. Professor Staub-French was a guiding light throughout this endeavour. Her insight, her capacity to uncover and understand what I was truly trying to express is remarkable. I am grateful for her confidence and her respect. I would like to thank the members of the jury, Professor April, Professor Katsanis and Professor Taylor for their insight and their time. I would also like to thank the members of the GRIDD and the BIM TOPiCS Lab for their support over these four years. I would further like to thank the participants of this research project: you are too numerous to list, but I thank you for your generosity and your support. In particular I am grateful for the support shown to me by Bob Cooke and his team at Division 15 Mechanical ltd., Neil McFarlane and his team at Alberta Infrastructure, Donna Clare, Allan Wilson, Crystal Mentes and the rest of the team at DIALOG, and Mike Roeper, Trevor Messal, Fallon Ladouceur and the rest of the team at Ledcor.

I would also like to thank my family: my mother, my father, my step-mother and my brother for their support throughout this journey. Last but surely not least, I could not have done any of this without my wife, Véronique. Her unflinching and unconditional love and support has played a fundamental role in ensuring the success of this undertaking. Along the way she has given me the most precious of all things: our incredible daughter and son. For that I will be forever grateful. Je t'aime.

UNE ÉTUDE SUR L'IMPACT DE LA MODÉLISATION DE L'INFORMATION DU BÂTIMENT DANS L'INDUSTRIE DE L'ARCHITECTURE, DE L'INGÉNIERIE, DE LA CONSTRUCTION ET DES OPÉRATIONS

Erik Andrew POIRIER

RÉSUMÉ

Cette thèse porte sur la collaboration dans l'industrie de l'Architecture, de l'Ingénierie, de la Construction et des Opérations (AICO). Les travaux de recherche qui y sont décrits identifient les caractéristiques de la collaboration, déterminent comment ces caractéristiques interagissent dans le contexte d'organisations temporaires et permanentes et comment cette collaboration peut être influencée par la livraison des projets appuyée par la Modélisation des Données du Bâtiment (BIM). D'un point de vue pratique, cette recherche est motivée par la volonté des partenaires industriels, avec lesquels nous travaillons, de mieux comprendre l'impact de la BIM et d'autres approches innovatrices utilisées pour la gestion des projets pour l'amélioration de certains indicateurs de performance lors de la livraison des projets. D'un point de vue théorique, cette recherche est motivée par l'incapacité de trouver une définition claire et donc du caractère flou de la collaboration dans le secteur de l'AICO. Nos travaux nous ont permis de confirmer qu'il y a une absence d'approches systématique et structurées dans la littérature scientifique visant à définir les caractéristiques de la collaboration pour l'industrie de l'AICO.

Cette recherche est donc à la fois normative et exploratoire. Son objectif principal est de développer une approche qui permettra de réaliser, gérer et évaluer l'impact de l'implantation d'une méthode innovatrice sur la collaboration lors de la livraison de projet. Le projet de recherche est situé dans le domaine des sciences de la conception (Design Science). La recherche a continuellement itéré entre le développement de l'approche et de son évaluation. En même temps, l'approche a été continuellement évaluée afin de s'assurer de sa pertinence et aussi de maintenir la rigueur dans le processus d'évaluation. Une perspective réaliste critique a été adoptée afin d'encadrer les bases épistémiques et ontologiques des nouvelles connaissances issues de la recherche et aussi afin d'appuyer la perspective essentiellement pragmatique traditionnellement utilisée en recherche dans le domaine des sciences de la conception. Une méthodologie d'association systématique appuyée d'une logique abductrice a été employée. Affichant des similitudes avec la théorie ancrée, cette méthodologie accepte un cadrage des connaissances a priori pour informer la recherche en cours. Cette méthodologie propose également que les connaissances issues de ce cadre de référence évolueront tout au long de la recherche et pourront être influencées par une nouvelle compréhension du phénomène sous étude. Des méthodes mixtes de collecte de données ont été utilisées sur les deux principaux sites de recherche. Le premier était un important projet de conception-construction institutionnel situé à Edmonton, en Alberta. La collecte de données sur ce site a commencé en février 2013 et est toujours en cours. Les données recueillies sur ce site ont permis une recherche approfondie du concept de la collaboration au sein d'une organisation de projet temporaire ayant pleinement implanté la BIM. Le second site est celui d'un petit entrepreneur en mécanique du bâtiment située à Vancouver, en Colombie-Britannique. La collecte de données sur ce site a commencé en avril 2012 et a pris fin en avril 2015. Les données recueillies sur ce site ont permis une recherche approfondie de la collaboration d'un point de vue organisationnel. Des données supplémentaires ont également été recueillies sur quatre autres sites afin d'effectuer des contrôles de pertinence portant sur l'approche en cours de développement.

Les résultats des travaux s'articulent selon l'approche développée; d'abord l'identification des concepts qui caractérisent la collaboration, puis la création d'un modèle à multiples niveaux qui décrit les relations entre les concepts et finalement la mise en œuvre de ce modèle. L'approche sert à informer, gérer et évaluer la collaboration facilitée par l'utilisation de la BIM dans le cadre précis de cette recherche. L'utilisation de cette approche pourrait aussi être utilisée pour d'autres méthodes innovatrices de réalisation de projets dans le futur. La mise en œuvre de cette approche évoque une théorie matérielle de la collaboration dans l'industrie de l'AICO sous la forme d'harmonisation entre les concepts qui ont été développés dans le modèle. Finalement, l'approche a été mise en application afin d'évaluer l'impact de la BIM sur la collaboration dans le secteur de l'AICO. L'évolution de ces différents concepts et indicateurs, autant ceux mesurés que ceux uniquement perçus, de même que la découverte d'alignements et de désaxages entre ces concepts ainsi que les impacts de la collaboration sont évalués en utilisant cette approche. Par ailleurs, l'évolution des concepts et la découverte des formes d'alignements par l'utilisation de cette approche peuvent servir d'indicateur de performance au sein d'environnements faisant appel à la collaboration instrumentée. Ainsi, l'approche développée dans ce projet de recherche permet de résoudre le problème identifié par les partenaires industriels. L'approche aborde également l'écart identifié dans la littérature quant à l'étude de la collaboration supportée au moyen de l'innovation. Telle que présentée dans le cadre de cette thèse, l'approche établit aussi des bases qui faciliteront une progression vers une enquête plus systématique et structurée de la collaboration dans le secteur AICO. Cependant, des travaux complémentaires sont nécessaires pour évaluer pleinement l'approche dans un contexte plus large du secteur de l'AICO.

Mots clés: Collaboration, Innovation, BIM, AICO, Sciences de la conception

INVESTIGATING THE IMPACT OF BUILDING INFORMATION MODELING ON COLLABORATION IN THE ARCHITECTURE, ENGINEERING, CONSTRUCTION AND OPERATIONS INDUSTRY

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ABSTRACT

The research work presented in this thesis investigates collaboration in the Architecture, Engineering, Construction and Operations (AECO) industry. More precisely, it investigates the characteristics of collaboration, their dynamics in the context of temporary and permanent organizations as well as the impact that the transition to innovative project delivery approaches, namely Building Information Modeling (BIM), is having on this collaboration. The research was practically motivated through our industrial partners' desire to better understand the impact of BIM and other innovative project delivery approaches on project outcomes. The research was theoretically motivated by the lack of a clear definition of collaboration in the AECO industry and its seemingly amorphous nature. This scarcity of systematic and structured approaches to investigate collaboration and its outcomes in the literature confirmed this.

The research was therefore both exploratory and prescriptive in nature. Its principal aim was to develop an artifact that allows consistent development, management and assessment of innovation enabled collaboration. As such, the research project was conducted using a design science research design. The research process continuously iterated between the development and building of the artifact and its local evaluation in context. In parallel, the artifact was concurrently evaluated to ensure its relevance and maintain the rigor of its development. A critical realist perspective was adopted to frame the epistemic and ontological foundation of knowledge being developed and also contradistinguish the predominantly pragmatic perspective traditionally adopted in design science research. The development and building of the artifact followed a systematic combining methodology. Showing similarities with grounded theory, this particular methodology accepts the *a priori* framing of knowledge to inform the investigation. It recognizes also that the knowledge held within this frame will evolve as the project progresses and as new insight is gained into the phenomena under investigation. Mixed-methods of data collection were conducted on two main research sites to inform and support the research project. The first site was that of a large institutional design-build project located in Edmonton, Alberta. Data collection on this site started in February 2013 and is still being carried out. The data collected on this site allowed an in-depth investigation of collaboration within a temporary project organization having fully implemented BIM. The second site was that of a specialty mechanical contracting small enterprise located in Vancouver, British Columbia. Data collection on this site started in April 2012 and ended in April 2015. The data collected on this site allowed a breadth of investigation into collaboration from an organizational perspective. Data was collected on four other sites to support relevance checks of the artifact being developed.

The findings of the work are presented through the artifact, namely the constructs developed to characterize collaboration, a multi-layered model representing the relationships between the constructs and the method of operationalization of this model. The artifact serves to inform, manage and assess BIM-based collaboration in the context of this particular research work, though it could be extended to include other innovative project delivery approaches as future work. The artifact also evokes a substantive theory of collaboration in the AECO industry in the form of alignments amongst constructs developed in the model. Lastly, the artifact is operationalized to investigate the impact of BIM on collaboration in the AECO industry. The evolution of the different constructs and indicators, both measured and perceived, the alignments and misalignments uncovered as well as the outcomes of collaboration are evaluated through the artifact. Furthermore, the evolution of the constructs and the alignments uncovered through the artifact can serve as an indicator of performance within collaborative environments. Thus, the artifact developed in this research project solves the problem that was set out by the industrial partners. It also addresses the gap that was uncovered in the literature with respects to collaboration through innovation. Further work is required to fully evaluate the artifact, however, it is believed that the groundwork to move towards a more systematic and structured investigation into collaboration in the AECO industry has been laid.

Keywords: Collaboration, Innovation, BIM, AECO, Design Science Research

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LIST OF ABREVIATIONS

AECO	Architecture, Engineering, Construction and Operations
BIM	Building Information Modeling
CD	Construction Documentation
CM	Construction Management
CO	Change Order
DA	Design Assist
DB	Design-Build
DBB	Design-Bid-Build
DSR	Design Science Research
GC	General Contractor
IDP	Integrated Delivery Process
IFC	Industry Foundation Class
IPD	Integrated Project Delivery
KPI	Key Performance Indicator
PLM	Product Lifecycle Modeling
RFI	Request for Information
SI	Site Instruction
SME	Small or Medium Enterprise
SQI	Société Québécoise des Infrastructures
SWOT	Strength, Weakness, Opportunity, Threat
TPO	Temporary Project Organization
UK	United Kingdom

INTRODUCTION

The many characteristics defining the Architectural, Engineering, Construction and Operations (AECO) industry, namely its project-based nature (Winch, 2010), the fragmentation of its supply chain (Cox and Ireland, 2002; Howard et al., 1989; Sun and Aouad, 2000; Vrijhoef, Koskela and Howell, 2003) and its increasing complexity (Baccarini, 1996; Dubois and Gadde, 2002a) frame the industry's axiomatic basis: collaboration is imperative; it is embodied through temporary project organizations (TPO), i.e. the temporary joining of individuals from different social, mental and object worlds into a functional unit; and it aims to fulfill a common motive – the building project – through pooling and application of individual expertise found within the TPO. The way in which this axiomatic framing is taken into consideration by industry stakeholders heavily influences the performance and value generated by the industry, which has, in the past, been curtailed. Indeed, the AECO industry is perceived as being wasteful, inefficient, litigious and antagonistic (Gallaher et al., 2004; Loosemore, Nguyen and Denis, 2000; Teicholz, 2004; 2013), which ultimately leads to client dissatisfaction (Egan, 1998).

As a way to counter the mitigated performance and lack of value generated by the industry, innovative approaches to project delivery, including tools, technologies, processes and structures, such as Building Information Modeling (BIM), Integrated Project Delivery (IPD), Integrated Design Processes (IDP) and Lean construction, have emerged over the past three decades. In their own ways, each of these innovations aim at maximizing and optimizing the performance and value generated by the AECO industry through better collaboration. However, the transition from traditional project delivery approaches to these innovative approaches is highly complex. It entails a reconfiguration of collaborative environments, a redefinition of relationships and a transformation of industry practices (Forgues and Koskela, 2009; Merschbrock, 2012; Taylor and Levitt, 2007). In this regard, the emergence of BIM has been seen to modify the objects through which individuals interact and collaborate (Dossick and Neff, 2011; Harty, 2008; Taylor, 2007b; Whyte, 2011) and through which activity is mediated. (Miettinen et al., 2012). While several strategies have been developed to implement these innovative approaches, namely BIM Project Execution Planning (Computer Integrated Construction Research Group, 2011; 2013), the Lean Project Delivery System (Ballard, 2000) or the Integrated Form of Agreement (Howell, Ballard and Tommelein, 2011), investigation into the underlying mechanisms put forth by these innovations and their impact on collaboration is still sparse. Moreover, the very concept of collaboration in the AECO industry is amorphous and ill-defined (Hughes, Williams and Ren, 2012; Kvan, 2000), which renders it difficult to investigate, inform, manage and assess both in theory and in practice.

The research project presented in this article based thesis aimed to investigate the impact that the transition to innovative project delivery approaches, BIM in particular, is having on collaboration in the AECO industry. Five articles are presented that have been either published, accepted for publication or submitted in peer reviewed academic journals. Each article can be read as a standalone article, however a distinct thread ties them all together: to answer the research questions, thus contributing to the research objectives. The research question that is addressed in this thesis is: What is the impact of innovative approaches to project delivery, namely BIM, on collaboration in the AECO industry? In order to formulate a complete answer to this question, the following research questions are posed: How can collaboration be characterized in the AECO industry? And how can we assess this impact on collaboration and on project outcomes? Finally, a prospective research question is posed: In light of this characterization and this assessment, how can we inform and manage innovative approaches to project delivery to enable collaboration?

The research project was rooted in the design sciences and adopted a critical realist perspective. Mixed method data collection was carried out on multiple research sites. A systematic combining process was used to analyse the data in order to develop and build the artifact. In turn, the assessment capabilities of the artifact were evaluated through local evaluation on the various sites. The principle contributions of this thesis are in the development and operationalization of an artifact that serves to frame an investigation into BIM-based collaboration and can thus act to inform, manage and assess collaboration and its outcomes. The artifact uncovers ‘courses of collaborative action’ which converge on specific outcomes that support the collaborative event along a structured, socio-cognitive path. The degree of alignment within and across these courses of actions, at the socio-cognitive, structural and performative levels, and their outcomes will dictate the level of success of the collaborative event. Secondary contributions lie in the development of a substantive theory of collaboration in the AECO industry, evoked through the alignments uncovered through the artifact. The theory is articulated as the concerted or negotiated alignment of two frames of references (or more), as defined through the artifact, that are juxtaposed to achieve a common motive. Lastly, the thesis contributes to the growing literature on performance assessment of BIM implementation by developing and testing a systematic approach to this assessment and performing an in-depth evaluation of the impact of BIM at the organizational and project level.

An overview of the research project is given in the first chapter. Its practical and theoretical motivations, its design and its outcomes are presented. A problem statement is made and research questions posed. The answers to these questions, in the form of the contributions of this research work are presented. The research project's design is described including the theoretical and philosophical foundations upon which the research project is built as well as the methodology. Techniques developed for validating the research project are also discussed. The five articles are summarized and their contribution to the thesis is presented. Each article is then included in full in the subsequent chapters. The final chapter presents a discussion on the research design and the research findings, the contributions of the work as well as opportunities for future work. Lastly, a general conclusion is made.

CHAPTER 1

OVERVIEW: RESEARCH MOTIVATIONS, DESIGN AND OUTCOMES

1.1 Introduction

This chapter presents an overview of the research project and this thesis. It presents the practical and theoretical motivations, the research design and its outcomes. It also presents the structure of this manuscript based thesis. The practical motivations are first exposed, namely the internal and external factors that motivated the research project. The theoretical motivations are then presented as a summary review of the literature pertaining to collaboration in the AECO industry: the building project is defined as a system, an institution and a process. With these complimentary views in mind, collaboration in the AECO industry is exposed. The transition to innovative project delivery approaches is discussed. Moreover, the outcomes of collaboration are discussed with a focus on their assessment and evaluation. A clear problem statement is then formulated from which the research questions are posed. Answers to each question are given in the form of research contributions. The research approach and methodology that lead to these answers and contributions are presented. Lastly, the structure of the thesis is outlined by presenting the articles, their contribution to the literature and their contribution to the thesis.

1.2 Practical motivation

From a practical perspective, the motivation to investigate this particular area comes from both internal and external sources. Internally, the research project was motivated by almost a decade of work as an intern architect and project manager for architectural firms located in Montreal, Quebec and Vancouver, British Columbia. Over the years, I was confronted with the same issues over and over again: individual stakeholders on the projects in which I was involved simply did not know how to truly collaborate, or what true collaboration was. Neither did I for that matter. The projects I had participated in fell victim to the same wasteful, inefficient, litigious and antagonistic practices that have been widely reported in the literature. On one project in particular, the general contractor, having delivered the building almost 11 months late, came back to us (the architecture firm) and the client with a $400,000 delay claim on a $5.5 million contract amount!

During this period, I also got familiarized with BIM (i.e. I implemented BIM in the architectural office I was working for in Montreal around mid-2007) and other innovative project delivery approaches (i.e. through completion of a Masters in Construction Engineering in 2010) as well as sustainable design (i.e. I obtained my LEED accreditation in 2009). I was therefore aware of the existence of better practices and better ways to deliver projects. Having a firsthand experience of the gap between the current situation within the industry and the examples of enlightened practices that have emerged over the years was highly motivational.

Externally, upon beginning my doctoral studies, I had the opportunity to work with various stakeholders in the Canadian AECO industry who were motivated to transition to innovative project delivery approaches, BIM in particular, in an attempt to improve collaboration and project outcomes. A common thread binding these stakeholders together was their awareness of the problem that they were facing: they were having issues with informing, managing and assessing this transition to BIM. They also had a vested interest in understanding the impact of these innovative project delivery approaches on collaboration and project outcomes. Therefore, both sources of motivation were aligned which allowed me to move forward with this line of inquiry into the impact of innovative project delivery approaches on collaboration in the AECO industry.

1.3 Theoretical motivation

1.3.1 The building project

A building project can be defined as a “complex, information dependent, prototype production process where conception, design and production phases are compressed or concurrent and highly interdependent, in an environment where there exists an unusually large number of internal and external uncertainties” (Pryke, 2004, p. 790) Three distinct views of the building project emerge from this definition: as a system, as an institution and as a process. All three views support and hold collaboration as a central tenet.

Building projects have been conceptualized as many different type of systems: open (Ren and Anumba, 2004), activity (Forgues and Koskela, 2009; Hartmann and Bresnen, 2011), emergent (Cicmil and Marshall, 2005), complex adaptive (Aritua, Smith and Bower, 2009; Fellows and Liu, 2012), socio-technical (Higgin and Jessop, 1965), production (Koskela, 1992) and information processing (Winch, 2010) systems, among others. While these different systems views offer distinct 'units of analysis', they all develop five intrinsic properties, as described by systems thinking (Kaspary, 2014): interaction/relationship, interdependency, autonomy/dependency, and self-production (i.e. autopoiesis (Maturana and Varela, 1992)). Building project as systems denote the networks of relationships between individual stakeholders, their structure and the flow of information within them.

Building projects also demonstrate the characteristics of institutions. Barley and Tolbert (1997) define institutions as "[…] shared rules and typifications that identify categories of social actors and their appropriate activities or relationships." (Barley and Tolbert, 1997, p.96) Institutions influence, shape and constrain actions carried out by actors through normative, regulatory and value based mechanisms (Tummolini and Castelfranchi, 2006). Building projects as institutions denote the social constraints on its structure, the framework within which the system evolves.

Lastly, building projects are process based: they have a beginning and an end; time becomes their most important resource (Huxham, 1996). They evolve and unfold through actions, interactions and transactions, across phases and milestones. The emergent and dynamic state of the building project implies an ontology of 'becoming', built around an ever-changing, continually constructed reality as opposed to an ontology of 'being', built around a finite and bounded reality anchored in substance (Cicmil and Marshall, 2005; Koskinen, 2012). This entails a constant flux, a continual transformed through actions, interactions and transactions carried-out within the TPO. From a practical perspective, building projects are supported by information processes, material processes and business processes (Medina-Mora et al., 1992). These processes resonate with the process orientation of the production system, as described by Koskela (1992), involving transformation, flow and value elements of the building project.

Across these different views, building projects are neither the result of rational decision making in that they involve human actors, nor reducible to a common logic in that they involve collective behavior (Coyne, 2005; Marcus and Saka, 2006). Building projects are subject to different interpretations, highlighting the need for shared knowledge and representation (Boujut and Blanco, 2003) to support negotiation and mutual understanding amongst individuals (Neff, Fiore-Silfvast and Dossick, 2010; Tryggestad, Georg and Hernes, 2010). They are also subject to competing interests and goals (Anvuur and Kumaraswamy, 2008). Ultimately though, building projects 'are sites of continuously evolving human action' (Cicmil and Gaggiotti, 2013, p.2). It is within this multifarious and highly complex context that collaboration occurs.

1.3.2 Collaboration in the AECO industry

The field of collaboration in the AECO industry is well researched. Work in this area spans decades and intersects other research domains such as organizational sciences, human resource management, ergonomics and science and technology studies (Human-Computer interactions, Computer Supported Cooperative Work, etc.). The notion of "collaboration" remains, however, a hard term to grasp: it has been overused, becoming a "[…] catchall to signify just about any type of inter-organizational or inter-personal relationship" (Gajda, 2004, p.66). The very definition of "collaboration" is elusive and amorphous which renders it difficult to implement and investigate. Past work in various fields, aimed at defining collaboration, has been quasi-cyclical in its recurrence (Appley and Winder, 1977; Gray, 1985; Hartono and Holsapple, 2004; Hughes, Williams and Ren, 2012). Throughout these cycles consensus remains elusive, a fact highlighted by Hartono and Holsapple (2004), yet facets of collaboration, developed in these various definitions, can be synthesized into the following definition:

> Collaboration is an interactive, constructive, and knowledge-based process, involving multiple autonomous and voluntary participants employing complementary skills and assets, with a collective objective of achieving an outcome beyond what the participants' capacity and willingness would allow them to individually accomplish (Hartono and Holsapple, 2004, p.20).

Bedwell et al (2012), highlighting the same issues with the concept of collaboration as outlined above, offer a more succinct definition of collaboration as "an evolving process whereby two or more social entities actively and reciprocally engage in joint activities aimed at achieving at least one shared goal" (Bedwell et al., 2012, p.130). For the authors, the concept of collaboration must span multiple levels of analysis, be explicit in defining its underlying processes, be process-oriented (as opposed to structure or outcome oriented) and must acknowledge its temporal nature. The framework that the authors propose articulates emergent states at the individual and collective level with collaborative behaviours, defined reciprocally through task and relationships, to model collaborative performance, i.e. the process. This process is mediated by contextual factors, such as characteristics of tasks, environment, structure and time. The nested and emergent cognitive and affective states developed in the framework are highly interesting as is the interaction between these states and individual behavioural traits. However, the framework identifies context primarily as an input. It intimates no reciprocal action or influence with the collaboration process itself. This is contrary to past work which has discussed the profound interaction between agents and their environment (e.g. Bourdieu, 1977; Giddens, 1984). The authors end by identifying a series of strategies aimed at enhancing the ability of organizations to collaborate, decoupling in effect the collaboration process from strategic approaches to fostering it which is notable.

Patel, Pettitt and Wilson (2012) also denote an issue with the concept of collaboration. Through an exhaustive literature review the authors identify seven main categories of factors involved in collaboration: context, support, tasks, interaction processes, teams, individuals, and overarching factors. The go on to identify 36 sub-factors, distributed among these main factors that include culture, goals, constraints, skills, trust, and so forth. The issue with the characterization of collaboration performed by the authors is that it conflates varying levels of factors as opposed to Bedwell et al's (2012) work which separates the process itself from the underpinning strategies to foster it. However, the extent of the review and the number of factors outlined is extremely valuable in attempting to understand collaboration.

Within the AECO domain, work has also focused on defining collaboration. For instance, Kvan (2000) investigates the nature of collaborative design and discusses the notion of collaboration and cooperation on a semantic level. He finds that "[…] collaboration is a deeper more personal synergistic process and the term should be used more selectively" (Kvan, 2000, p.414). Hughes, Williams and Ren (2012) also inquire into the notion of collaboration in the AECO industry and provide the following definition:

> Collaboration within the UK construction industry is a non-adversarial team based environment, where through the early involvement of key members and the use of the correct contract, everyone understands and respects the input of others and their role and responsibilities. The relationships are managed with the help of regular meetings, early warning systems, open dialogue and risk sharing to produce an atmosphere of mutual trust where information is shared, problems can be solved together and everyone contributes towards a common aim motivated by a fair method of pain share gain share to produce a win-win outcome. (Hughes, Williams and Ren, 2012, p.365)

The authors propose another three definitions of collaboration tailored to specific stakeholder perspectives, which raises questions of the generalizability of their definition. They also frame the definition within the UK construction industry's context. However, the definition highlights the notion of relationships, a perspective shared by many other authors. For instance, Pryke and Smyth (2012) echo the importance of relationships in collaboration and see management of these relationships as one of four paradigmatic approaches to managing projects, the others being traditional project management approaches, information processing approaches, and functional approaches. Emmitt (2010) also focusses on relationships and investigates their dynamics by studying group interactions and issues such as trust, communication, decision making, context, conflict and learning. Chiocchio et al. (2011) perform an in depth review of the concept of collaboration and teamwork. They also investigate trust and conflict and posit that these elements evolve over time in an integrated design setting to affect project performance. Phua (2012) identifies culture, identity, empowerment and trust, while Anvuur, Kumaraswamy and Fellows (2012) identify pride and self-respect, and Liu and Walker (1998) identify self-efficacy, project complexity, commitment, expectancy, rewards, goals and environmental variables as factors influencing project performance in a collaborative setting.

Tying these various bodies of work together is the individual level of inquiry at which they happen, emphasizing the individual's importance within the TPO and throughout the collaborative episode. In this light, past work has developed fundamentals of project collaboration which ultimately aim to provide a frame for these individual level factors in a way that mitigates their negative effects (Constructing Excellence, 2011; Homayouni, Neff and Dossick, 2010; Singh, Gu and Wang, 2011; Yeomans, Bouchlaghem and El-Hamalawi, 2006). (2006) (published subsequently by Constructing Excellence (2011)) identify these collaboration fundamentals, which include:

1) Early involvement of all project stakeholders,
2) Selection by value,
3) Aligned commercial arrangements,
4) Common processes and tools,
5) Performance measurement,
6) Long-term relationships.

These elements speak to larger overarching principles of collaboration which are reflected in both the generic definition of collaboration provided by Hartono and Holsapple (2004) and the AECO industry specific definition provided by Hughes, Williams and Ren (2012). These overarching principles can be broken down into four distinct yet interconnected statements about collaboration, which resonate with other past work in this field:

1) Collaboration is a socially constructed and purposeful phenomenon (Nicolini, Mengis and Swan, 2012) which involves the interaction between multiple actors from different social, mental and object worlds (Peters et al., 2013);

2) Collaboration is a process involving a specific goal (a motive), a beginning and an end (Thomson and Perry, 2006);
3) Collaboration is structured and set within a given environment (Gray, 1985);
4) Collaboration is supported through shared artifacts (Boujut and Blanco, 2003).

Distilled, these statements highlight four foundational elements of collaboration: structure, process, agents and artifacts[1]. These four elements interact: they are interrelated and mutually adjusting. They are also subject to external pressures. Thus is framed the concept of collaboration that is carried out throughout this thesis.

1.3.3 Innovative approaches to project delivery in the AECO industry

Over the past three decades, new strategies have been developed to overcome the inherent complexity of building projects and to try to extract the industry from its wasteful and inefficient state. These strategies are aimed at fostering and facilitating collaboration in the AECO industry (e.g. Integrated practices (Elvin, 2007), BIM (Eastman et al., 2011), Lean construction (Koskela, 1992)). BIM has been conceptualized as a set of interacting tools, technologies and processes (Eastman et al., 2011) that are guided by norms and rules (policies) to support AECO practitioners in their development of the building project (Succar, 2009). BIM is a systemic, disruptive and radical innovation (Lehtinen, 2012; Poirier, Staub-French and Forgues, 2015b). Evidence suggests that increased collaboration through BIM will increase project performance (Grilo and Jardim-Goncalves, 2010). Indeed, a basic premise of BIM is collaboration (National Institute of Building Science, 2007): On one hand, BIM supports and enables collaboration; on the other, collaboration is required to fully implement BIM. In other words, to be effective, BIM must be adopted across organizational and knowledge boundaries within a project team (Harty, 2008). The implementation process

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[1] For an in depth review of the four foundational elements described please refer to section 3.4

requires ‘mutual adjustment’ between project actors (Taylor, 2007a) and involves negotiations chiefly around expectations (i.e. identifying how the model will be used; who will do what in the model) (Computer Integrated Construction Research Group, 2011), interests (i.e. identifying who benefits from the model)(Schweber and Harty, 2010)) and capabilities (i.e. identifying to what extent can these expectations be met) (Succar, Sher and Williams, 2013).

Integrated approaches such as IPD and IDP target specific areas of collaboration, attempting to remove operational, functional, technical and social barriers. IDP is defined as

> An approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints. It relies upon a multidisciplinary and collaborative team whose members make decisions together based on a shared vision and a holistic understanding of the project. (BC Green Building Roundtable, 2007, p.7)

IPD is defined as:

> A project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction. (American Institute of Architects, 2007, p.i)

Lastly, Lean Construction has emerged over the past three decades as a driver for reconfiguration and reconceptualization of production in the AECO industry. Lean construction is seen as “[...] a new way to manage construction. The objectives, principals, and techniques of lean construction taken together form the basis for a new project delivery process. [...] Lean construction provides the foundation for an operations-based project delivery system.” (Forbes and Ahmed, 2011, p.45) At its base, Lean construction is a philosophy. However, over the years various tools and techniques have been developed to operationalize the lean philosophy in practice e.g.(e.g. Ballard, 2000).

If we focus on BIM, its emergence and increasing popularity come at a cost: BIM is fundamentally changing the relationships and interfaces within the AECO industry, with information in particular. While one of the more prominent perceived benefits of BIM is the increase in collaboration that the transition to a shared digital information repository allows (Bryde, Broquetas and Volm, 2013), many barriers and challenges still abound. Technological barriers to collaboration through BIM are being largely addressed in the literature, through the creation of a standardized coding scheme for building information exchange, the Industry Foundation Class (IFC) (Laakso and Kiviniemi, 2012), and Cloud BIM (Redmond et al., 2012) for instance. However, the barriers to collaborative BIM are not limited to technological issues. Organizational and procedural issues relating to collaborative project delivery are also prevalent. For instance, when looking at the most significant barriers to full collaborative BIM adoption, issues pertaining to interactions between project team members, for instance willingness to share information, consistently rank amongst the most important issues hindering full collaboration through BIM (Won et al., 2013). Issues such as project procurement and contractual mechanisms (Ashcraft, 2008), individual scope and responsibilities (Dossick and Neff, 2010), varying levels of capability (Taylor and Bernstein, 2009) and the definition of roles and responsibilities (Linderoth, 2010) are hindering the transition to full BIM-based collaboration. In other words, the passage to BIM marks a profound shift in the very foundations of collaboration:

1) BIM is transforming the relationships between the projects actors, their objects of practice (Neff, Fiore-Silfvast and Dossick, 2010), and their 'object worlds' (Berente, Baxter and Lyytinen, 2010);
2) BIM is transforming the relationships between project actors and project information (Crotty, 2011);
3) BIM passively structures and actively shapes the collaborative environment (Tryggestad, Georg and Hernes, 2010);
4) BIM pushes for transparency and openness (achieved incrementally or no) (Taylor and Bernstein, 2009);
5) BIM is transforming how technology is being used within the project environment (Fischer and Kunz, 2004);

6) BIM is resetting the many boundaries of TPO, including practical, cognitive, functional, temporal and geographical (Alin, Iorio and Taylor, 2013; Dossick and Neff, 2011);
7) BIM is involving new forms of contractual mechanisms to structure and delineate the collaborative environment (Ilozor and Kelly, 2012; Kuiper and Holzer, 2013);
8) BIM is transforming the roles and responsibilities within the TPO (Ku et al., 2008).

While some of these challenges are being addressed to a certain extent by the other innovative approaches to project delivery mentioned above, it remains that there remains many challenges in their implementation, above and beyond those that are introduced through BIM. More importantly though, there appears to be lacking a fundamental understanding of what constitutes collaboration and how to best inform it with regards to these innovative approaches to project delivery, BIM in particular.

1.3.4 Assessing outcomes of collaboration

The outcomes of collaboration are three-fold: value, performance and knowledge. Desirable outcomes of collaboration are project success, learning and innovation and commitment to future collaboration (Dietrich et al., 2010). Project success is a function of the value generated through the collaborative episode, namely through goal attainment (Liu and Walker, 1998), i.e. product success, and its performance, i.e. process success. The perception of project outcomes and their consequences are products of individual TPO member's expectation of success, the amount of effort exerted, and the expectation of the outcome and its consequence (Liu and Walker, 1998) Both concepts, value and performance are closely related, however value is a subjective concept (De Chernatony, Harris and Dall'Olmo Riley, 2000) whereas performance is seen as being more tangible through operationalization of its measures. Taken together, value and performance speak to the attainment of goals and their optimization in an efficient manner over the course of the building project.

The first two outcomes – value and performance – are closely tied and relate both to the product of the building project and its process. Value has been defined as "[…] a customer's perceived preference for and evaluation of those product attributes, attribute performances, and consequences arising from use that facilitate (or block) achieving the customer's goal and purposes in use situation" (Woodruff, 1997, p.142). In the AECO industry, value has been defined as a relationship between function, time, cost and quality (Kelly, Male and Graham, 2014), which tie it closely to performance (Atkinson, 1999).The dimensions of performance measurement are multiple. Traditionally in the AECO industry, performance is related to project management outcomes, the aforementioned indicators minus function. Tracking these indicators are seen as critical in order to compel progress in the industry (Bassioni, Price and Hassan, 2004). Measures developed in the UK and in the US also include satisfaction of both product and process as well as profitability among others (Center for Construction Innovation, 2015; Construction Industry Institute, 2013) Additional key performance indicators have been discussed such as measures of innovation and sustainability, which relate back to value generation (Rankin et al., 2008) With the emergence of innovative project delivery approaches the measurement and evaluation of their impact and performance is receiving increasing attention. Work has focused on different areas such as the impact of BIM and IPD at the project level (Ilozor and Kelly, 2012; Khanzode, Fischer and Reed, 2008) and organizational level (Love et al., 2013; Mom and Hsieh, 2012), and measuring return on investment (ROI) (Barlish and Sullivan, 2012; Giel and Issa, 2011). The issue with these measures is that most are lagging (Kagioglou, Cooper and Aouad, 2001) and act as proxies for the assessment of collaboration. Measures, such as capabilities and maturity (Succar, Sher and Williams, 2013; Taylor and Bernstein, 2009; Zutshi, Grilo and Jardim-Goncalves, 2012) as well as the quality of collaboration which is determined through communication, coordination, mutual support, aligned efforts, and cohesion (Hoegl and Gemuenden, 2001) offer a more 'predictive' or leading view on the effectiveness of collaboration. However, these measures still require considerable resources to implement and use efficiently and adequately. They also require considerable knowledge to interpret and act upon correctly.

1.4 Problem statement

The focused restructuring of collaborative environments in the AECO industry, through the implementation of "collaboration fundamentals" for example, has been deemed insufficient to overcome the inherent paradox and complexity of building projects due to the "assumptions made about the linearity of the unfolding of human action, time–space finality, rational decision-making before the structural intervention […], and the nature of power relationships […]" (Cicmil and Marshall, 2005, p.532). This speaks to the fact that the context of the building project and the TPO is by no means static, a notion that is supported by many authors, and is in fact emergent and dynamic, subject to cycles of order and disorder, which further structure the context of collaboration (Kaspary, 2014). Elements of control, intervention and prediction get in the way of innovation, creativity and knowledge generation (Cicmil and Marshall, 2005). In parallel, structural change, or 'renewal initiatives' through industrialization, organizational renewal, integration, and re-engineering, among others, have had modest impact so far in the industry due to an apparent neglect of the systemic view of production (Koskela, 2003). The review of the literature also highlights an apparent neglect of the systemic view of collaboration which could further explain this modest impact.

The problem is thus framed: innovative approaches to project delivery, BIM in particular, aim to foster and facilitate collaboration in the AECO industry. These approaches mark a fundamental shift in how individuals collaborate to deliver projects. While there is general acceptance that this shift entails a reconfiguration of collaborative environments, a redefinition of relationships and a transformation of industry practices, there is still sparse work investigating how this should be carried out. Furthermore, the very notion of collaboration, remains amorphous and ill-defined. This constrains the full potential of these innovations: if we want to improve collaboration, we must be able to inform, manage and assess it. Conversely, to ensure that these innovations are having the desired effect, we must be able to evaluate the impact they are having on collaboration. Past work has thoroughly investigated specific areas that touch on or affect collaboration, however, there is an apparent neglect of the systemic view of collaboration has been highlighted in the literature. This is echoed in practice by industry stakeholders who are struggling to manage and assess collaboration enabled through innovation and its outcomes. An understanding of what collaboration is and how it can be defined is therefore needed to consistently inform, manage, and assess collaboration and its outcomes from both a systemic and systematic perspective. This in turn can assist in developing means and methods to evaluate the impact that innovative approaches to project delivery are having on collaboration.

1.5 Research questions and contributions

Having outlined the problem and the need we, as an industry, are faced with from a practical and theoretical perspective, I pose this main research questions: (RQ 01) *What is the impact of innovative approaches to project delivery, namely BIM, on collaboration in the AECO industry?* In order to formulate a complete answer to this question, I pose the following research questions (RQ 02) *How can collaboration be characterized in the AECO industry?* and (RSQ 03): *How can we assess this impact on collaboration and on project outcomes?* I also pose a prospective research question: (RQ 04) *In light of this characterization and this assessment, how can we inform and manage innovative approaches to project delivery to enable collaboration?*

The first research question addressed is RQ 02: *How can collaboration be characterized in the AECO industry?* To answer this question, I developed a series of constructs and related them within a model to conceptualize an individual's frame of reference within a TPO, layered across the agentic (socio-cognitive), structural and performative (action) domains. The constructs and their relationships are illustrated in Figure 1.1. The model that articulates these constructs is illustrated in Figure 1.2. My characterization of collaboration in the AECO industry is thus defined as the concerted or negotiated alignment of two frames of references (or more), i.e. the constructs and their relationships (Figure 1.1) as articulated in the model (Figure 1.2), that are juxtaposed to achieve a common motive. The degree of alignment between these frames of references will dictate the level of collaboration and the outcomes of a collaborative episode.

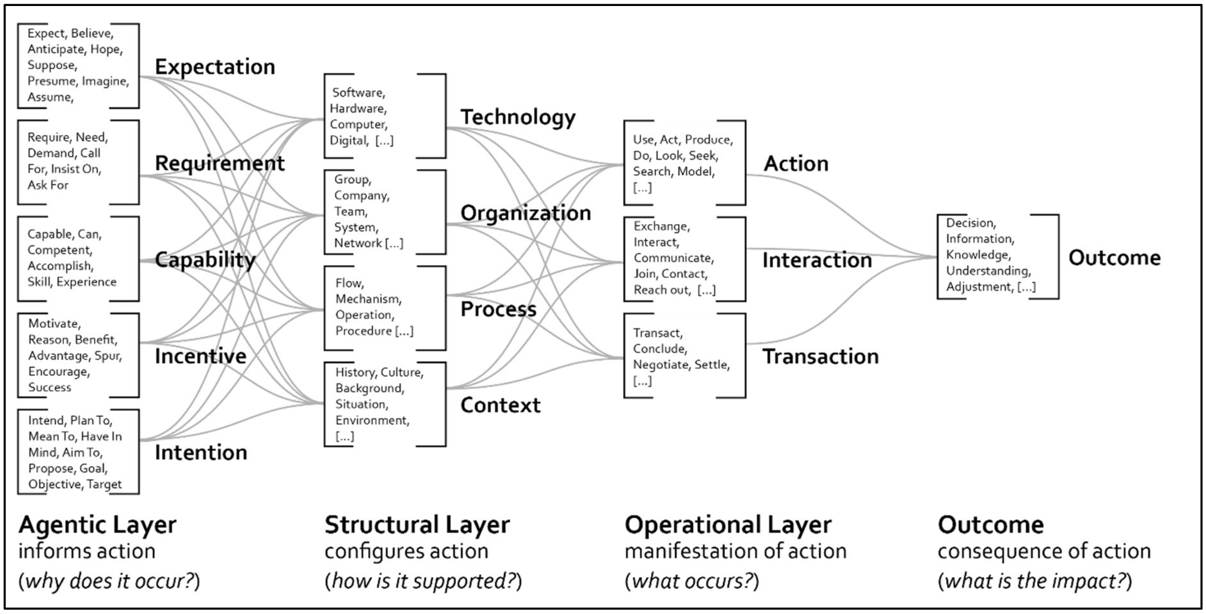

Figure 1.1 Characterizing collaboration: the constructs and their relationships

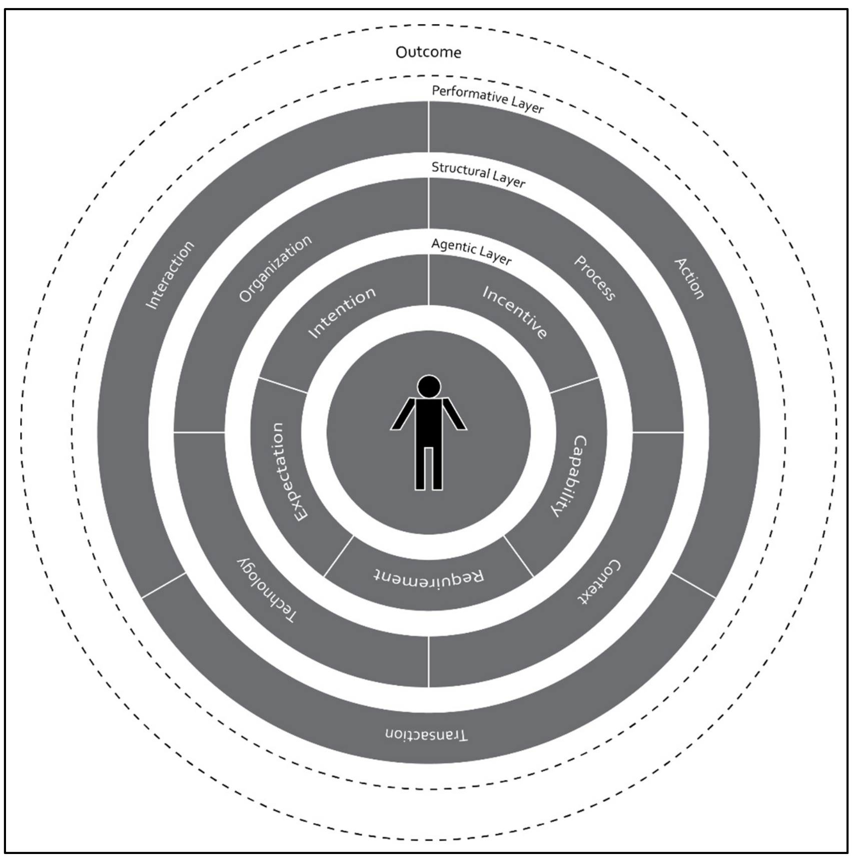

Figure 1.2 Characterizing collaboration: the model

Building upon the answer to RQ 02, I address RQ 03: *How can we assess this impact on collaboration and on project outcomes?* To answer this question, I first looked into the domain of performance assessment in the AECO industry and looked at benchmarking and performance measurement. I defined key performance indicators, metrics and measures that could help assess the impact of BIM, namely labor productivity. I then developed a method to operationalize the model and its constructs and leveraged the experienced and knowledge gained in the field of benchmarking and performance assessment to inform this method. The method of operationalization is illustrated in Figure 1.3.

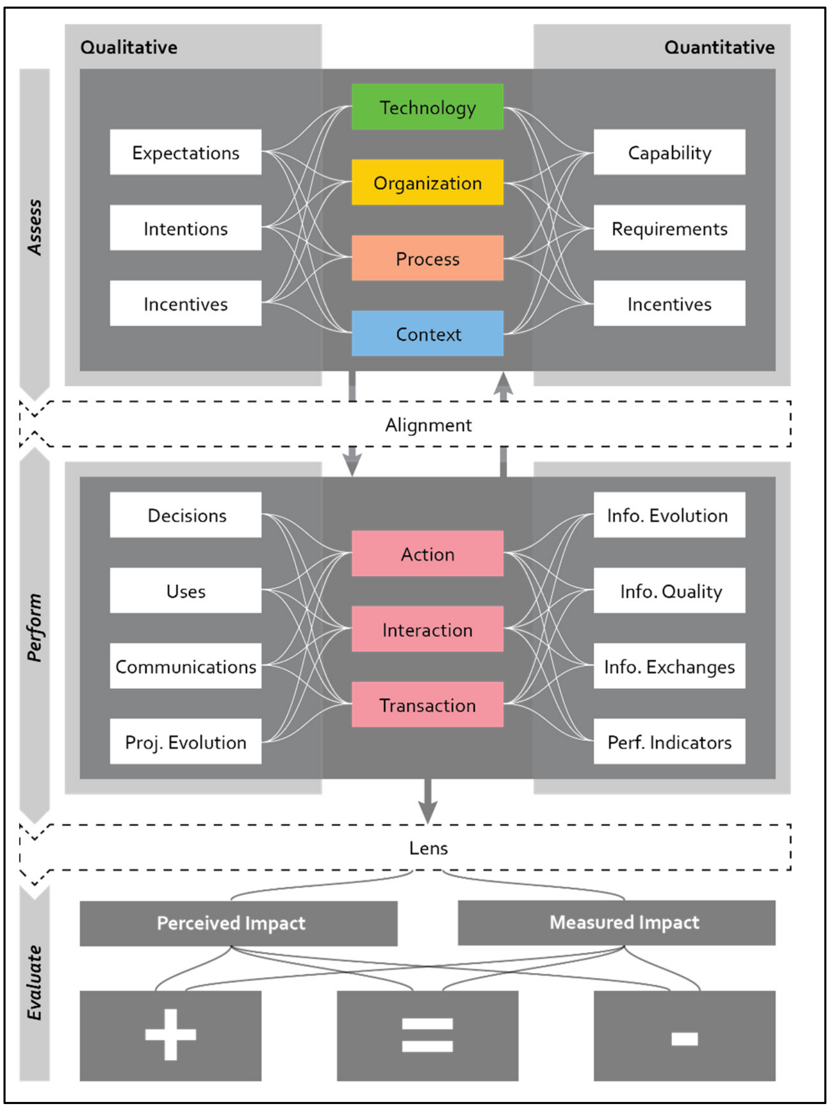

Figure 1.3 Assessing impact: method of operationalization

The method developed in Figure 1.3 operationalizes the model, the constructs and their relationships. These four elements compose the artifact that is at the core of this research project. The artifact develops indicators of collaboration by assessing the strengths of the alignments found within the model. These alignments are evaluated both quantitatively and qualitatively. The performance of the collaborative episode and the TPO is a function of the strength of these alignments and measured through a series of indicators. Lastly, impact is evaluated as either measured or perceived, be it positive, neutral or negative.

Having answered both RQ 02 and RQ 03, I can now address the main research question RQ 01: *What is the impact of innovative approaches to project delivery, namely BIM, on collaboration in the AECO industry?* I put forth that the emergence of BIM is impacting the frames of references of individual TPO member, not only through a change in the objects of practice as highlighted in other works (Dossick and Neff, 2011; Harty, 2008; Taylor, 2007b; Whyte, 2011), but in the courses of collaborative action that are internalized and externalized within these frames of references and specifically through the outcomes of these courses of action and their alignments across networks and time.

From a practical perspective, one of the specific measures that was investigated to assess the impact of BIM on collaboration at a micro-level was labor productivity. This was done by comparing areas where BIM and prefabrication were used to where BIM wasn't used on a single project conducted on site 02 (Figure 1.4). A misalignment across the project team's expectations, capabilities and requirements towards BIM use ultimately resulted in the abandonment of BIM for the project overall. Where BIM was used, the internal alignments between the frames of references of the mechanical contractor's BIM coordinator and the site superintendent, i.e. the alignment of expectations towards technology use and outcomes (in the form of spool drawings) and the intentions towards process outcomes (off-site prefabrication), resulted in positive outcomes for the organization's scope of the project. In this case, the areas that were modeled and prefabricated showed an increase in productivity ranging from 75% to 241% over the areas that were not modeled, which indicates a positive quantifiable impact of BIM on project outcome in the situation studied.

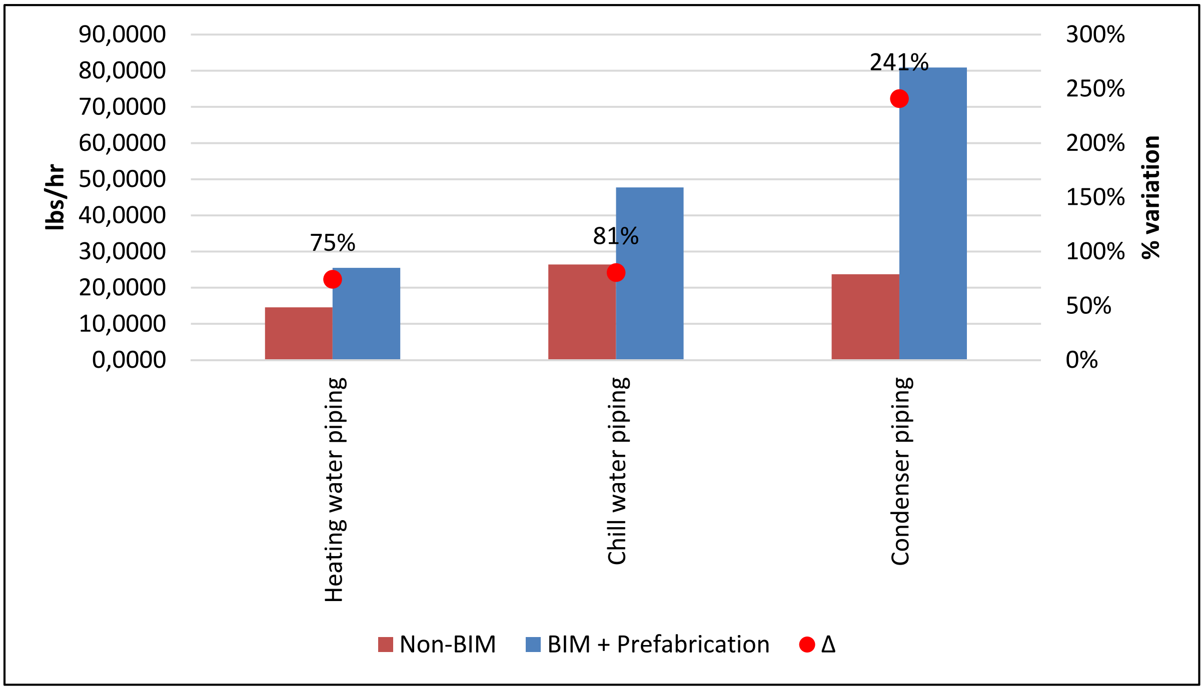

Figure 1.4 Productivity rate per system – BIM + Prefabrication vs. Non-BIM (site 02)

Lastly, I posed a prospective RQ 04: *In light of this characterization and this assessment, how can we inform and manage innovative approaches to project delivery to enable collaboration?* This question is posed to prompt future work (discussed in section 7.5). The artifact has been built and evaluated as a retrospective analysis tool to assess the impact of BIM on collaboration and project outcomes so far. However, it is proposed that the artifact can serve to inform and manage, thus take a leading role (instead of a lagging one), in supporting the development of innovation enabled collaboration.

1.6 Research approach

A design science research (DSR) approach was adopted throughout the research project. The strengths (and also complexity) of DSR lie in the iterative and concurrent building and evaluation of an artifact and the search for balance between the relevance and the rigor of its outcomes. In the field of collaboration research in the AECO industry, there is not only a need to describe and explain collaboration as a phenomena, but also to inform and manage it to ensure its success, which is why a DSR approach was adopted. To contrast the primarily pragmatic nature of the artifact's application domain, a critical realist perspective was taken to frame the artifact's knowledge domain (i.e. its epistemic and ontological foundation). To operationalize the DSR approach, namely to support the building and evaluation process, a systematic combining methodology was employed using mixed-methods of data collection across two major research sites and four smaller sites. Figure 1.5 illustrates the research project's overarching research approach reported in this thesis.

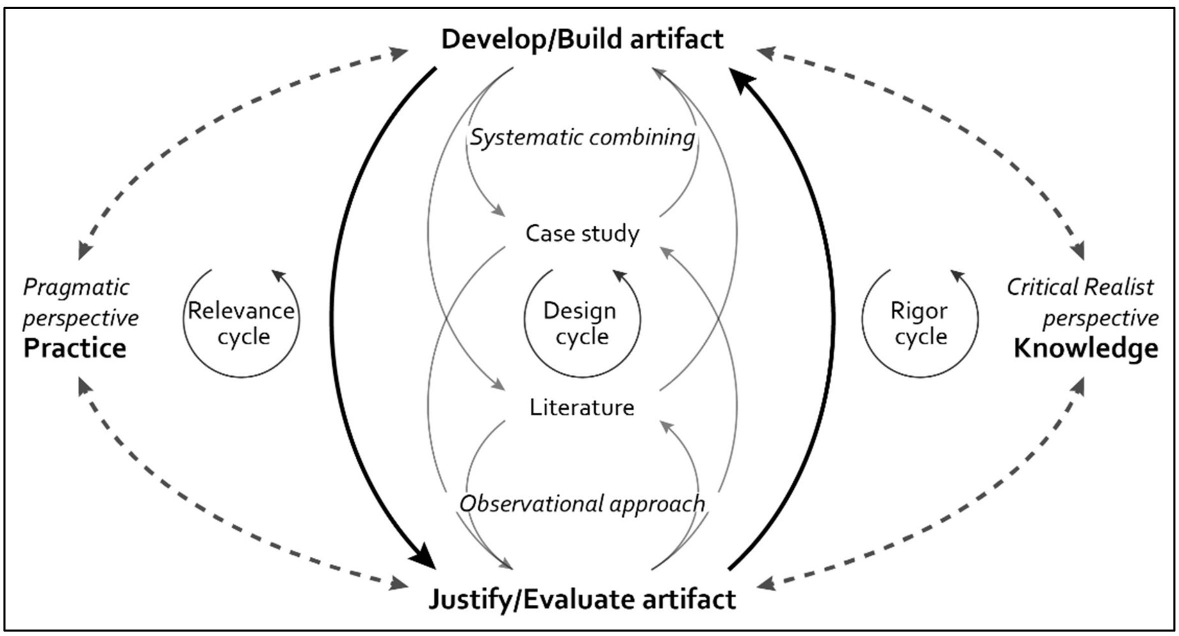

Figure 1.5 Research approach
Adapted from Hevner et al. (2004) and Hevner (2007)

1.6.1 Design science research and the sciences of the artificial

A clear distinction has been drawn between the behavioural sciences, which cover the natural and social domains, and design sciences, which cover the artificial domain (Cross, 2006). The principle difference between both fields lies in the explanatory and descriptive power of the natural sciences as opposed to the prescriptive power of the design sciences (March and Smith, 1995). Both are not mutually exclusive and act to inform one another (Hevner and Chatterjee, 2010). According to Hubka and Ernst Eder (1987):

> Design science addresses the problem of determining and categorizing all regular phenomena of the systems to be designed, and of the design process. Design science is also concerned with deriving from the applied knowledge of the natural sciences appropriate information in a form suitable for the designer's use (Hubka and Ernst Eder, 1987, pp.124-125)

Design science research (DSR) is embedded in the sciences of the artificial, hence it deals with "knowledge about artificial objects and phenomena" (Simon, 1996, p.3). DSR has gained traction in the computer sciences, software engineering and research on information systems (IS) where the development and application of practical information technology (IT) artifacts has been at the forefront of the research agenda for decades (Iivari, 2007). While the preponderance of work in the design sciences has targeted developing IT artifacts and focused on IS, the boundaries for the sciences of the artificial, as laid out by (Simon, 1996, p.5), are broader in scope:

1) Artificial things are synthesized (though not always or usually with full forethought) by human beings;
2) Artificial things may imitate appearances in natural things while lacking, in one or many respects, the reality of the latter;
3) Artificial things can be characterized in terms of functions, goals adaptation;
4) Artificial things are often discussed, particularly when they are being designed, in terms of imperatives as well as descriptives.

Collaborative, multi-disciplinary TPOs in the AECO industry are "designed" or "fabricated" (Nicolini, Mengis and Swan, 2012). Collaboration is, in effect, an artificial phenomenon and can thus fall within the realm of DSR when attempting to not only describe it, but also to explore and propose artifacts to improve it, a proposition supported by Van Aken (2005). Moreover, parallels have been drawn between TPOs in the AECO industry and information systems (Winch, 2010), which further anchors this particular perspective on DSR.

DSR is characterized by its constructive and pragmatic nature (Hevner et al., 2004). Being principally prescriptive, the goal of DSR is utility: it attempts to create things that serve human purpose (March and Smith, 1995). Indeed, a key component of DSR is the relevance of the products of research and the knowledge it generates (Van Aken, 2005). The products of DSR, the artifacts, are described as follows by March and Smith (1995, pp.253, 256-258):

- Constructs: the basic language of concepts used to characterize phenomena;
- Models: the combination of constructs, used to describe tasks, situations or artifacts;
- Methods: the ways of performing goal-driven activities;
- Instantiations: the physical implementation intended to perform certain tasks.

For Van Aken (2005), the product of DSR is the technological rule: "a chunk of general knowledge linking an intervention or artefact with an expected outcome or performance in a certain field of application" (Van Aken, 2005, p.23). The author goes on to state that: "A technological rule follows the logic of 'if you want to achieve Y in situation Z, then perform action X'. The core of the rule is this X, a general solution concept for a type of field problem. […] The solution concept can be an act, a sequence of acts, but also some process or system." (Van Aken, 2005, p.23). It could be concluded that technological rules, as envisioned by Van Aken (2005), are the embodiment of March and Smith (1995) different levels of artifacts. However, this technological rule is not limited to the field of computer sciences and IS as the author expands it to the management sciences.

Various guidelines have been developed to guide DSR and ensure that it is carried out properly. Perhaps the best known DSR guidelines are those developed by Hevner et al. (2004) (restated in Hevner and Chatterjee (2010)). The authors provide seven guidelines for DSR in the IS domain (Table 1.1). Van Aken (2005, in Järvinen (2004)) also provides DSR guidelines, but adapt them to management research (Table 1.2). Methods and criteria for evaluating the artifacts being built in DSR have also been developed. Hevner et al. (2004) provide a series of methods for design evaluation (Table 1.3). Järvinen (2004), expanding on March and Smith (1995), provide evaluation criteria for the different artifacts produced in DSR (Table 1.4)

Table 1.1 Design science research guidelines
Taken from Hevner and Chatterjee (2010, p.12)

Guideline	Description
Guideline H01: Design as an artifact	Design science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation
Guideline H02: Problem relevance	The objective of design science research is to develop technology-based solutions to important and relevant business problems
Guideline H03: Design evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods
Guideline H04: Research contributions	Effective design science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies
Guideline H05: Research rigor	Design science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact
Guideline H06: Design as a search process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment
Guideline H07: Communication of research	Design science research must be presented effectively to both technology-oriented and management-oriented audiences

Table 1.2 Design science research guidelines
Taken from Van Aken (2005, in Järvinen (2004, pp.111-112))

Guideline	Description
Guideline VA01: Descriptive relevance or external validity	The raison d'être of a technological rule is its external validity as established by testing multiple case-studies
Guideline VA02: Goal relevance or the extent to which results refer to matters the practitioner wishes to influence	In a prescription-driven research program, goal relevance is a key criterion for the choice of rules to be developed;
Guideline VA03: Operational validity or the extent to which the practitioner is able to control the independent variables in the model	The very nature of a technological rule assures its operational validity;
Guideline VA04: Non-obviousness	Because a technological rule is not forced into a reductionist format as quantitative causal models are, there is little danger of overly obvious research results;
Guideline VA05: Timeliness	A practitioner need arising from the 'incredible long period of time' required to adequately assess organizational phenomena and the scientist's reluctance to make recommendations before all the facts are in: in this respect the technological rule has no advantage over the causal model; for classes of management problems for which timeliness is a real issue, the practitioner will have to deal with consultants rather than academic researchers.

Table 1.3 Design evaluation methods
Taken from Hevner et al. (2004, p.86)

Approach	Method
Observational	**Case Study:** Study artifact in depth in business environment **Field Study:** Monitor use of artifact in multiple projects
Analytical	**Static Analysis:** Examine structure of artifact for static qualities (e.g., complexity) **Architecture Analysis:** Study fit of artifact into technical IS architecture **Optimization:** Demonstrate inherent optimal properties of artifact or provide optimality bounds on artifact behavior **Dynamic Analysis:** Study artifact in use for dynamic qualities (e.g., performance)
Experimental	**Controlled Experiment:** Study artifact in controlled environment for qualities (e.g., usability) **Simulation:** Execute artifact with artificial data
Testing	**Functional (Black Box) Testing:** Execute artifact interfaces to discover failures and identify defects **Structural (White Box) Testing:** Perform coverage testing of some metric (e.g., execution paths) in the artifact implementation
Descriptive	**Informed Argument:** Use information from the knowledge base (e.g., relevant research) to build a convincing argument for the artifact's utility **Scenarios:** Construct detailed scenarios around the artifact to demonstrate its utility

Table 1.4 Evaluation criteria for artifacts
Taken from Järvinen (2004, p.121)

Constructs	Model	Method	Instantiation
Completeness	fidelity with real world phenomenon	Operationality: Ability to perform the intended task Ability of humans to effectively use the method if its algorithmic	Efficiency and effectiveness of the artifact and its impact on the environment and its users
Simplicity	Completeness	Efficiency generality	Emergent changes with positive and negative unanticipated outcomes
Understandability	Level of detail	Ease of use	Investment appraisal techniques
Ease of use	Robustness	Application domain	Economic, technical, physical impacts
Communication	Internal consistency	Driving and blocking mechanisms	Social, political, historical contextual impacts
Cognition	Form and content		Cost/benefit : range measurement, valuation, allocation, periodization
	Richness of knowledge representation		Corrective, adaptive, perfective and preventive maintenance
			Division of power

DSR has been criticised for failing in certain regards. For instance, DSR has been criticised for focusing too much on information technologies and failing to consider the organizational and social domains (Drechsler, 2012). Furthermore, the theoretical foundations of the artifacts being developed are seen as lacking in many cases and work in this area has tried to reconcile both the theoretical knowledge and practical knowledge (e.g. Kuechler and Vaishnavi, 2008). It remains that the pragmatic roots of DSR tend to reduce the view of "truth" to a very limited and specific context and focus on utility. In order to help address these shortcomings, a critical realist perspective was adopted in the research project to frame the view of "truth" and provide an epistemic and ontological foundation to support the DSR approach.

1.6.2 Critical realism, the framing of knowledge and causality

Critical realists distinguish how we, as individuals, view the world, and how this world exists. Indeed, critical realism assumes that the world and our knowledge of it exist independently (Sayer, 1992). This knowledge of the world is socially constructed: it is in constant flux. For Bhaskar (2009); (2013) traditional approaches to scientific discovery and research, be it the positivistic (realist) or constructivist (relativist) tradition, tend to conflate ontology (existence and being) and epistemology (knowledge and language), phenomena that he's termed *epistemic fallacy* ("statements about being are to be interpreted as statements about knowledge" (Bhaskar, 2013, p.4) and *ontic fallacies* ("[which] ignores the cognitive and social mechanisms by which knowledge is produced from antecedent knowledge, leaving an ontology of empirical knowledge events (raw perceptions) and a de-socialized epistemology" (Bhaskar, 2013, p.21). Critical realism attempts to deal with these 'fallacies' by bridging the positivist-interpretivist divide, joining ontological realism and epistemological constructivism (Maxwell, 2012).

A critical realist view considers the world in a differentiated and stratified manner – layers defining the domain of real, actual and empirical – which operate on different time scales (Carlsson, 2003). Mechanisms operate in the domain of the real and generate phenomena which manifest themselves through specific events in the domain of actual. These events may or may not be observed and experienced in the domain of the empirical (Bhaskar, 2013; Sayer, 1992). Table 1.5, as developed by Bhaskar (2013, p.14), illustrates this stratification and in which domain the different manifestations of reality reside.

Table 1.5 Manifestations of reality in the critical realist stratification
Taken from Bhaskar (2013, p.14)

	Domain of real	**Domain of actual**	**Domain of empirical**
Mechanism	✓		
Event	✓	✓	
Experience	✓	✓	✓

The foundation of the critical realist perspective is to discover "the underlying structures that generate particular event patterns" (Carlsson, 2003, p.7), i.e. the generative mechanisms or the causes of an event, a relationship, etc. In essence, establishing causality is fundamental (Maxwell, 2012). This is done through a process of retroduction, a "[…] mode of inference in which events are explained by postulating (and identifying) mechanisms which are capable of producing them […]" (Sayer, 1992, p.107), which is discussed further in section 1.7.

The decision to adopt a critical realist perspective in this research project was made for several reasons: first, according to Easton (2010, p.121) "the most fundamental aim of critical realism is explanation; answers to the question "what caused those events to happen?"" This could seem at odds with the pragmatic and prescriptive approach underlying DSR, whose fundamental aim would be to answer the question "how can this event be improved?" It is argued here that critical realism's search for "truth" is central to design-science's search for utility. Critical realism supports a wider construction of "truth" which can enable the development of a more robust artifact. Second, critical realism supports mixed-method data collection by providing a coherent epistemic and ontological frame thus providing a coherent and consistent foundation to investigate a phenomenon as complex and multifarious as collaboration (Carlsson, 2003). Third, the notion of causality is important if we are to create an artifact that will serve its intended purpose. Critical realism not only accepts causality, it makes it a central feature in its framing of the world (Maxwell, 2004). Lastly, while some research in the AECO domain has adopted a critical realist perspective, namely (Smyth and Pryke, 2008) who studied collaborative relationships, trust in particular (Smyth, 2008), and (Fox, 2014) who looked specifically at BIM adoption, this perspective is still sparse.

1.7 Research methodology

A systematic combining process anchored in retroductive/abductive reasoning was used to inform this research project (Dubois and Gadde, 2002b; 2014). According to (Dubois and Gadde, 2002b, p.554): "Systematic combining is a process where theoretical framework, empirical fieldwork, and case analysis evolve simultaneously, and it is particularly useful for development of new theories." The authors describe systematic combining "[…] as a nonlinear, path-dependent process of combining efforts with the ultimate objective of matching theory and reality." (Dubois and Gadde, 2002b, p.556) Systematic combining involves matching, directing and redirecting the data being collected and analyzed with existing theory and the theory being developed. In this case, we equate theory development with the development of an artifact as described in DSR.

Retroductive logic is a different approach to reasoning from the deductive (associated with the positivist approach) or inductive (associated with the interpretivist approach) approaches. In the deductive approach, a hypothesis is formulated from existing theory and then empirically tested and verified. It follows a specific and recognized sequence: the scientific method. In the inductive approach, substantive theories are developed and built through constructs that emerge from data grounded in real-world settings. In the retroductive approach, which shows similarities to abduction[2], all possible theoretical explanations for specific observations are

[2] 'Retroduction' (pub. 12.03.13-18:29). Quote in M. Bergman & S. Paavola (Eds.), The Commens Dictionary: Peirce's Terms in His Own Words. New Edition. Retrieved from http://www.commens.org/dictionary/entry/quote-lessons-history-science-6. [July 2, 2015]

considered in an attempt to formulate hypothesis about the phenomenon under study (Bryant and Charmaz, 2007). As Josephson and Josephson (1996) write: " *Abduction, or inference to the best explanation*, is a form of inference that goes from data describing something to a hypothesis that best explains or accounts for the data." (emphasis in original)(Josephson and Josephson, 1996, p.5) As opposed to the inductive approach where *a priori* knowledge is set aside in the collection and analysis of data and the subsequent formulation of theory (the grounded theoretical approach (Glaser and Strauss, 2009), in the context of systematic combining the theoretical framework that is developed for the investigation is used to support the reasoning process and is continually being modified throughout " […] partly as a result of unanticipated empirical findings, but also of theoretical insights gained during the process." (Dubois and Gadde, 2002b, p.559). This being said, it is important to note that all three approaches to reasoning – deductive, inductive, abductive and retroductive – are not mutually exclusive. Many qualitative works use an inductive/retroductive/abductive-deductive framework through which theories are developed and, serving as hypotheses, are subsequently tested and evaluated (e.g. Kuechler and Vaishnavi, 2008).

Lastly, the research process is illustrated in Figure 1.6. The process is centered on the building and the evaluation of the artifact. One of the key elements of the systematic combining process is that data collection and data analysis are concurrent, continuous and iterative. This is similar to a grounded theoretical approach (Glaser and Strauss, 2009), however the method of sampling is different. The data sample for the research project is described below.

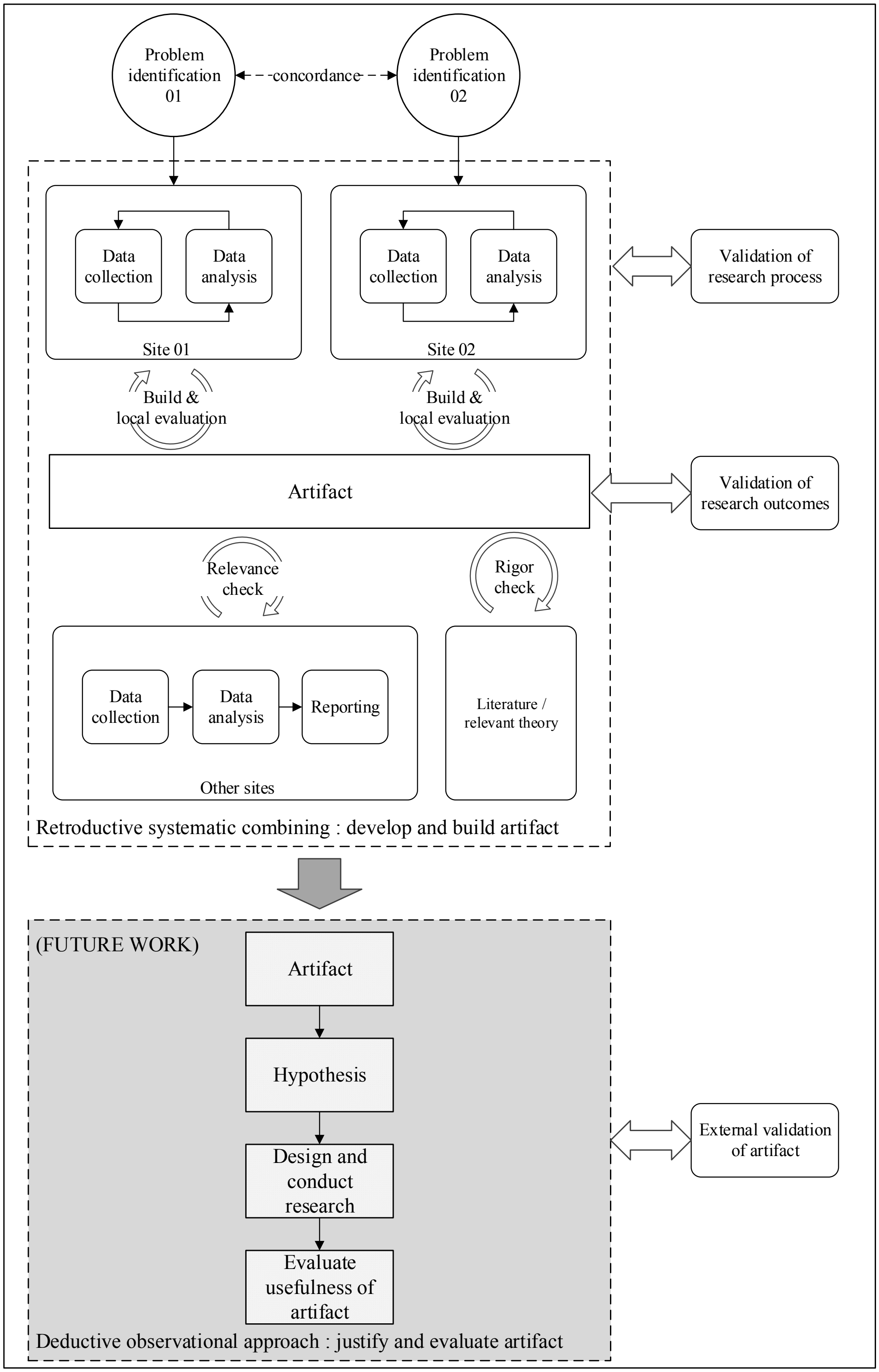

Figure 1.6 Research process

1.7.1 Data collection

The investigation into collaboration in the AECO industry presented in this thesis was informed by multiple data sources. Primary data was sourced from two sites on which mixed-methods of data collection were performed. Both sites involved case studies although one intervention was carried out as an action-research project (refer to CHAPTER 6). Both case studies and mixed-methods are increasingly popular in the AECO research domain (Abowitz and Toole, 2010; Taylor, Sturts Dossick and Garvin, 2011) as they allow a more complete and robust investigation of the phenomena under study in context (Yin, 2014) and also provide the grounding that is required to build and evaluate relevant and rigorous artifacts (Järvinen, 2004). Other data sources included two workshops and two large intervention projects. Figure 1.7 illustrates the overall doctoral studies timeline from the beginning (September 2011) to the end (September 2015) and includes the different milestones, the data collection sites as well as an overview of the evolution of the artifact as data analysis was being carried out.

Data collection was continuous throughout the research project. Both sites respected one of DSR's main principles that the research project must address a problem in practice (Hevner et al., 2004). Both research projects were initiated upon request of an industrial partner looking at implementing innovative approaches to project delivery, namely BIM, and wanting to assess their impact on project outcomes. Throughout the research the focus varied between the permanent organization (organizational level) and the TPO (project level). That being said, the principle units of analysis of this research project were the individuals evolving within their respective collaborative environments at both of these levels.

1.7.1.1 Site 01: The Royal Alberta Museum project

The first site involved the case study of the Royal Alberta Museum project, a $ 260 M design-build project, located in Edmonton, Alberta. The data collected in this case study was principally used to design and build the artifact, which was locally evaluated in turn.

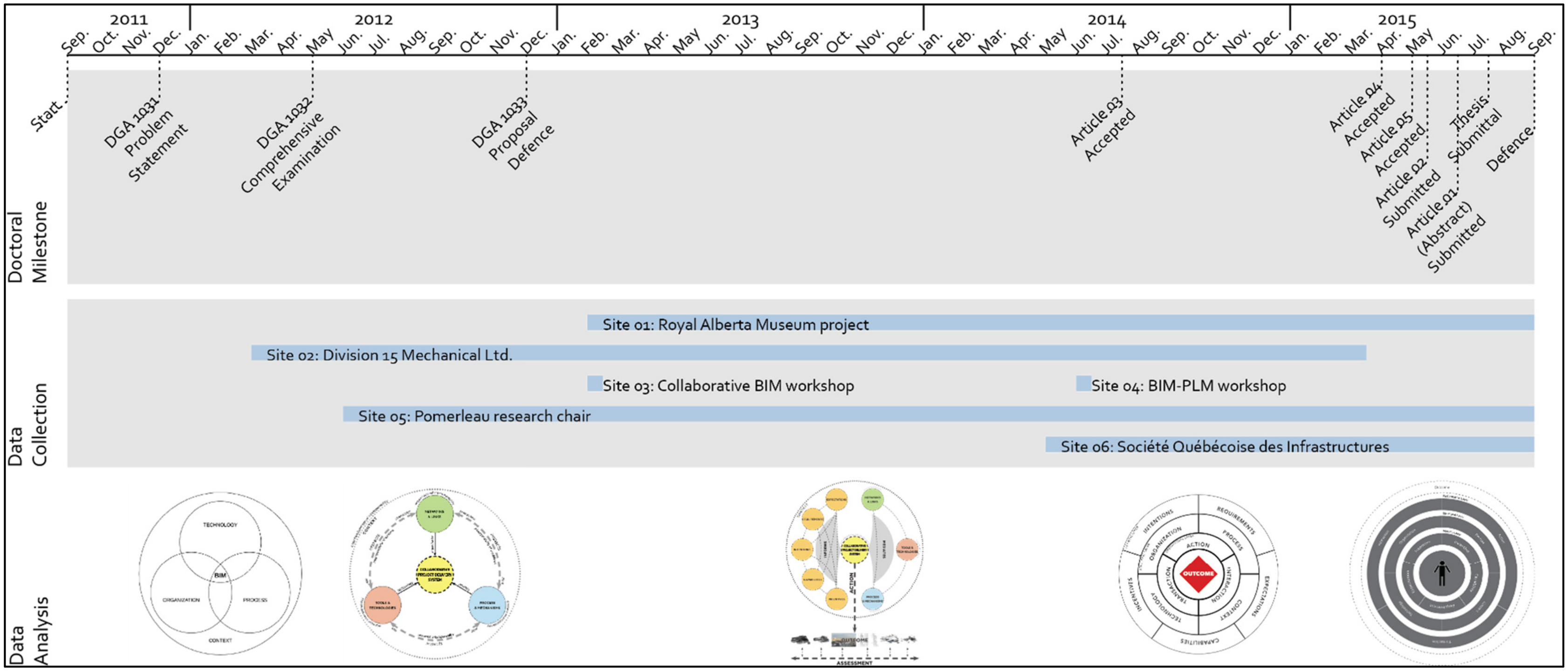

Figure 1.7 Doctoral studies timeline

Our involvement in this particular site came at the request of the project's client and owner, the Alberta provincial government, to research the impact of BIM on project delivery and document the lessons learned to inform future BIM projects commissioned by the government. The government was particularly interested in the collaborative aspects of BIM and design-build and the potential to improve project performance and value generation. We started collecting data in February 2013, which coincided with the beginning of the construction documentation (CD) phase. We kept a consistent presence throughout the CD phase (November 2014 - 22 months) and construction phase. Data collection is still underway with base building construction slated to be completed in June 2016 (Figure 1.8).

The qualitative data collected at this site consisted in semi-structured interviews (refer to Appendix IV for an outline of individuals interviewed), project meeting observation and some field observations. We conducted a total of 98 interviews with 43 different individuals belonging to the various stakeholders in the TPO. Certain key individuals were interviewed up to five times at six month intervals (i.e. for the first four rounds of interviews) to capture evolution of thought as the project progressed and to revisit certain themes over the course of the research project. The interviews were semi-structured and all based on an overarching protocol which addressed two main themes: the individual's personal, project and organizational contexts and the use of BIM. We also observed and analyzed the minutes for various types of meetings including steering committee (i.e. governance), design review and coordination, BIM coordination, trade coordination and scheduling.

The quantitative data collected at this site consisted in survey questionnaires (a total of three were conducted), all forms of project data such as formal communications (requests for information (RFI), change orders (CO), site instructions (SI) etc.), schedules, timesheets, project documentation (specifications and drawings), etc. Lastly, we analyzed 53 bi-weekly iterations of the models produced by the design team (architecture, structural, mechanical and electrical, for a total of 212 models) during the CD and beginning of construction and analyzed them following a rigorous protocol (refer to Appendix III and Appendix IV). Several reports were produced and reviewed by the project team and the client.

1.7.1.2 Site 02: Division 15 Mechanical Ltd.

The second site involved Division 15 Mechanical Ltd, a small mechanical contracting enterprise located in Vancouver, British Columbia. The data collected on this site was also used to design and build the artifact as well as locally evaluate it. Our involvement in this site came at the request of the organization's president & CEO to investigate the BIM adoption and implementation process and help the organization determine the impact of BIM on project outcomes at both the organizational and project level. Data was collected at both the organizational level as well as at the project level on eight projects in which the organization was involved (four of the projects are described in CHAPTER 4, section 4.5, a fifth is described in CHAPTER 5, section 5.4, and three other projects were studied retrospectively, also described in CHAPTER 5). While part of the research carried out on this site could be defined as case studies (refer to CHAPTER 4 and CHAPTER 5), we also conducted an action-research project with the organization which entailed a different approach to data collection and analysis (refer to CHAPTER 6) We started collecting data in April 2012 and kept a consistent presence within the organization until the end of the research project in April 2015 (Figure 1.9)

The qualitative data collected at this site consisted in semi-structured interviews (refer to Appendix V for an outline of individuals interviewed), meeting observations, field observations and informal discussions with various members of the organization. We conducted a total of 11 interviews with 8 different individuals belonging to the organization and one client representative. The interviews were semi-structured and all based on an overarching protocol which addressed two main themes: the individual's personal, project and organizational contexts and the use of BIM. Meeting observation was principally conducted at the organizational level (BIM steering committee meetings) and some meetings for project 4 were observed. Field observations were mainly carried out on project 4 (refer to CHAPTER 6, section 6.5, for an in-depth description of project 4).

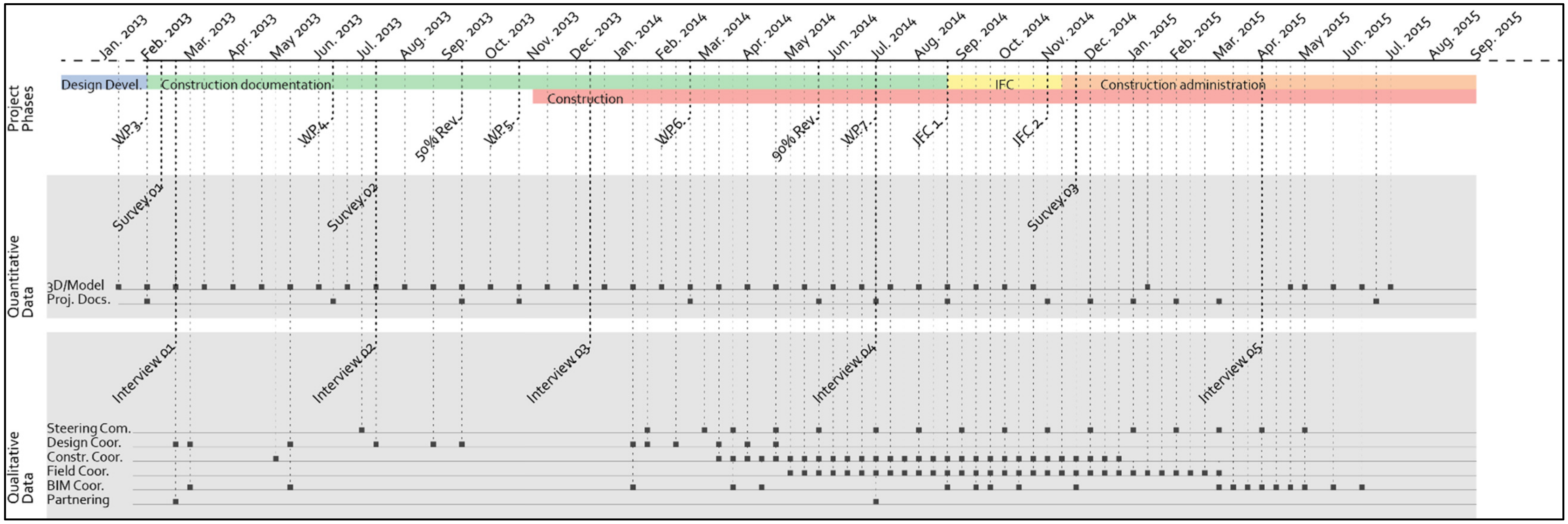

Figure 1.8 Site 01 timeline

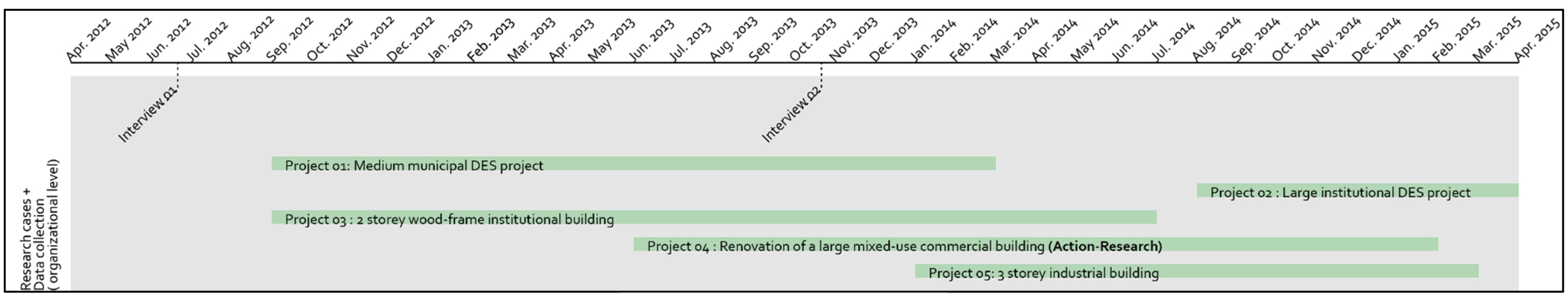

Figure 1.9 Site 02 timeline

The quantitative data collected at this site consisted in all forms of project data such as formal communications (requests for information (RFI), change orders (CO), site instructions (SI) etc.), schedules, budgets, timesheets, and project documentation, including specifications and drawings as well as project models and spool drawings, collected on all projects. Organizational documents such as the BIM implementation plan and the BIM standard were also collected and reviewed. Several reports were produced and reviewed by the organization.

1.7.1.3 Other sources of data

Other sources of data collected in this research project were used as relevance checks. These sources consisted of two workshops and two large intervention projects. The first workshop was held in Montreal, Quebec in February 2013 (site 03). It was set around collaborative BIM and its deployment in the Quebec AECO industry. The workshop was attended by 18 participants from both academia and industry. It was structured around a round table discussion on three themes: 1) BIM in education, 2) considerations of industry culture in BIM deployment and 3) contractual relationships in TPOs and their impact on collaborative environments. The workshop concluded with a SWOT analysis focussing on the barriers to collaborative BIM. Having been held relatively early in the research project, the principal contribution of this workshop was to anchor some of the practical considerations and barriers to collaboration and BIM in the AECO industry (with a focus on the Quebec context), serving as further practical motivation to the problem domain. The workshop also provided empirical data in the form of survey results and SWOT analysis results.

The second workshop was also held in Montreal, Quebec in June 2014 (site 04). It was entitled *BIM & PLM: Transitioning to Building Information Modeling and Product Lifecycle Management in the Quebec Construction Industry - Challenges, Possible Solutions and Proposed Action Items*. The workshop was attended by 35 participants from both academia and industry. The workshop focused on Hydro-Quebec, a state-controlled crown corporation generating, transmitting and distributing electricity throughout Quebec and to parts of northeastern North-America. It was structured around defining a desired state for BIM-PLM deployment and exploring possible avenues for optimization of Hydro-Quebec's current project delivery process. The workshop first converged on a vision for the future of BIM-PLM throughout the construction supply chain and identified the challenges to achieve this vision. It then identified solutions to these challenges and proposed a feasible action plan to achieve this vision. The workshop was held at a moment in this research project that the artifact being developed had gone through three iterations. While the artifact itself was not presented at this workshop, the qualitative data gathered (i.e. all presentations and discussions were recorded and transcribed for analysis) provided further empirical evidence to support its evaluation.

The first large intervention project was that of Pomerleau General Contractors (site 05). The principle objective of the Pomerleau research chair, held by Professor Daniel Forgues, is to build new theoretical and empirical knowledge to reorganize and integrate industry practices around BIM. Secondary objectives investigated the technological, organizational and process dimensions of BIM adoption and implementation. The scope of work that I was tasked with was to develop a benchmarking framework, including identifying key performance indicators (KPI) and metrics, to support the BIM adoption and implementation process and evaluate its impact on various measures including collaboration. This project contributed to the development and building of the artifact and provided quantitative data in the form of surveys. The KPIs and metrics developed were reviewed and adopted by the organization, providing some third party evaluation and validation.

The second large intervention project was that of the Société Québécoise des Infrastructures (SQI) (site 06). The SQI is the Quebec government's real estate arm. It is currently looking to transition to BIM and to develop a mandate for BIM on all of its projects by April 2016. The research team was tasked to provide technical information and supporting documentation to inform the development of a strategic plan for the SQI to move forward with its BIM implementation process. This information came from three sources: existing literature, semi-structured interviews carried-out with global leaders in BIM adoption and implementation in the UK, the USA, Finland, Norway, and Canada and an observation mission to Sutter Health's Cathedral Hill Medical Center project in San Francisco conducted in September 2014 where observation and interviews were carried out over a three day period. This project provided qualitative data to support the evaluation of the artifact from a broader perspective than the one offered by the case studies. Both reports, the strategic plan and the observation mission's report, were reviewed by SQI representatives.

1.7.2 Data analysis: building and evaluating the artifact

The artifact was built using a qualitative data analysis process grounded in retroductive (i.e. showing similarities to abductive) reasoning and supported through the systematic combining methodology as described above. All interviews for sites 01, 02, 04 and 06 were transcribed and coded in Nvivo 10 (QSR, 2010). In building the artifact, different coding strategies were used (Miles, Huberman and Saldaña, 2013). According to Walker and Myrick (2006) "Coding is an iterative, inductive, yet reductive process that organizes data, from which the researcher can then construct themes, essences, descriptions, and theories." (Walker and Myrick, 2006 p.549) The process of coding, according to Miles, Huberman and Saldaña (2013), constitutes the basic form of analysis. Coding is done by applying labels "[…] that assign symbolic meaning to the descriptive or inferential information compiled during a study." (Miles, Huberman and Saldaña, 2013, p.72).

To guide the analysis, an initial framework was developed (Figure 1.10). This preliminary conceptual framework developed different dimensions which define the collaborative project delivery system: the technological dimension, the organizational dimension and the procedural dimension (adapted from Staub-French and Khanzode (2007)) as well as the contextual dimension. This conceptual framework resonates with others, such as Leavitt's diamond (Leavitt, 1965), the People-Process-Technology framework or the Technology-Organization-Environment framework (Tornatzky and Fleischer, 1990) based in IS research, the Model-Team-Process approach (Staub-French, Forgues and Iordanova, 2011) developed by DPR construction, the Product-Organization-Process (P-O-P) model (Garcia et al., 2004) developed at Stanford University's Center for Integrated Facility Engineering's (CIFE) or the Technology-Process-Policy (T-P-P) fields developed by Succar (2009).

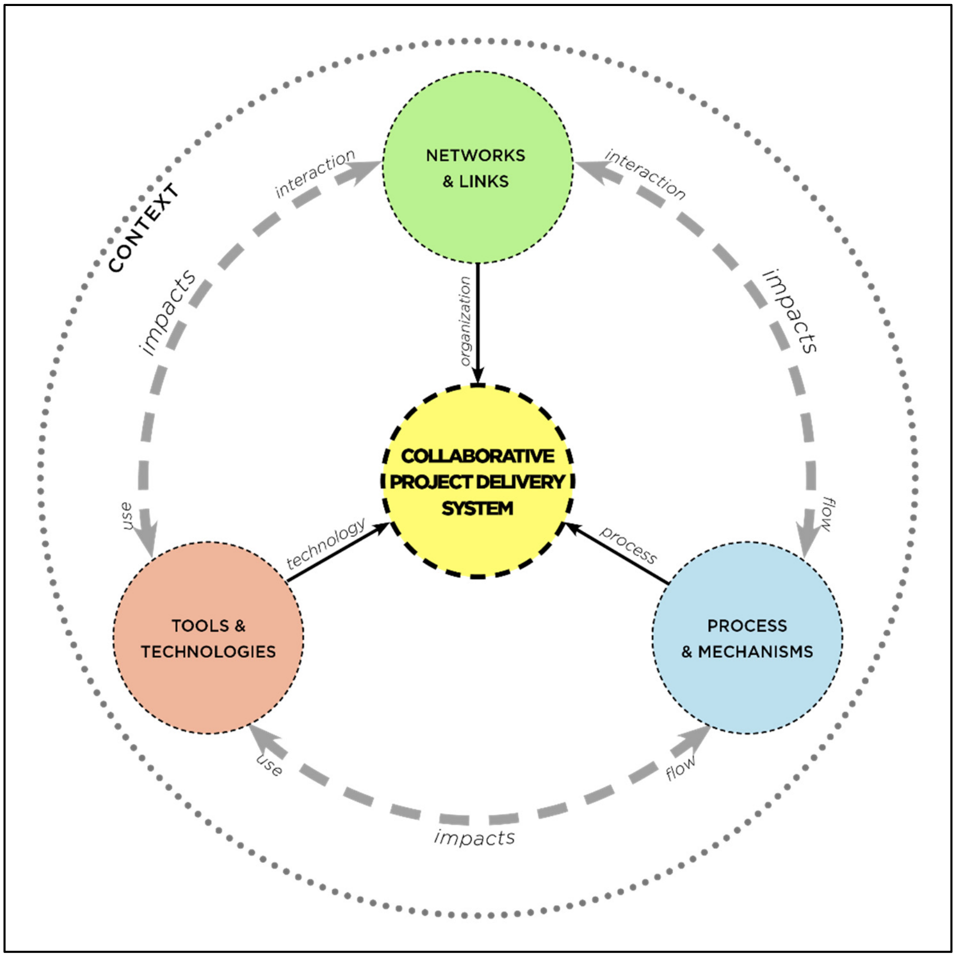

Figure 1.10 Initial conceptual framework

I started by coding to the framework, but soon found that it became too constraining and narrow. During this first cycle of coding the scope of analysis rapidly expanded and so I had to adopt a more open approach to the coding process (Holton, 2007). Initial patterns emerged during the analysis of the first two rounds of interviews conducted on site 01 and the first interviews conducted on site 02, which helped to inform the coding strategy moving forward. The strategy revolved around understanding how individuals framed their 'internal course of collaborative action' with regards, but not limited, to BIM-based collaboration. This meant adopting the individual as the unit of analysis and coding to both the response to the interviewers prompt (the performed action) and the action implied by the interviewee, dealing in a sense with Giddens' double hermeneutic (Giddens, 1984), i.e. the interpretation of the interpretation. We also had to differentiate between descriptions of past or present actions and forecasting of future actions. This first layer of analysis served to orient the specific actions that were being carried out by the individuals in the collaborative environment. We then wanted to understand the outcome or consequence of that action, whether it was positive, negative or neutral. This was done to establish a qualitative and interpretative causal link between actions and outcomes in the BIM-based collaborative environment. To further define this 'internal course of collaborative action, we then investigated what was structuring or configuring these actions. To do so, we relied on the initial framework illustrated in Figure 1.10. This added another layer to our analysis. At this point we were gaining an understanding for individual perceptions of what was happening and how it was supported or structured. The first three layers of analysis, outcomes, actions and structures were coded using both process codes and descriptive codes as defined by (Miles, Huberman and Saldaña, 2013). That being said, we were still lacking an answer to why it was happening and why it was happening in a particular way, i.e. what prompted the individual to act in the way that he did, what guided it or constrained it? For us, this was central to uncovering a complete 'internal course of collaborative action' that could help to explain how and why people collaborate. Therefore we added a fourth layer of analysis to interpret why the individual acted in the way that was discussed. We ended up with a layered coding strategy which ultimately resembled causation coding as described by (Miles, Huberman and Saldaña, 2013).

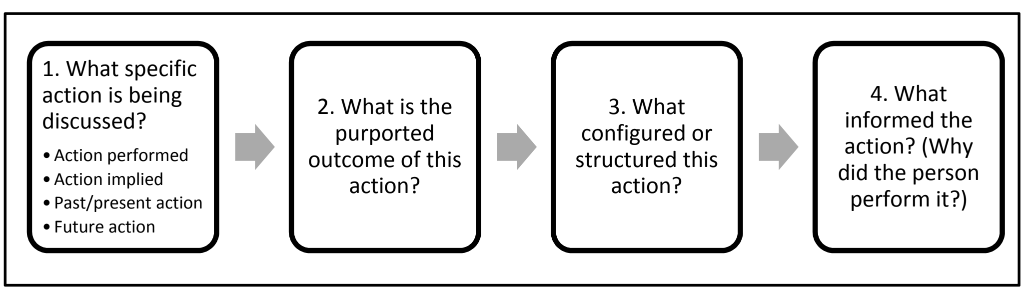

Figure 1.11 Coding strategy

To illustrate how the coding strategy was implemented we present an example that relates the owner's decision to not require BIM on the project of site 01. Table 1.6 provides a rough frame to define a 'course of collaborative action' across the layers of the frame of reference and defines a rough causal structure of the owner's decision to implement BIM on the project. We can see that the main 'course of collaborative action' was informed by a general consensus, or alignment, on the part of the owner's management team as to the perception of the industry context lacking sufficient capabilities to deliver a BIM-based project. Ultimately, this resulted in the BIM requirements being limited to the proposal stage:

> When we started thinking about implementing BIM on the project, some of us were keen on doing it. [We thought] "Let's just make it a review requirement to hand over a BIM model". I don't think at that point anyone thought it would go to FM at all. But what it came down to, is the bridging architect, who developed the RFP, said that he wasn't sure that the industry was there yet to make it a requirement for the job. We then reduced it down to them having to provide the model at the proposal stage to validate areas. (Project Coordinator, Owner (1st rd.))

Table 1.6 Coding Example 01: Owner's perspective on BIM implementation in the project

Question	Finding
What specific action is being discussed? Action performed Action implied	 Discussing how the decision to implement BIM was taken Defining the scope of BIM requirements on the project
What is the purported outcome of this action?	BIM requirements limited to the proposal stage
What configured the action perceived and implied?	A perception of the industry context with regards to BIM capabilities
What informed the action? (Why did the individual perform the action?)	A consensus around a perceived lack of BIM capabilities within the industry

This type of analysis was performed on the qualitative data for the first three rounds of interviews on site 01 and the first round on site 02 as well as some of the data from site 06. As we went further into the analysis, clear patterns emerged within the layers in which specific and unique categories were uncovered. We also extended the analysis beyond BIM to broaden the scope of investigation and attempt to capture the multifarious and complex nature. As these categories were uncovered, the constructs, which would define the language of the artifact, were developed and refined. Linguistic cues were defined in support of the targeted questions and served to inform and standardize the analysis process, and hence the construct building process. What emerged from this exercise was a characterization of ‘courses of collaborative action’ articulated within a frame of reference and developed across four layers as defined by the questions outlined in Figure 1.11. This characterization is illustrated in Figure 1.2.

For the quantitative data, analysis was carried out in different manners. Most quantitative project data collected on site 02 was used to evaluate project outcomes and develop key performance indicators and measures of project success (refer to CHAPTER 5 and CHAPTER 6). The quantitative data collected on site 01 was both survey based and, as mentioned, the bi-weekly individual disciplinary project models. The surveys were used to provide a context and validate perceptions about benefits and challenges of both project context and the use of BIM. The results were presented in the reports provided to the project team and the client. The methodology and results of the model analysis are presented in Appendix III and Appendix IV.

1.7.3 Validation: evaluating the research process and its outcome

In the context of this research project validation represents two concomitant processes. The first process is the evaluation of research methods and findings. Naturally, valid research methods and findings (i.e. data collection and analysis) would yield a valid artifact. The second process is the evaluation and justification process for the artifact itself, a process that is proper to DSR. In this case, validation implies evaluating the usefulness of the artifact and it is assessed following methods such as those identified by Hevner et al. (2004) (Table 1.3) and criteria such as those identified by Järvinen (2004) (Table 1.4). In essence, we are evaluating the process (the research), the outcome of that process (the findings) and the reinterpretation and operationalization of those outcomes (the artifact). It is important to recall that the collection, analysis and validation processes carried out in this research project were concurrent, continuous and iterative and did not play out as discrete events. Furthermore, seeing as the research project was more qualitative in nature (for both the develop/build and justify/evaluate processes), we look towards validation of qualitative approaches to research over validation of quantitative approaches.

The concept of rigor is applicable to all types of research, regardless of their design. Rigor in research, or “goodness”, has to do with “[…] the soundness of its method, the accuracy of its findings, and the integrity of assumptions made or conclusions reached […]”(Long and Johnson, 2000, p.30). In DSR, rigor of the research is the fifth guideline as presented by Hevner et al. (2004) and included in Table 1.1. Furthermore, in DSR “[…] rigor is derived from the effective use of the knowledge base—theoretical foundations and research methodologies. Success is predicated on the researcher’s skilled selection of appropriate techniques to develop or construct a theory or artifact and the selection of appropriate means to justify the theory or evaluate the artifact.” (Hevner et al., 2004, p.88)

The traditional notions of reliability and validity are anchored in the quantitative/positivist research tradition (Guba and Lincoln, 1989). Consensus has been fostered long ago around the criteria, measures of objectivity and methods of evaluating the different types of validities (internal, external, construct, etc.). In the field of qualitative research there is little consensus to be found on clear notions of methods and measures to evaluate the validity of research (Creswell and Miller, 2000; Guba and Lincoln, 1989; Maxwell, 1992). Guba and Lincoln (1989) map concepts of validity in the positivist tradition to concepts that they developed for the qualitative field. For instance, the authors speak of “authenticity” instead of “validity”, “trustworthiness” instead of “reliability”. Many other authors have developed their own taxonomies of qualitative research validation measures and methods to a point where there seems to be general confusion as to what measures are appropriate in validating qualitative research (Creswell and Miller, 2000). One of the ways to filter these approaches to validation is to look at the perspective, paradigm or epistemological position adopted by the authors having developed the various validation techniques (Creswell and Miller, 2000). For example, whereas Guba and Lincoln (1989) clearly position themselves in the constructivist paradigm, (Maxwell, 1992, 2004, 2012) and Miles, Huberman and Saldaña (2013) adopt a realist perspective, which informs how they view validation in qualitative research. This is but an example of a long standing debate. Taking cues from Miles, Huberman and Saldaña (2013), we will skirt this debate and focus on the common procedures which have found footing within the field by using the pairings that Miles, Huberman and Saldaña (2013) have developed to outline the main, if not overlapping, issues to be addressed in qualitative research, which are presented in Table 1.7 (Miles, Huberman and Saldaña, 2013).

Table 1.7 Indicators of research rigor/goodness
Taken from Miles, Huberman and Saldaña (2013, p.311-315)

Measure	**Description**
1) Objectivity, confirmability,	*Neutrality of the research process, divulging of researcher bias.* Supported through reflexivity, making explicit research methods and procedures, allowing for an “audit trail” and consideration of rival conclusions for results.
2) Reliability, dependability, auditability,	*Quality, integrity, consistency and stability of research processes over time.* Supported through clear research questions, breadth and depth of data collection, and parallelism of data collection and findings.
3) Internal validity, credibility, authenticity,	*The value of the truth uncovered, the credibility of the findings.* Supported through prolonged engagement, “thick” and rich descriptions, triangulation of methods and data sources, linkage of data to theory, negative evidence and rival explanations have been sought and considered, review of findings by project participants (member-checking).
4) External validity, transferability, fittingness,	*Generalizability and transferability of findings to another context.* Supported through a full description of the research sample to permit adequate comparison to other samples, congruence, connection or confirmation of findings with prior theory, replication of findings in another context.
5) Utilization, application, action orientation.	*The contribution of the research and its findings to the participants, the consumers and the population at large.* Supported through communication of the findings, the amount of usable or applicable knowledge, the development of new capabilities.

Clear parallels can be drawn between some of the indicators identified by Miles, Huberman and Saldaña (2013), presented in Table 1.7, and the guidelines developed by Hevner and Chatterjee (2010); Hevner et al. (2004), namely guidelines 3,4 5 and 7 presented in Table 1.1. These parallels further strengthen the concomitant process of process validation and artifact evaluation discussed above and that is central to this research project. The particular validation and evaluation methods used in this research project are described for the process (the research), the outcome of that process (the findings) and the reinterpretation and operationalization of those outcomes (the artifact).

1.7.3.1 Objectivity, confirmability

The objectivity and confirmability of the research is supported by providing sufficient background on both the research process as well as the context in which the research was being conducted. Each article contains a section which outlines these specific contexts, except for article 02 (CHAPTER 3) which was more theoretical in nature and based on the literature. Extra attention was also put on providing adequate information on the sequence of data collection and analysis (Figure 1.7). Article 01 (CHAPTER 2) and article 03 (CHAPTER 4) establish the links between the data and the conclusions leading to the creation of the artifact directly while article 02 (CHAPTER 3) explores the theoretical background and rival conclusions. Lastly, a discussion on personal biases and assumptions and their impact is provided in section 7.2.

1.7.3.2 Reliability, dependability, auditability

The reliability, dependability, auditability of the research is ensured through clear research questions (section 1.5) and through explicitly specified paradigms and research perspectives (section 1.6). Research protocols were developed for both principle research sites, which included data collection mechanisms such as interview scripts, survey questionnaires, and observation procedures, and data analysis mechanisms, such as conceptual frameworks and theoretical categories for subsequent analysis. Computer Assisted Qualitative Analysis Software (CAQDAS), in this case Nvivo 10 (QSR International, 2013), was used throughout the research project. The software automatically produces a log for audit purposes and captures all manipulations on the data performed within the software. For the works described in articles 04 (CHAPTER 5) and article 05 (CHAPTER 6) the data collection and analysis were carried out in concert with the organization itself and constantly validated.

1.7.3.3 Internal validity, credibility, authenticity

The internal validity, credibility, authenticity of the research is supported thorough rich description in articles 01 (CHAPTER 2), article 03 (CHAPTER 4) and article 04 (CHAPTER 5). The artifact and the outcomes from its operationalization have been presented in forms of reports, which have been reviewed by project participants (although future work is needed to further validate the artifact, which is discussed in section 7.5) and considered to be accurate or have been amended where applicable. Triangulation of data sources, of collection and analysis methods, and interdisciplinary triangulation, as described by Love, Holt and Li (2002), has been performed throughout the research project. Articles 01 and 03 (CHAPTER 2 and CHAPTER 4) discuss triangulation of data sources and methods whereas article 02 (CHAPTER 3) describes the interdisciplinary triangulation that was performed. Lastly, negative evidence and rival explanations have been considered throughout the data analysis process. One of the ways in which this was done was by posing the questions shown in Figure 1.11. The questions prompted consideration of all possible rival explanations and also highlighted negative evidence, i.e. the nonoccurrence or absence of evidence, during the coding process. It also helped in maintaining objectivity and reducing bias. Lastly, some form of methodological replication was conducted between the two principle research sites. The limitations of this particular approach are discussed in section 7.2.

1.7.3.4 External validity, transferability, fittingness

The external validity, transferability, fittingness of the research is supported by a fully transparent description of the research samples at the various sites (refer to appendix IV, V and VI). The findings, while novel in their articulation through the development of the artifact, are congruent with work in this area as discussed in article 01 and 02 (CHAPTER 2 and CHAPTER

3). Furthermore, the artifact itself was evaluate locally through application on data from both sites during the iterative build/evaluate cycle. The limitations of these approaches are discussed in section 7.2 and 7.3.

1.7.3.5 Utilization, application, action orientation

The utilization, application, action orientation of the research is consistent with one of the principle guidelines of DSR as discussed in section 1.6.1, which is to develop an artifact that is useful in practice and solves a real-world problem. The application of the research findings, in this case the artifact, is directly linked to its external validity, transferability, fittingness. The evaluation criteria developed in Table 1.4 can serve as a basis to determine its potential for application. That being said, the action orientated-ness of this indicator of research rigor/goodness as described by Miles, Huberman and Saldaña (2013) also attempts to evaluate the impact on study participants and users of the findings. In each of the research sites, our involvement came at the request of an industry stakeholder to solve a practical problem, except for site 03 which was based around direct interactions between academia and industry in the form of a workshop (site 04 was initiated upon request from an industry partner). Through direct interaction and reporting of findings back to the industry stakeholders it is expected that they gain a better understanding of their situation and can act upon this knowledge to develop new capabilities. This is further discussed in section 7.4.

1.8 Structure of the thesis

This section presents the organization of the articles that constitute this thesis. Each article stands alone in its own right, however a distinct thread ties them all together: to answer the research questions. Articles 01 and 02 (CHAPTER 2 and CHAPTER 3) answer the main research question as well as the two first sub-questions. They set the groundwork to answer the fourth research question. Both chapters contribute to the overall artifact that is put forth in this thesis from a practical and theoretical perspective. Article 03 (CHAPTER 4) specifically addresses sub-question 01 and contributes to the development of the artifact, namely context as a defining category of collaboration, thus contributing to answer the main research question.

Articles 04 and 05 (CHAPTER 5 and CHAPTER 6) address the impact and outcomes assessment portion of the main research question and sub-question 03 and lay some groundwork to answer the fourth research question.

Three conference papers are presented in the appendices which are deemed to further support the research project. Appendices I and II address sub-questions 01 and 02 in particular and contributes to the development of the artifact, namely the agentic, structural and performative layers as defining categories of collaboration. Appendix III addresses the impact and outcomes assessment portion of the main research question and sub-question 03. All three papers contribute to formulating an answer to the fourth research question. The contribution of each article and paper to the research project is presented in Table 1.8.

Table 1.8 Article and paper contributions to research questions

	RQ01	**RQ02**	**RQ03**	**RQ04**
Article 01	✓	✓	✓	✓
Article 02	✓	✓	✓	✓
Article 03	✓	✓		
Article 04	✓		✓	✓
Article 05	✓		✓	✓
Paper 01	✓	✓		✓
Paper 02	✓	✓		✓
Paper 03			✓	✓

1.8.1 Article 01 - Investigating BIM-based collaboration to support its management and assessment

Article 01 presents and discusses the practical development, operationalization and validation of the artifact developed in the research project: a multi-layered framework that supports the management and assessment of BIM-based collaboration. The article discusses the implications of the transition to BIM on collaboration through the framework. The development of the constructs, the model and the method of instrumentation, which form the framework are presented.

Article 01 contributes to the knowledge domain by first characterizing collaboration in a way that allows its operationalization. From this characterization, an artifact is built and evaluated to support an assessment of the impact and outcomes of BIM-based collaboration. In turn, it is suggested that the artifact developed to assess, can also be used to inform and manage this collaboration. It presents an original approach on the study of innovative project delivery approaches, namely BIM, aimed at fostering collaboration. Article 01 contributes to the thesis by describing the building, evaluation and assessment stages of the multi-layered framework. It addresses all research questions (RQ 01, RQ 02, RQ 03 and RQ 04).

1.8.2 Article 02 - Collaboration through innovation: implications for expertise in the AECO industry

Article 02 anchors the artifact within the theoretical domain. The constructs and the model of collaboration developed in the multi-layered framework are mirrored with the literature. A process view of the building project and a systems view of collaboration are developed in the article. The critical realist perspective is applied to support this theoretical investigation. Article 02 was submitted to be part of a special issue on expertise in the AECO industry and thus expands on the question of collaborative expertise and practice.

Article 02 contributes to the knowledge domain by applying a theoretical lens to the study of collaboration and expertise in the AECO industry. The article highlights the implications of the transition to novel project delivery approaches on expertise and practice from a theoretical perspective. It also frames the concept of collaboration and reviews collaboration theory and practices. Article 02 contributes to this thesis by laying the theoretical foundation for the multi-layered framework. It addresses all research questions (RQ 01, RQ 02, RQ 03 and RQ 04).

1.8.3 Article 03 - Embedded contexts of innovation: BIM adoption and implementation for a specialty contracting SME

Article 03 investigates context as a structuring element in the innovation process through an account of BIM adoption and implementation in a small mechanical contracting enterprise.

The article provides a rich description of the various contextual factors that affect how BIM is deployed at the project level from an organizational perspective. It describes the radical and incremental innovations that take place as the organization evolves in its innovation process. The contextual factors are seen to affect different aspects of collaboration at both organizational and project levels. The focus of the article is also on a small enterprise and a mechanical specialty contracting firm, a perspective which is underrepresented in the literature but makes up the majority of the Canadian AECO industry.

Article 03 contributes to the knowledge domain by identifying four distinct yet embedded context that influence the innovation process for a specialty contracting SME. The industry context, the institutional context, the organizational context and the project context each structure in their own right the organization's BIM adoption and implementation process. This ultimately impacts its capability to collaborate through BIM. Furthermore, the article contributes to the growing literature on BIM adoption, by discussing BIM as a radical innovation which is subsequently followed by a series of incremental innovations as the organization furthers its capabilities. Article 03 contributes to the thesis by exposing the challenges with the innovation process for organizations seeking to improve project delivery and collaboration. The article develops and expands the 'Context' category within the artifact and explores the agentic layer in a preliminary fashion: mentions are made of the capabilities, expectations, incentives, requirements and intentions categories which are articulated in the artifact. It addresses first two research questions (RQ 01 and RQ 02).

1.8.4 Article 04 - Assessing the performance of the BIM implementation process within a small specialty contracting enterprise

Article 04 investigates the challenges of assessing the performance of the BIM adoption and implementation process as well as measuring and evaluating the impact of BIM within a small specialty contracting enterprise. The article develops an evolutionary approach to the assessment of the BIM implementation process within the organization. It posits that the lack of collaboration on the part of the other TPO members with regards to the implementation and use of BIM seriously hinders the benefits reaped by both the organization and the TPO.

Article 04 contributes to the knowledge domain by presenting a systematic approach to the assessment of BIM implementation within a specialty contracting SME through the evaluation of the variability of key performance indicators across time. The article presents and discusses five measures of performance: (1) predictability of project cost, (2) predictability of project scope, (3) predictability of productivity indicators (4) predictability of project schedule, and (5) predictability of project quality. In large part, these indicators are seen to be affected by the level of collaboration and BIM use developed by the different TPOs with which the organization is collaborating. However, being a specialty contractor, the organization was seen to have limited influence both on this level of collaboration and how BIM was being used on the projects studied. This speaks to the lack of alignments as developed in the artifact. Article 04 contributes to the thesis by developing the performance assessment perspective outlined in the artifact's method of operationalization. It also develops and expands the 'outcomes' category with regards to BIM adoption, implementation and collaboration and provides a basis to measure and assess these outcomes and this impact. It exposes the challenges with the measurement and assessment of the impact of BIM on project outcomes and within the organization. It also exposes the challenges faced in attempting to foster alignment within a TPO based on contextual and organization factors such as delivery mode, contract types and supply chain capability and requirements. It addresses the third research question (RQ 03) and helps to formulate an answer to the last prospective research question (RQ 04).

1.8.5 Article 05 - Measuring the impact of BIM on labor productivity in a small specialty contracting enterprise through action-research

Article 05 builds on the work carried out in article 04 by focusing on the impact of BIM on labor productivity. It presents the result of a 1 year action-research project, which systematically investigated labor productivity within a small mechanical contracting enterprise having implemented BIM. Article 05 contributes to the knowledge domain by measuring the impact of BIM on labour productivity for a mechanical contracting enterprise. It implements the systematic approach developed in article 04. The article exposes the challenges of measuring and assessing the impact of BIM on project outcome. Article 05 contributes to the thesis by developing and expanding the 'outcomes' category as well as the serves as empirical feedback for the ‘incentives’ category. The article provides a basis to measure and assess the outcomes and their impact on labor productivity. It addresses the third research question (RQ 03) and helps to formulate an answer to the prospective research question (RQ 04).

1.8.6 Conference papers – Appendices I, II and III

1.8.6.1 Paper 01 - Informing action in building information modeling (BIM) based multi-disciplinary collaboration

Paper 01 explores how actions are informed at the individual level in BIM based multi-disciplinary collaboration. It presents the five categories of the agentic layer that make up part of the multi-layered framework (the artifact). Paper 02 contributes to the knowledge domain by developing five categories of individual level constructs which are seen to inform action in a collaborative setting. The paper offers an alternative view of why actions are performed in a certain way in the context of BIM based collaboration. It also offers a complimentary view to typical BIM project execution planning. The paper contributes to the thesis by presenting and expanding on the five categories which constitute the agentic layer and the relationships between these categories. It also positions the agentic and performative layers within the artifact and discusses concepts that are closely associated to it, namely alignment. It addresses the first two research questions (RQ 01 and RQ 02) and helps to formulate an answer to the prospective research question (RQ 04).

1.8.6.2 Paper 02 - Dimensions of interoperability in the AEC industry

Paper 02 introduces a conceptual framework that exposes the dimensions of technology, organization, process and context and discusses the interrelatedness between these dimensions. It develops the structural layer, its constructs and the relationships between the categories of this particular layer through the lens of interoperability. Paper 01 contributes to the knowledge domain by offering a broader view of interoperability than the purely technological view that is preponderant in the current literature. It contributes to the thesis by positioning the structural layer and certain concepts associated to it, namely interoperability, within the artifact. It addresses the first two research questions (RQ 01 and RQ 02) and helps to formulate an answer to the prospective research question (RQ 04).

1.8.6.3 Paper 03 - Investigating model evolution in a collaborative BIM environment

Paper 03 presents the finding of a research project that investigated the evolution of a BIM for design and construction purposes. The objective of the paper was to develop measures to investigate the evolution of a BIM in a collaborative and multi-disciplinary project setting. Paper 03 contributes to the knowledge domain by developing and presenting four categories of measures of information evolution: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. These measures can serve as a benchmark to evaluate the efficiency of the modeling and ultimately the project delivery process. They also act as a proxy to evaluate the level of collaboration. The paper contributes to the thesis by developing part of the method of operationalization of the model. It also provides one of the strategies to quantitatively assess BIM-based collaboration through model evolution. It develops both the performative and outcomes layers of the model and develops the performance assessment cycle of the method of operationalization. It addresses the third research question (RQ 03) and helps to formulate an answer to the last prospective research question (RQ 04).

CHAPTER 2

INVESTIGATING BIM-BASED COLLABORATION TO SUPPORT ITS MANAGEMENT AND ASSESSMENT

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2.1 Abstract

The concept of collaboration in the AECO industry, while fundamental and ubiquitous, is coming of age as innovative approaches to project delivery and asset lifecycle management make their way into everyday practice. The focus of these innovative approaches is to foster and facilitate collaboration within temporary project organizations in order to improve their performance and the value generated by them. While collaboration, as an entity, is receiving significant attention in both the practical and theoretical domains, there still remains ambiguity as to what collaboration really means. Multiple definitions have been produced and factors seen to affect collaboration have been widely researched, however there is still a need to expand on the concept of collaboration from a systemic perspective and in a systematic way. There is also a need to focus at the individual level of analysis, as it is at this level that collaboration happens. Lastly, there is a need to transition from the traditional descriptive and explanatory approach to the study of collaboration to a more prescriptive one to accompany the transformation of practice that is currently underway in the AECO industry.

This article presents the findings of a research project that aimed to investigate the impact of BIM on collaboration in the AECO industry. The objectives of the research were to first characterize collaboration in a way that would allow its consistent operationalization across different project environments and subsequently build an artifact that would support this operationalization. The artifact was then evaluated to ensure its relevance and utility in assessing the impact of BIM on collaboration. A design science research approach, leveraging a systematic combining methodology, was adopted to build and evaluate the proposed artifact. The artifact is built through a combination of constructs developed to characterize collaboration that are articulated within a model and operationalized using a specific method of instantiation. The characterization of collaboration in the AECO industry as defined in this paper is conceptualized as the concerted or negotiated alignment of two frames of references (or more), i.e. the constructs and their relationships as laid out in the model, that are juxtaposed to achieve a common motive as structured by the building project. The scope of the artifact developed was subsequently expanded to inform and manage multi-disciplinary BIM-based collaboration and assess the outcomes and impact of this collaboration.

2.2 Introduction

The concept of Building Information Modeling (BIM) holds the notion of multi-disciplinary collaboration as its central tenet (National Institute of Building Science, 2007). Many sources posit that effective BIM-based collaboration shows distinct benefits leading to improved project performance and better value (eg. Eastman et al., 2011; Grilo and Jardim-Goncalves, 2010). However, the emergence of BIM and its increasing popularity come at a cost: relationships and interfaces within the Architecture, Engineering, Construction and Operations (AECO) industry are being disrupted. The transition to BIM-based project delivery implies a reconfiguration of collaborative environments, a redefinition of relationships and a transformation of industry practices (Forgues and Koskela, 2009; Merschbrock, 2012; Taylor and Levitt, 2007). In this regard, the emergence of BIM has been seen to modify the objects through which individuals interact and collaborate (Dossick and Neff, 2011; Harty, 2008; Taylor, 2007b; Whyte, 2011) and through which activity is mediated. (Miettinen et al., 2012).

While research is increasingly focusing on these novel relationships and interfaces, there remains a lot of work to be done to investigate BIM-based collaboration from a systematic and structured perspective. Namely, there is a need to bridge the lagging explanatory and descriptive nature of current investigations into BIM implementation and collaboration with more leading, prescriptive research endeavors to begin informing, managing and appropriately assessing BIM-based collaboration. While frameworks have been developed around BIM adoption and implementation at both the organizational and project levels, aspects of collaborative practices to support better performance and value are still largely underrepresented and thus require further investigation. Multiple definitions have been produced and factors seen to affect collaboration have been widely researched, however there is still a need to expand on the concept of collaboration from a systemic perspective and in a systematic way (Xue, Shen and Ren, 2010). There is also a need to focus at the individual level of analysis, as it is at this level that collaboration happens. Lastly, there is a need to transition from the traditional descriptive and explanatory approach to the study of collaboration to a more prescriptive one to accompany the transformation of practice that is currently underway in the AECO industry.

This article presents the findings of a research project which systematically investigated emerging BIM-based collaboration within multi-disciplinary temporary project organizations. The research project's objectives were to (1) characterize collaboration to allow its consistent investigation and evaluation across scales and from differing perspectives, (2) envision a way to better inform, manage and assess BIM-based collaboration based on this characterization and (3) assess the impact of BIM on collaboration and project outcomes. The research project spanned a three year period and involved multiple research sites. It was rooted in the design-sciences and assumed a critical realist perspective to set the epistemic and ontological frame. The research process was iterative, based on a systematic combining process, to concurrently build and evaluate the artifact. The outcomes of the research project are the artifact, a framework which supports a scalable management and assessment of BIM-based collaboration for the AECO industry.

2.3 Building Information Modeling and collaboration

Collaboration has been defined and conceptualized as many things. For the purposes of this paper we adopt Hartono and Holsapple (2004) definition of collaboration (p.20): "Collaboration is an interactive, constructive, and knowledge-based process, involving multiple autonomous and voluntary participants employing complementary skills and assets, with a collective objective of achieving an outcome beyond what the participants capacity and willingness would allow them to individually accomplish" Furthermore, collaboration is episodic, requires an internal governance structure and is influenced by its context (Hartono and Holsapple, 2004, P.20). This definition of collaboration speaks to larger overarching principles of collaboration. These can be broken down into four distinct yet interconnected statements about collaboration, which resonate with other past work in this field:

1) Collaboration is a socially constructed and purposeful phenomenon (Nicolini, Mengis and Swan, 2012) which involves the interaction between multiple actors from different social, mental and object worlds (Peters et al., 2013);
2) Collaboration is a process involving a specific goal (a motive), a beginning and an end (Thomson and Perry, 2006);
3) Collaboration is structured and set within a given environment (Gray, 1985);
4) Collaboration is supported through shared artifacts (Boujut and Blanco, 2003).

Distilled, these statements highlight four foundational elements of collaboration: structure, process, agents and artifacts. These four elements interact: they are interrelated and mutually adjusting. They are also subject to external pressures. Collaboration is a basic premise of BIM (NIBS, 2007). BIM is seen as a set of interacting tools, technologies and processes (Eastman et al. 2011) guided by principles, norms and rules (policies) (Succar, 2009). BIM is also a systemic, disruptive and radical innovation (Lehtinen, 2011, Poirier et al. 2015). To be effective, BIM must be adopted across organizational and knowledge boundaries within a project team (Harty, 2008). The implementation process requires 'mutual adjustment' between project actors (Taylor, 2007 – speaking of firms) and involves negotiations chiefly around expectations (how will the model be used; who will do what in the model - CIC, 2009), interests (who benefits from the model – Schweber and Harty, 2010) and capabilities (to what extent can these expectations be met - Succar et al. 2010, 2013). The passage to BIM marks a profound shift in the very foundations of collaboration:

1) BIM transforms the relationships between the projects actors, their objects of practice (Neff et al. 2010), and their 'object worlds' (Berente et al. 2010);
2) BIM is ultimately transforming the relationships between project actors and project information (Crotty, 2011);
3) BIM passively structures and actively shapes the collaborative environment (Tyggestad et al. 2010);
4) BIM seeks transparency and openness (achieved incrementally or no) (Taylor and Bernstein, 2008);
5) BIM is transforming how technology is being used within the project environment (Fischer and Kunz, 2004);
6) BIM is resetting the many boundaries of Temporary Project Organizations (TPO), including practical, cognitive, functional, temporal and geographical (Allin et al. 2013, Dossick and Neff, 2011);
7) BIM is involving new forms of contractual mechanisms to structure and delineate the collaborative environment (Illozor and Kelly, 2012, Kuiper and Holzer, 2013);
8) BIM is transforming the roles and responsibilities within the TPO (Ku et al. 2008).

Various frameworks have been developed to investigate and inform the BIM knowledge domain to better understand the implications of this shift or to provide solutions (Cerovsek, 2012, Kassem et al. 2014). Succar's (2009, Succar et al. 2010, 2013) body of work involving BIM capability, maturity, and competency as well as his framework aimed at developing the BIM knowledge domain is considerable. He reinterprets and frames concepts such as maturity, stages, lenses and fields found in other domains, adapts and frames them to the BIM domain. His work has been often citied (Succar, 2013) and the ontological foundation he has developed is helping academia and the industry (through his active involvement) move towards a comprehensive basis for BIM. However, the focus is almost exclusively on BIM such that the attention given to collaboration is secondary; for example, collaboration is only one of four possible states in this body of work. That being said, Succar et al. (2010, 2013) recognize the importance of having the right competencies to properly require, implement and deliver BIM to support collaboration and work towards providing a way to rigorously evaluate these competencies.

Taking a systems thinking approach, Cervosek (2011, 2012) develops the 'BIM cube', "[…] a conceptual framework to provide guidelines for research in BIM project communication" across a building's lifecycle, a building model lifecycle and a BIM technology's lifecycle (p.421). The framework is oriented towards intervening and researching specific areas to further develop BIM tools and technologies by taking into account complementary research methodologies, evolving practices and models and the semiotics of communication. Specifically with regards to collaboration, Cerovosek (2011, 2012) provides a specific standpoints for the evaluation of BIM-based collaboration (amongst others).

Singh et al. 2011 develop a technically oriented framework to support BIM-based collaboration through a BIM-server. While the framework is techno-centric the authors recognize the importance of the organizational, procedural and human aspects of BIM and recommend to focus on these aspects prior to the implementation of a technical solution. Jung and Joo (2011) posit that 'practical BIM implementation effectively incorporates BIM technologies in terms of property, relation, standards, and utilization across different construction business functions throughout project, organization, and industry perspectives'. The authors present a framework that is based in the literature and is aimed at facilitating 'practical implementation' taking into account technological factors and construction business functions at a given level of analysis. The framework does not discuss collaboration.

Attempts to operationalize some of these frameworks have been developed, such as Kassem et al. (2014) who build on Succar's (2009) framework to propose a protocol for BIM-based collaboration during the design stage of a building project. Succar et al. (2013) operationalizes parts of his own framework through his BIM maturity model and competency assessment tool. With these works in mind, there still remains a gap between the development of these theoretical frameworks and the operationalization of the concepts put forth within them. They are also BIM centric in that it is unknown how they will age and if they will remain relevant as the technology supporting BIM changes. Lastly, collaboration plays second chair in many of these frameworks as well as in many other works. There is a need to re-center the focus on collaboration, it foundational elements: structure, process, agency and artifacts, to see how BIM can support and enable it, not the other way around.

2.4 Research design

The principal aim of the research project was to investigate the impact of BIM on collaboration in the AECO industry. The investigation was motivated from a theoretical point of view by the scarcity of systemic approaches to collaboration and analysis at the level of the individual in the literature. Practical motivation came from our industrial partners' desire to understand the impact of innovative project delivery approaches, BIM in particular, on project outcomes. This led to the following main research questions: What is the impact of innovative approaches to project delivery, namely BIM, on collaboration in the AECO industry? In order to formulate a complete answer to this question, we posed the following research questions: How can collaboration be characterized in the AECO industry? And how can we assess this impact on collaboration and on project outcomes? Lastly, we pose a prospective research question, which can lay out a way forward to further investigate this particular domain: In light of this characterization and this assessment, how can we inform and manage innovative approaches to project delivery to enable collaboration?

Figure 2.1 illustrate the overall research design of this project. Given the practical and prescriptive orientation of the research questions, we adopted a design science research (DSR) approach as described by Hevner et al. (2004), Järvinen (2004), March and Smith (1995) and Van Aken (2005). The principal goal of DSR is to create useful artifacts that serve human purposes (March and Smith, 1995). To contrast the primarily pragmatic perspective of DSR, we adopted a critical realist perspective to frame the research project's epistemic and ontological foundation. Critical realists distinguishes how we, as individuals, view the world, and how this world exists. Indeed, critical realism assumes that the world and our knowledge of it exist independently (Sayer, 1992). This knowledge of the world is socially constructed: it is in constant flux (Bhaskar, 2009; 2013). It supports both ontological realism and epistemological constructivism (Maxwell, 2012). The fundamental aim of the critical realist perspective is to uncover truth: to explain the cause of an event, its generative mechanism (Easton, 2010, p.121). This search for truth is central to the search for utility in design science research: the lens through which this truth is uncovered, the knowledge generated, can serve to support and ensure the usefulness of the artefact. In other words, understanding the generative mechanisms of specific events addressed through the research project will help build better artefacts.

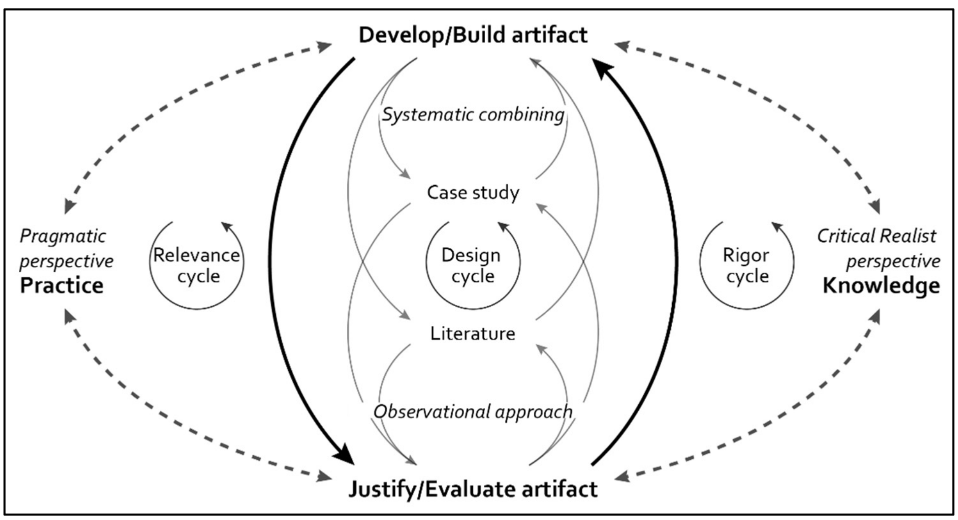

Figure 2.1 Research design
Adapted from Hevner et al. (2004) and Hevner and Chatterjee (2010)

Design science research projects are characterized by an iterative develop/build and justify/evaluate cycle. To support these iterative cycles, we employed a systematic combining process (Dubois and Gadde, 2002b; 2014). According to Dubois and Gadde (2002b): "Systematic combining is a process where theoretical framework, empirical fieldwork, and case analysis evolve simultaneously, and it is particularly useful for development of new theories." (Dubois and Gadde, 2002b, p.554) The authors describe systematic combining "[…] as a nonlinear, path-dependent process of combining efforts with the ultimate objective of matching theory and reality." (Dubois and Gadde, 2002b, p.556) The build-evaluate cycles developed in DSR are supported by the systematic combining process through complementarity of the relevance and rigor cycles of DSR (Hevner et al., 2004) and the matching and directing of the systematic combining process (Dubois and Gadde, 2002b).

2.4.1 Data collection

Primary data was sourced from two sites on which mixed-methods data collection were performed. Other data sources included two workshops and two large intervention projects. Data collection was continuous throughout the research project. Both main research sites respected one of DSR's main principles that the research project must address a problem in practice (Hevner et al., 2004). Both main research sites were integrated upon request of an industrial partner stating a particular need. Both industrial partners, the owner mandating the project for site 01 and the president and CEO of the organization for site 02, stated concordant needs which is why they were chosen for this project. Throughout the research the focus varied between the permanent organization (organizational level) and the TPO (project level) as both main sites involved case studies at different levels of analysis. However, the principle units of analysis of this research project was at the individual's level, namely the individual stakeholders evolving within their respective collaborative environments.

Table 2.1 Description of two main research sites

	Site 01	Site 02
Case	Major new institutional construction project	Small specialty mechanical contracting enterprise
Perspective	Project	Organization
Type	Single case study	Multi-case study (8 projects)
Location	Edmonton (AB), Canada	Vancouver (BC), Canada
Duration	February 2013 to Present	April 2012 to April 2015
Delivery mode	Design-Build	Various (Design-Bid-Build, Construction Management, Design Build, etc.)
Budget	$ 260 M	$ 29.5 M (total project value)
Unit of analysis	Individual	Individual
Description	Studied the project team members directly involved in the delivery of the project. Studied all disciplines, major specialty contractors and owner	Studied the changes brought on by the adoption of BIM within the organization throughout 6 different projects where BIM was implemented
Qualitative data sources	• 98 semi-structured interviews with 52 different individuals from 10 different stakeholder organizations in the TPO • Certain key individuals were interviewed up to five times at six month intervals • Observed meetings and analyzed minutes for - steering committee (governance) - design review and coordination, - BIM coordination - trade coordination and scheduling.	• 11 semi-structured interviews with 8 different individuals from the organization and 1 client representative • Observed BIM steering committee meetings over a two year period • Observed BIM coordination meetings on several projects studied • In-depth field observation on one project

	Site 01	Site 02
Quantitative data sources	• 3 Surveys at 9 month intervals • Project data: - schedules - timesheets - project documentation (specifications and drawings) - requests for information (RFI), - change orders (CO), - site instructions (SI) - Analysis of 53 bi-weekly iterations of the models produced by the design team (architecture, structural, mechanical and electrical, for a total of 212 models)	• Organizational data: - BIM implementation plan - BIM standards • Project data: - budgets - schedules - timesheets - project documentation (specifications, drawings and models) - spool drawings - requests for information (RFI), - change orders (CO), - site instructions (SI)

2.5 Building and evaluating the artifact

The process to build an artifact in DSR iterates between its development and its evaluation; both are inextricably tied. In the following section we discuss the development of the artifact, its evolution and its local evaluation based on the two research sites described in section 2.4.1. The principal outcome of DSR is an artifact that serves human purpose (Hevner et al., 2004). As mentioned, we were involved in both research sites at the request of our industrial partners to investigate the impact of BIM on project outcomes. To guide this investigation, an initial framework was developed (Figure 2.2). This preliminary conceptual framework developed different dimensions which define the collaborative project delivery system: the technological dimension, the organizational dimension and the procedural dimension (adapted from Staub-French and Khanzode (2007)) as well as the contextual dimension. This conceptual framework resonates with others, such as Leavitt's diamond (Leavitt, 1965), the People-Process-Technology framework or the Technology-Organization-Environment framework (Tornatzky and Fleischer, 1990) based in IS research, the Model-Team-Process approach (Staub-French, Forgues and Iordanova, 2011) developed by DPR construction, the Product-Organization-

Process (P-O-P) model (Garcia et al., 2004) developed at Stanford University's Center for Integrated Facility Engineering's (CIFE) or the Technology-Process-Policy (T-P-P) fields developed by Succar (2009).

The main source of data used to build the artifact came from the semi-structured interviews conducted throughout the research project on both sites. All interviews were transcribed and coded in Nvivo (QSR International, 2013). We started by coding to the framework, but soon found that it became too constraining and narrow. During this first cycle of coding we rapidly expanded the scope of analysis and adopted a more open approach to the coding process (Holton, 2007). Initial patterns emerged during the analysis of the first two rounds of interviews conducted on site 01 and the first interviews conducted on site 02, which helped to inform the coding strategy moving forward. The strategy revolved around understanding how individuals framed their 'internal course of collaborative action' with regards, but not limited, to BIM-based collaboration. This meant adopting the individual as the unit of analysis and coding to both the response to the interviewers prompt (the performed action) and the action implied by the interviewee, dealing in a sense with Giddens' double hermeneutic (Giddens, 1984), i.e. the interpretation of the interpretation. We also had to differentiate between descriptions of past or present actions and forecasting of future actions. This first layer of analysis served to orient the specific actions that were being carried out by the individuals in the collaborative environment. We then wanted to understand the outcome or consequence of that action, whether it was positive, negative or neutral. This was done to establish a qualitative and interpretative causal link between actions and outcomes in the BIM-based collaborative environment.

To further define this 'internal course of collaborative action, we then investigated what was structuring or configuring these actions. To do so, we relied on the initial framework illustrated in Figure 2.2. This added another layer to our analysis. At this point we were gaining an understanding for individual perceptions of what was happening and how it was supported or structured. The first three layers of analysis, outcomes, actions and structures were coded using

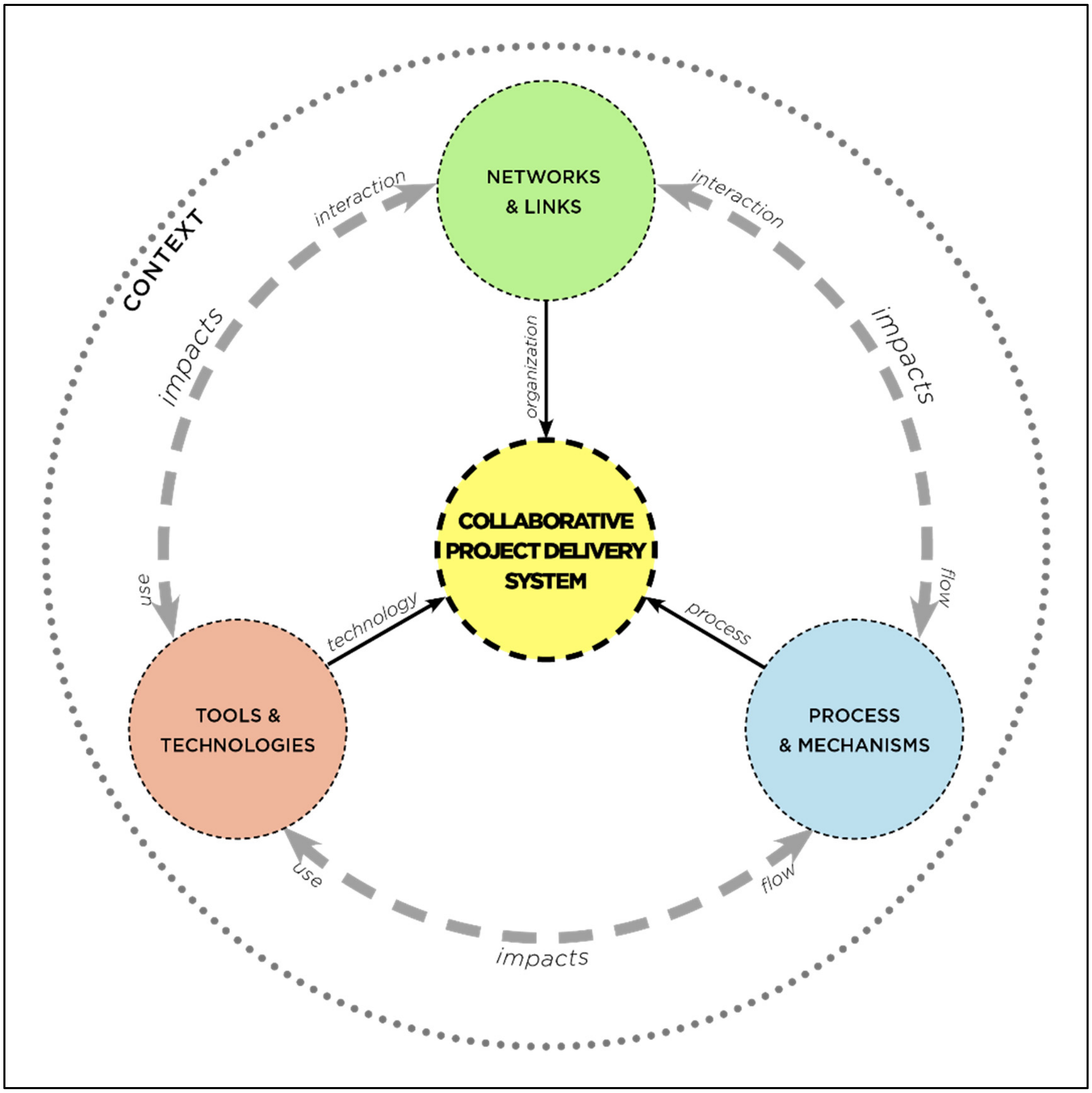

Figure 2.2 Initial conceptual framework

both process codes and descriptive codes as defined by Miles, Huberman and Saldaña (2013). That being said, we were still lacking an answer to why it was happening and why it was happening in a particular way, i.e. what prompted the individual to act in the way that he did, what guided it or constrained it? For us, this was central to uncovering a complete 'internal course of collaborative action' that could help to explain how and why people collaborate. Therefore we added a fourth layer of analysis to interpret why the individual acted in the way that was discussed. We ended up with a layered coding strategy which ultimately resembled causation coding as described by Miles, Huberman and Saldaña (2013) (Figure 2.3).

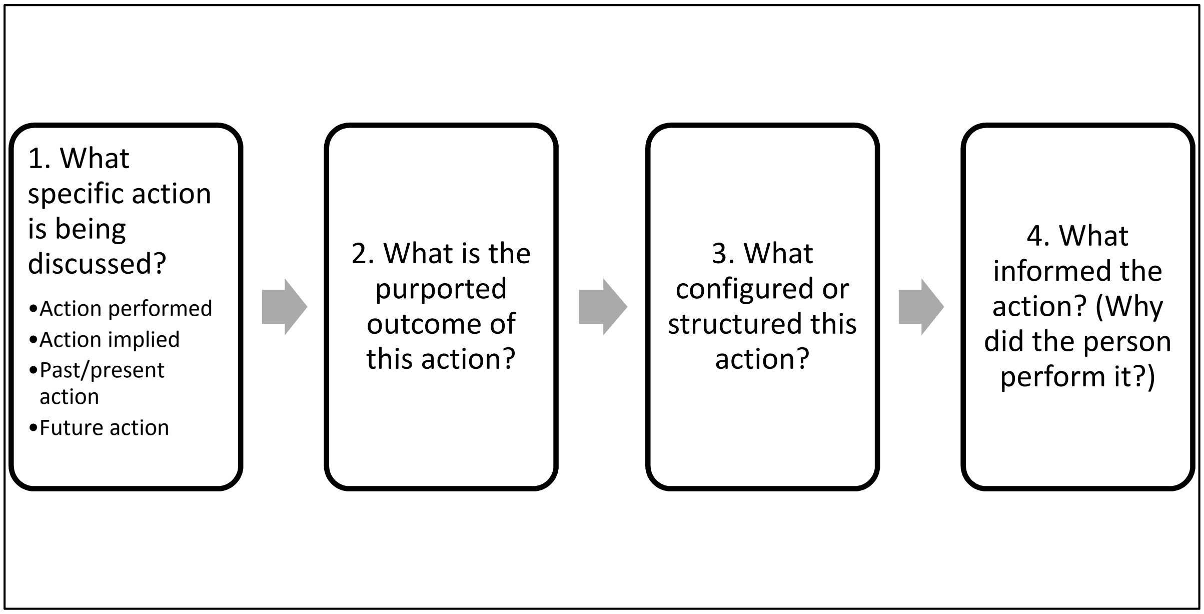

Figure 2.3 Coding strategy

To illustrate how the coding strategy was implemented we present a first vignette which relates the owner's decision to not require BIM on the project of site 01. Vignette 1 (Table 2.2) provides a rough frame to define a 'course of collaborative action' across the layers of the framework and defines a rough causal structure of the owner's decision to implement BIM on the project. We can see that the main 'course of collaborative action' was informed by a general consensus, or alignment, on the part of the owner's management team as to the perception of the industry context lacking sufficient capabilities to deliver a BIM-based project. Ultimately, this resulted in the BIM requirements being limited to the proposal stage:

> When we started thinking about implementing BIM on the project, some of us were keen on doing it. [We thought] "Let's just make it a review requirement to hand over a BIM model". I don't think at that point anyone thought it would go to FM at all. But what it came down to, is the bridging architect, who developed the RFP, said that he wasn't sure that the industry was there yet to make it a requirement for the job. We then reduced it down to them having to provide the model at the proposal stage to validate areas. (Project Coordinator, Owner (1st rd.))

Table 2.2 Data analysis example –
Owner's perspective on BIM implementation in the project

Question	**Finding**
What specific action is being discussed? Action performed Action implied	 Discussing how the decision to implement BIM was taken Defining the scope of BIM requirements on the project
What is the purported outcome of this action?	BIM requirements limited to the proposal stage
What configured the action perceived and implied?	A perception of the industry context with regards to BIM capabilities
What informed the action? (Why did the individual perform the action?)	A consensus around a perceived lack of BIM capabilities within the industry

This type of analysis was performed on the qualitative data for the first three rounds of interviews on site 01 and the first round on site 02. As we went further into the analysis, clear patterns emerged within the layers in which specific and unique categories were uncovered. We also extended the analysis beyond BIM to broaden the scope of investigation and attempt to capture the multifarious and complex nature. As these categories were uncovered, the constructs, which would define the language of the artifact, were developed and refined. Linguistic cues were defined in support of the targeted questions and served to inform and standardize the analysis process, and hence the construct building process. What emerged from this exercise was a characterization of 'courses of collaborative action' articulate within a frame of reference and developed across four layers as defined by the questions outlined in Figure 2.3. This characterization is illustrated in Figure 2.4.

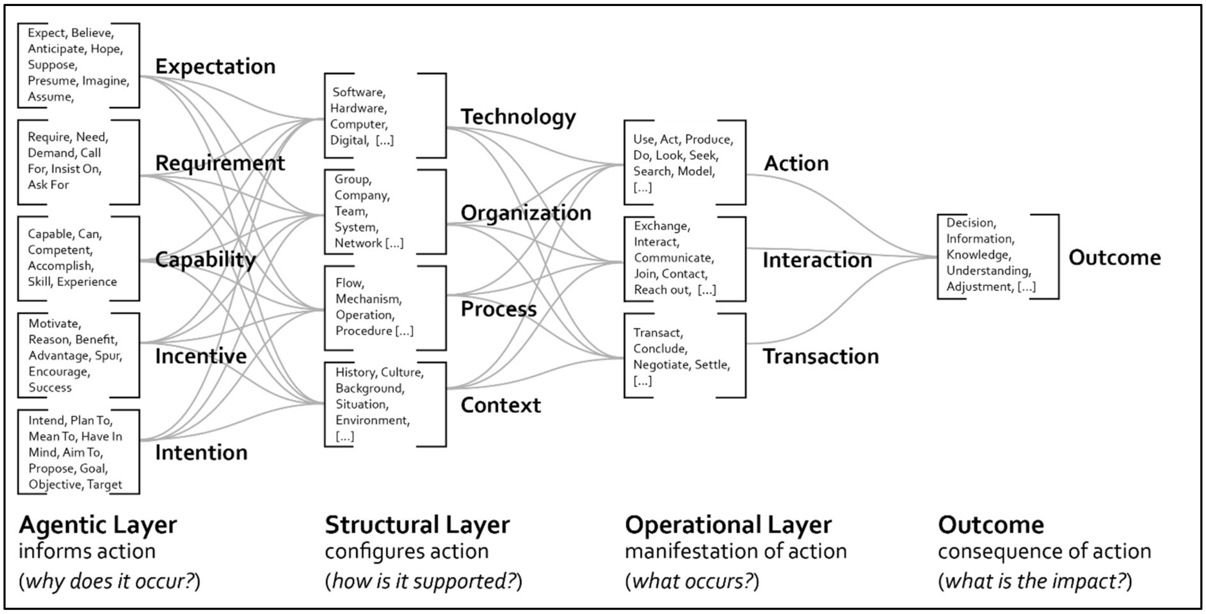

Figure 2.4 Characterization of collaboration: constructs and relationships

The constructs and their relationships were articulated within a model. The model evolved from the initial framework illustrated in Figure 2.4 through the iterative build/evaluate process and went through a total of four iterations. The model, in its current state, is illustrated in Figure 2.5. The movement across the layers of the model, moving outward from center and back, illustrate the 'course of collaborative action'; its represents a frame of reference for collaboration at the individual level. The circular form intimates a non-linear relationship within and between layers, while the spaces between the layers act as buffers.

The outer layer represents the *outcome*, i.e. the result of the action that was performed by an agent and its consequence (Feather and Newton, 1982). The *outcome* represents many different things, but typically will have a positive (+), negative (-) and/or neutral (=) consequence in the collaborative episode. *Outcomes* are tangible elements inhabiting the collective space within the collaborative environment. The value ascribed to these outcomes will determine their consequence (Heckhausen, 1977) The perception of project outcomes and their consequences are products of individual TPO member's expectation of success, the amount of effort exerted, and the expectation of the outcome and its consequence (Liu and Walker, 1998)

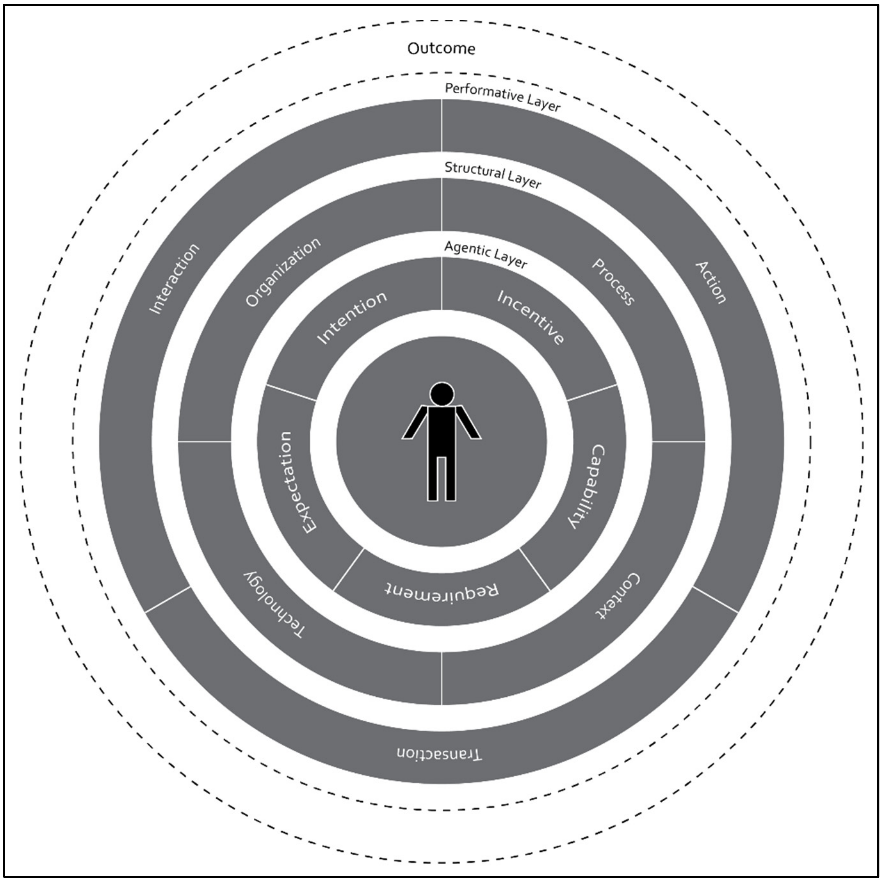

Figure 2.5 Characterization of collaboration: the model

The *Performative* layer is the manifestation of action. In our analysis, this corresponded to understanding *what* action was carried out. As mentioned, we categorized two levels of action in trying to account for the double hermeneutic (Giddens, 1984): the first level was the action performed by the interviewee in responding to the question whereas the second level was the action implied in his response. We also differentiated past/present from future action. The types of action, interaction or transaction were differentiated to separate individual action from collective action. In this model action represents "[…] a continuous flow of conduct […]"(Giddens, 1984, p.3), whereas interaction represents "a reciprocal action or influence" (Oxford English Dictionary, 2013) and transaction represents "an exchange or interaction between people" (Oxford English Dictionary, 2013). We are careful to differentiate transaction and interaction whereby the outcome of a transaction results in the exchange of a tangible element which has intrinsic or explicit value.

The *Structural layer* has been developed in many fields including the AECO domain. The categories of the structural layer are seen to configure and structure agency and influence *how* action occurs. These categories represent the organizational, technological, procedural and contextual dimensions which define the collaborative project delivery system. In the context of BIM-based collaboration, our analysis reaffirms the relevance of this particular lens, applied to the study of multi-disciplinary collaboration in the AECO industry. Its articulation within this construct, however, does represent a departure from the current literature in that it is part of a larger system which structures agency, rather than four parts forming a whole. In its interaction with both the agentic and performative layers, the extent to which this particular layer influences the overall system can be further explored.

The inner layer, termed the *Agentic layer*, encompasses the categories that embody *the reason for the agent to perform an action* and *the agent's reason to perform that action* (Miller, 2006). Exploring the reasons behind individual's actions is highly complex and has been addressed by many people across many domains. The boundaries of the enquiry in this case are limited to the building project and the AECO domain. Within this context, our analysis led us to trace elements that informed or prompted the 'course of collaborative action' back to one or more of the following categories: expectations, requirements, intentions, incentives and/or capabilities. These categories were seen to inform *why* action occurred in a certain way. There exist other actor level constructs that have been developed in the literature, such as culture, trust, identity and empowerment (Chiocchio et al., 2011; Emmitt, 2010; Phua, 2012). They are not represented in this construct because we found that these element were subsets of the categories presented here. For example, trust can be equated to the expectation that another individual will act, or intends to act, in a manner that does not negatively impact oneself, the project or the organization (Chow, Cheung and Chan, 2012; Smyth, 2008; Wong et al., 2008).

An *Expectation* (or expectancy) are "the belief that something will happen or be the case in the future" (Oxford English Dictionary, 2013). They concern both an expected event and the occurance that it will take place(Heckhausen, 1977). Expectations are articulated around outcomes and their consequences, which as described above, are determined by the value ascribed to these outcomes. These notions touch on the many theories of motivation, cognition, instrumentality, valence etc which have been developed over the past half-century in the works of Bandura (2001) Feather (1992) Locke and Latham (1994) Vroom (1964) amongst many many others. Central to the expectation construct as defined within this artifact and in the context of the AECO industry is the fact that expectations are largely implicit, they may have been expressed or formulated in one form or another, but they are unenforcible per say. To a certain extent they constitute informal obligations. They also constitute an informal or intangible source of motivation (Vroom, 1964). Expectations will be entrenched in disciplinary, organizational and project domains.

A *Requirement* constitutes “a condition which must be complied with” (Oxford English Dictionary, 2013). Requirements are, in essence, formalized, enforceable and measurable expectations. They constitute formal obligations and are hierarchical, i.e. different requirements will carry different weights. Various project stakeholders formulate requirements according to internal and external project constraints such as building codes, project programs and deontological codes. In the context of BIM-based collaboration, contractual BIM requirements set out by the owner will dictate how the model is to be developed and handed-off at the end of the project for his future use. In this regard, the lack of clear requirements is often cited as one of the top barriers to BIM (Won et al., 2013).

Intention is “volition which one is minded to carry out” (Oxford English Dictionary, 2013). For Bandura, “an intention is a representation of a future course of action to be performed. It is not simply an expectation or prediction of future actions but a proactive commitment to bringing them about.” (Bandura, 2001, p.6). Intentions imply commitment to the attainment of goals through the development of plans (Locke and Latham, 1994). As developed in the artifact, intentions exist as both intentions *to* act and intentions *that* action happens, as discussed by Grosz and Kraus (1996), and indicating a level of influence an individual has on its environment. These intentions are directed towards the building project and are aimed towards fulfilling this overarching goal and its constituent parts (sub-goals). The notion of intentions here is narrower than that of given to the far-reaching concept which equates agency and intention (Bandura, 2001). In this case, intention is clearly stated rather than implied.

A *capability* is an agent's "power or ability to do something" (Oxford English Dictionary, 2013). We differentiate between an individual's objectively measured capability to produce a specific outcome and the perception of his own capability to act (self-efficacy). Both approaches are important in that they will play a role in informing courses of action, although self-efficacy has been seen to play a more important role in this sense (Liu and Walker, 1998; Locke and Latham, 1994). From an objective point of view, the notion of capability, including concepts such as capacity, ability, competency or maturity, has been explored in past research on information technologies, information systems and BIM (Succar, Sher and Williams, 2013).

Incentives "motivate or encourage someone to do something" (Oxford English Dictionary, 2013). Incentives come under various forms, namely financial incentives, personal gains (i.e. reputational) or direct benefits related to the use of tools or processes and other types of gains. They can also have a negative impact, i.e. disincentive, acting as barriers constraining the 'course of collaborative action'. Similarly to requirements, incentives, as developed in the artifact, are formal, explicit and measurable. They help to anchor commitment and intentions (Locke and Latham, 2002).

The 'course of collaborative action' involves essentially the internalization and externalization of individual belief, thought or intention through movement across the layers of the model. Externalization (or materialization) represents the structuring of this belief, thought or intention into action when moving from inner to outer layer. Internalization of action (or learning) represents action which is structured into thought or belief when moving back from the outer layer to the inner layer (Figure 2.6). This 'course of collaborative action', a learning and negotiation process, become central to collaboration in that it produces outcomes, necessary to achieve the goals and in turn those outcomes modify agency as they are structured and reinterpreted. Multiple 'courses of collaborative action' can occur simultaneously to produce a single outcome. This movement, back and forth, from inner layer to outer layer and back to inner layer, is embodied and mediated through the artefacts and objects which contain information and knowledge (Boujut and Blanco, 2003; Nicolini, Mengis and Swan, 2012; Styhre and Gluch, 2010; Trompette and Vinck, 2009; Vinck and Jeantet, 1995; Zager, 2002). In the case of BIM-based collaboration, the BIM and other project documents carry this information and knowledge across the layer and spans the collective space. The degree of alignment within and between categories will determine the ease of this flow. The constructs, their relationships and the model forms 2/3 of the proposed artifact and answers the second research question: How can collaboration be characterized in the AECO industry? We offer this answer: Collaboration in the AECO industry can be characterized or defined as the concerted or negotiated alignment of two frames of references (or more), i.e. the constructs and their relationships (Figure 2.4) as articulated in the model (Figure 2.5), that are juxtaposed to achieve a common motive.

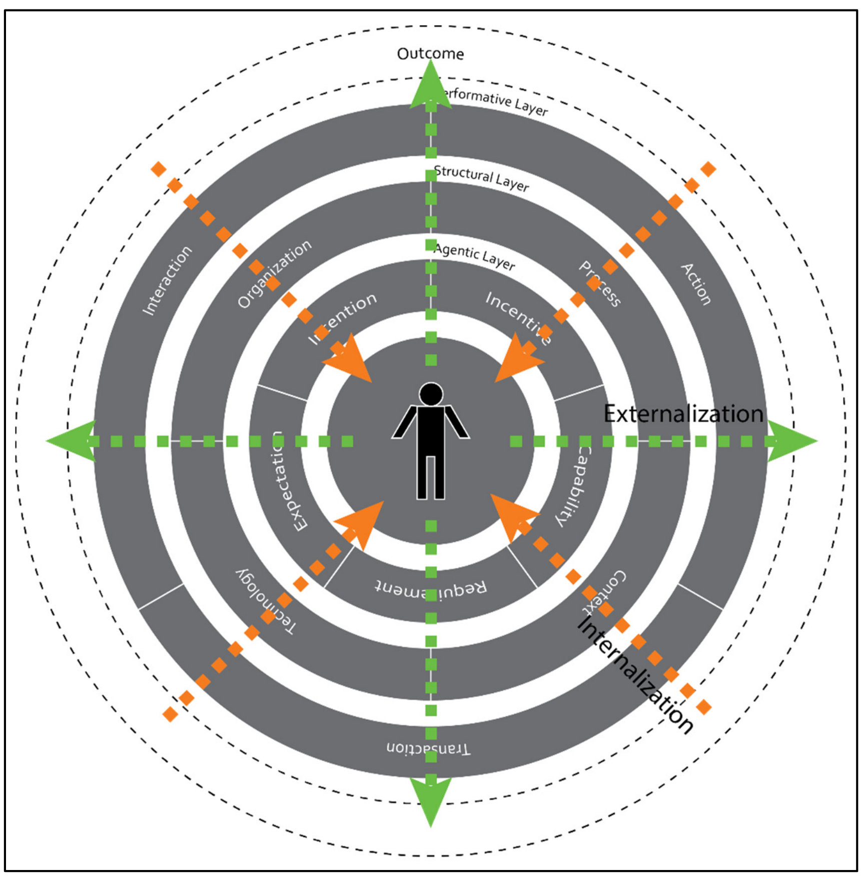

Figure 2.6 Internalization/Externalization process:
Collaborative courses of action

In order to validate the frame of reference we visualized the 'courses of collaborative action', namely the relative weight of each category discussed during the interview and the interactions between these categories. Figure 2.7 illustrates this course for an architectural technician. While we lose sight of individual mechanisms in this view, it allows us to discern overall trends in an individual's 'course of collaborative action'. In this particular case, a lot of focus was put on the interactions between requirements, expectations and processes, the resulting actions and their consequences from the technician's perspective. When scaled to the project team level, we can visualize this course in much the same way for a group of people. Figure 2.8 illustrates the alluvial diagram for all architectural respondents.

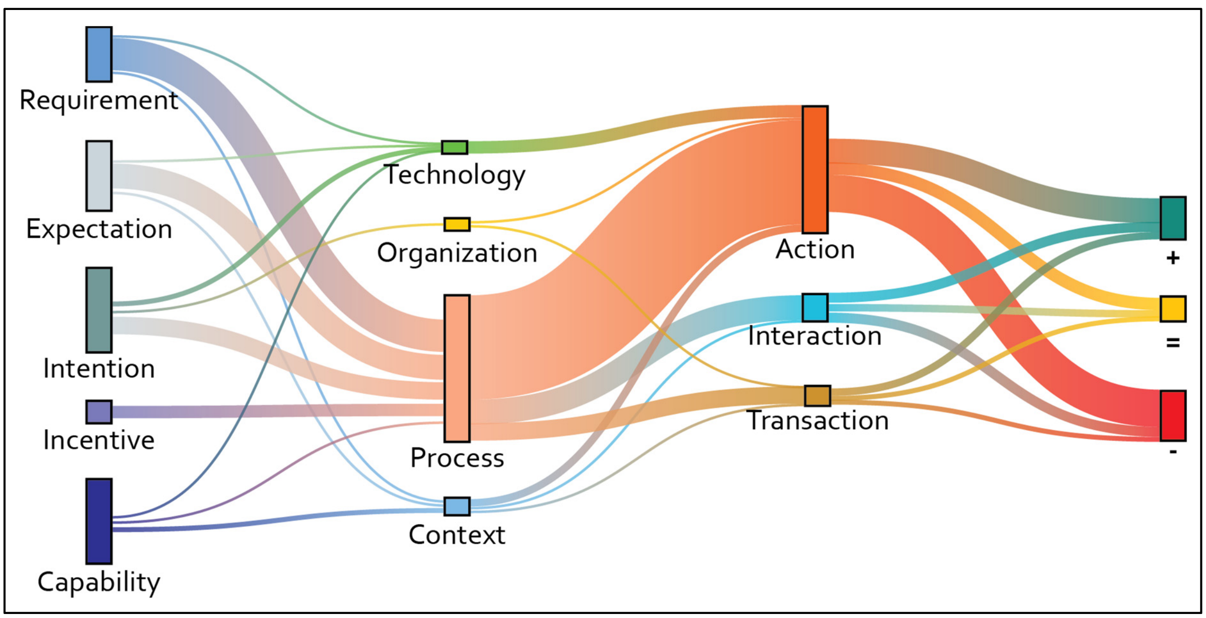

Figure 2.7 Alluvial flow diagram-coding-architectural technician round 01

The frame of reference having been defined and validated, we developed a (method) to operationalize it. This method supports the uncovering of alignments and/or misalignments between actors during the collaboration episode. It leverages the qualitative and quantitative data that was collected at the different sites. The operationalization protocol is illustrated in Figure 2.9. Together, the constructs, the model and the method constitute the artifact. As discussed earlier BIM-based collaboration can be conceptualized as being founded upon four

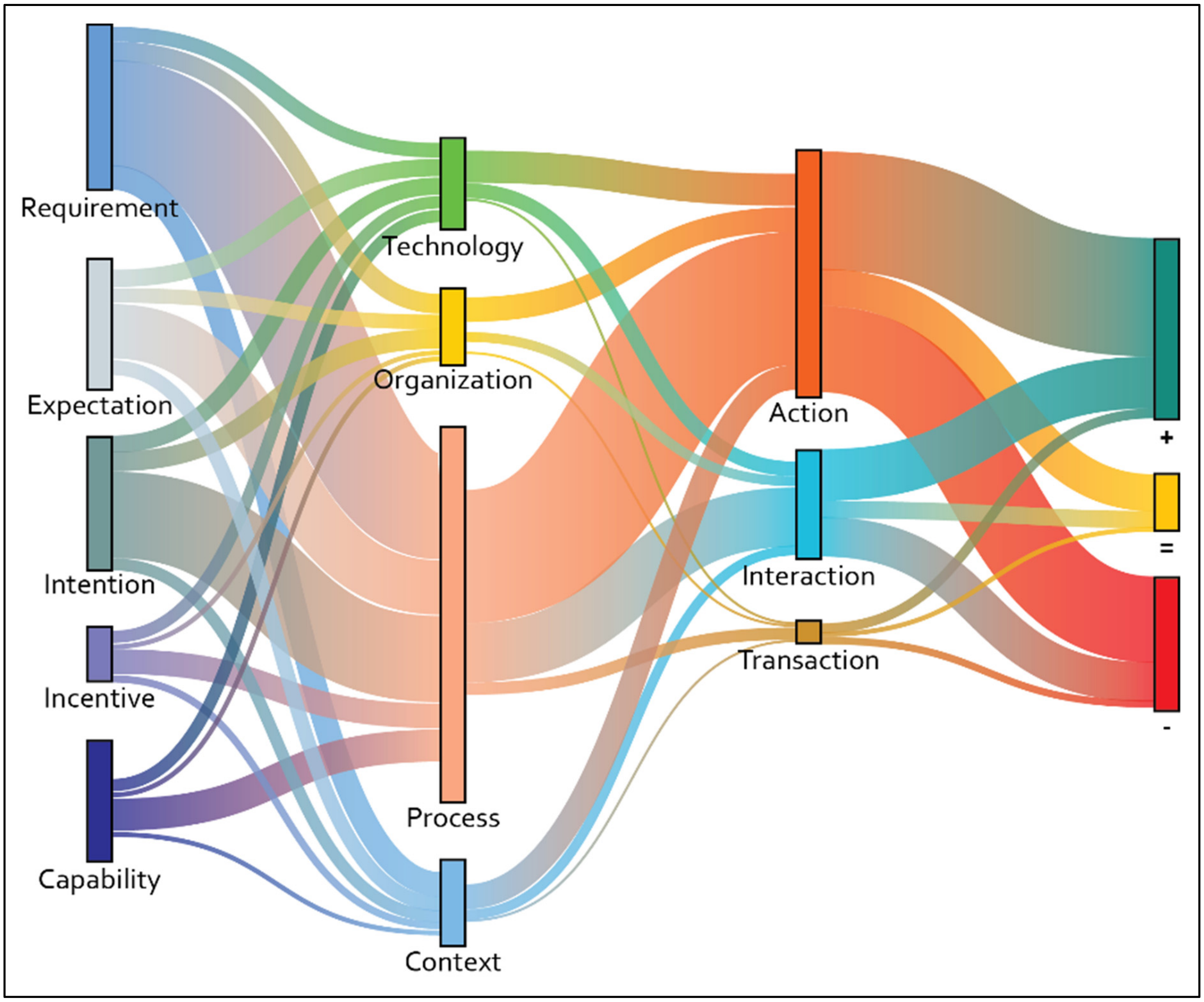

Figure 2.8 Alluvial flow diagram - coding all architectural project team members round 01

elements: structure, actors, processes and objects. The framework reinterprets these foundational elements and reaffirms the interactions amongst them. The premise of the framework is that effective collaboration occurs through the negotiated and concerted alignments of the various frames of reference populating a TPO. A tighter alignment will result in better collaboration whereas misalignments will result in breakdowns in collaboration or missed opportunities for the TPO. The concept of alignments have been developed in the past by authors such as Leavitt (1965)and Henderson and Venkatraman (1993) to illustrate correspondence within relationships. It is a concept that also resonates with the concept of mutual adjustment (Taylor, 2007). The types of alignment that were uncovered during analysis are presented in Table 2.3.

The method of operationalization is supported by mixed-methods of data collection. Both qualitative and quantitative data are used in the investigation and assessment of collaboration which is divided into three parts: the initial benchmarking of the context of collaboration, the ongoing assessment over the course of the collaborative episode and the exit evaluation. Central to this operationalization, and as evoked in the vignettes, is the notion of alignments within and between categories.

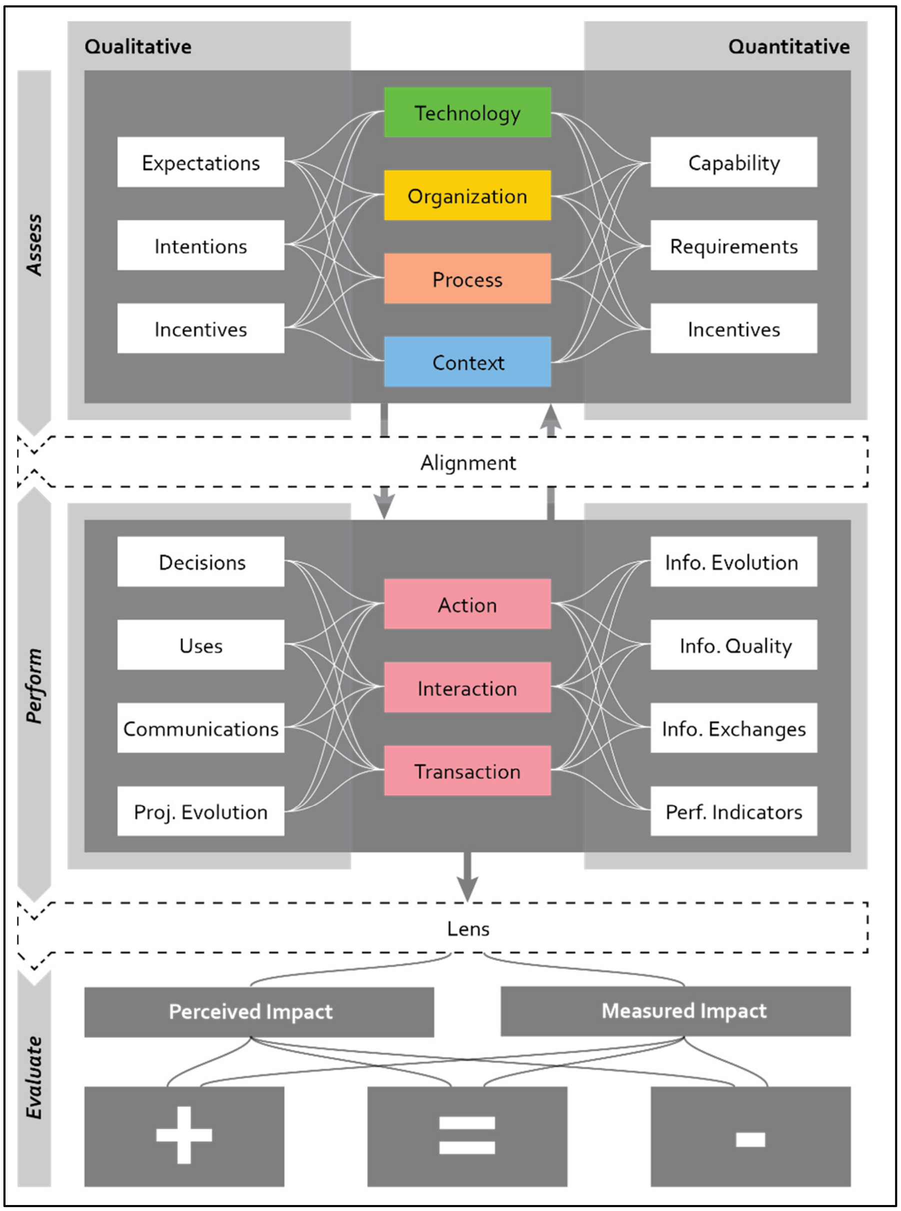

Figure 2.9 Method of operationalization

Table 2.3 Alignments types

Degree	Scale	Scope	Duration
Within Category	Individual	Intra-Disciplinary	Temporary
Between Category – within layer	Project Team	Inter-Disciplinary	Project Phase
Between Category – across layer	Organization	Single-System	Project Lifecycle
	Industry	Multi-System	Permanent

This process of building the artifact was closely accompanied by its local evaluation on each research site. On site 01, we performed five rounds of interviews and analysis in total. By the third round, the artifact was fully developed. We used the data from the next two rounds of interviews to evaluate the artifact and apply it for analysis purposes. We did take care to not modify the interview script so as to not introduce bias in the data collection and thus end up with a self-fulfilling prophecy (Merton, 1948). This was ensured by having two interviewers present, including one who was not performing data analysis and could thus remain objective. As a way to evaluate the artifact, we presented it to the industry partner on site 01 and received some feedback as to its utility. We also prepared a series of reports back to the project teams on both sites as a way to validate the internal validity/credibility/authenticity of the process and findings (Miles, Huberman and Saldaña, 2013).

2.6 Assessing the impact of BIM on collaboration

We instantiated the artifact to support our assessment of the impact of BIM on collaboration. The assessment portion of the artifact is contained within the upper portion of the method of operationalization. We provide two vignettes to illustrate this. The first vignette presents how the decision to implement BIM was taken. Vignette 1a (Figure 2.10) presents the owners perspective. It illustrates the owner's decision to limit the project's BIM requirements to the proposal stage and not require BIM deliverables over the project's lifecycle from the project coordinator's perspective:

> When we started thinking about implementing BIM on the project, some of us were keen on doing it. [We thought] let's just make it a review requirement to hand over a BIM model. I don't think at that point anyone thought it would go to FM at all. But what it came down to, is the bridging architect, who developed the RFP, said that he wasn't sure that the industry was there yet to make it a requirement for the job. We then reduced it down to them having to provide the model at the proposal stage to validate areas. (Project Coordinator, Owner (1st rd))

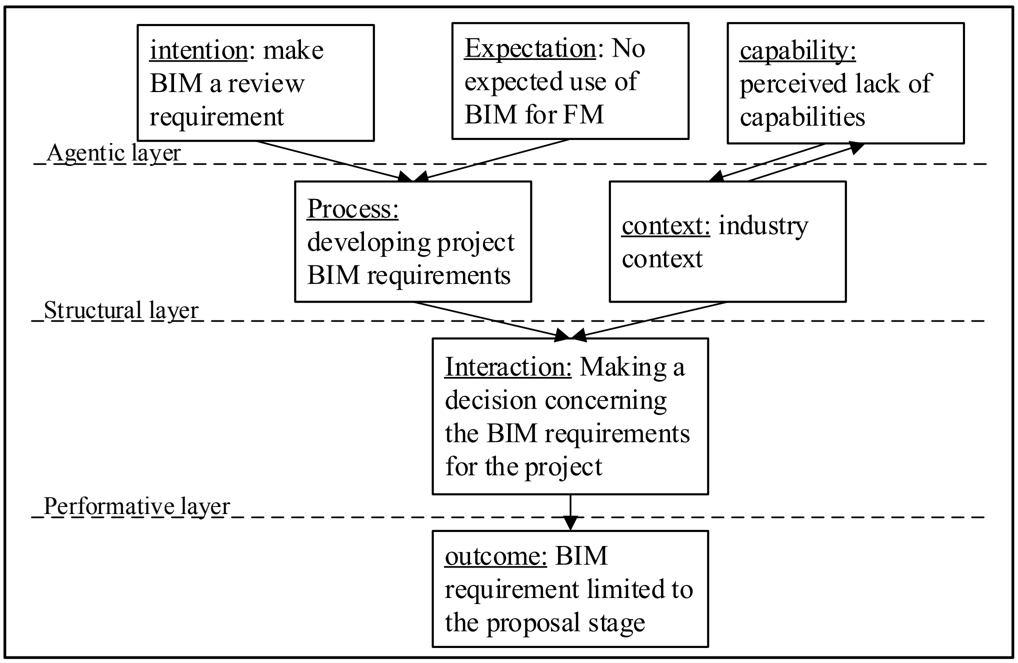

Figure 2.10 Vignette 01a – Owner perspective on BIM implementation in the project

Vignettes 1b (Figure 2.11) and 1c (Figure 2.12) presents the architect's and the general contractor (GC) perspective respectively. Vignette 1b presents the architect's job captain's perspective:

> We've [the design firm] said we were going to [BIM software] as a model for production for the last two years, so that's the standard now. We don't work in [2D] CAD […] (Job Captain, Architect (1st rd))

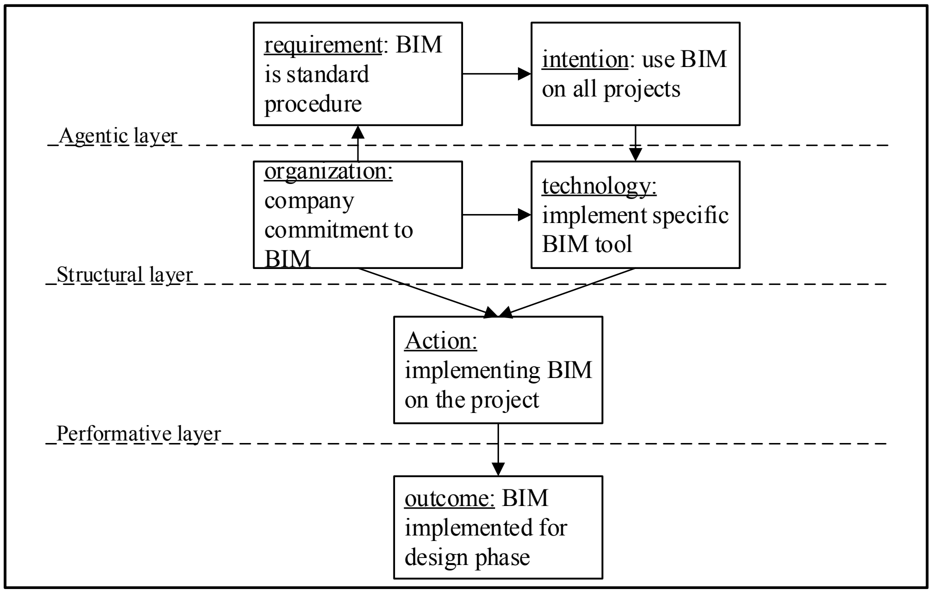

Figure 2.11 Vignette 01b – Architect's perspective on BIM implementation in the project

Vignette 01c presents the GC's project director's perspective:

> I think that there was an expectation that the BIM be developed beyond the proposal stage. It was really a no-brainer decision for [the General Contractor], considering our prior experience. (Project Director, General Contractor (1st rd))

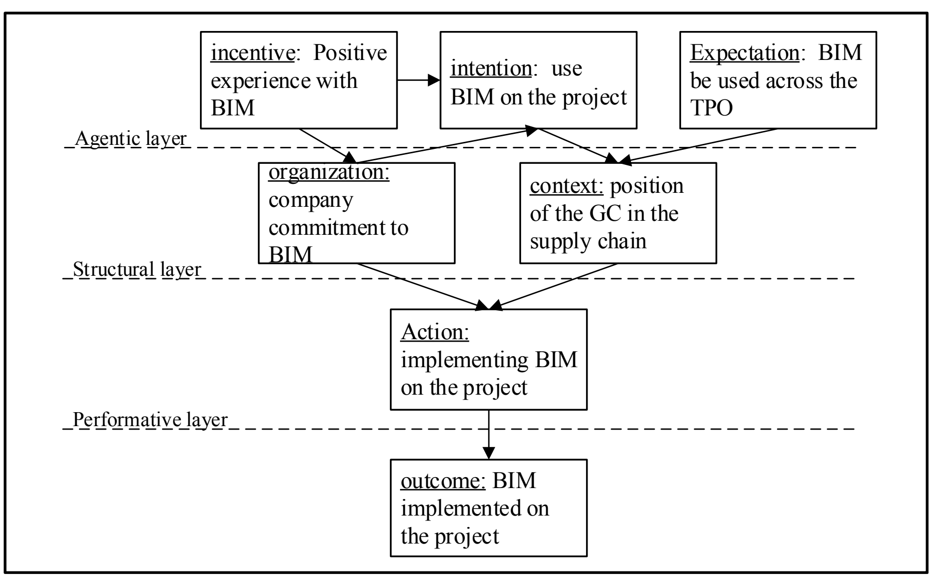

Figure 2.12 Vignette 01c – GC's perspective on BIM implementation in the project

Vignette 01 relays three perspectives on BIM implementation on site 01. The action developed in vignette 01a, the outcome of the decision to limit the scope of BIM requirements in the project, presented the opportunity for the project team to cease utilizing BIM after the proposal stage. However, the decision to fully implement BIM on the project came from the design-build team. More precisely it came from the clear alignment of intentions towards BIM use from the GC and the architect/design team. This alignment was structured through both organizational contexts, which resulted in concerted collective action. On the other hand, we uncover a misalignment between the owner's and the TPOs 'course of action' when we juxtapose all three sub-vignettes. Indeed, there is a misalignment between the Owner's BIM requirements and the TPO's intentions towards BIM. In this case, given the project context being a design-build and the position of the GC, the alignment of intentions between the designer and the GC trumped the lack of BIM requirements from the owner. This speaks more broadly to relationships uncovered through the model, the mis/alignments within or between categories and their influence on the various 'courses of collaborative action' (in this case the decision to implement BIM). Figure 2.13 illustrates this varying 'courses of collaborative action' within the model and the alignment / misalignment of their outcomes.

Vignette 01 illustrates three different intra-organizational collaborative episodes, the decision to implement BIM at the organizational level, be it across the organization or within the project. It illustrates a very important event in site 01. In this regard, this event, the decision to implement BIM would impact the rest of the project lifecycle. The second vignette presents the consequences of BIM implementation from the electrical engineer's perspective. Vignette 2a illustrates how the electrical engineer, faced with a complete shift in practice, moving from schematic drawings to 3D models, and a lack of tool capabilities, she has had to rationalize the decision to move ahead with BIM from a 'holistic' perspective, i.e. for the greater good of the organization and the TPO in this specific project :

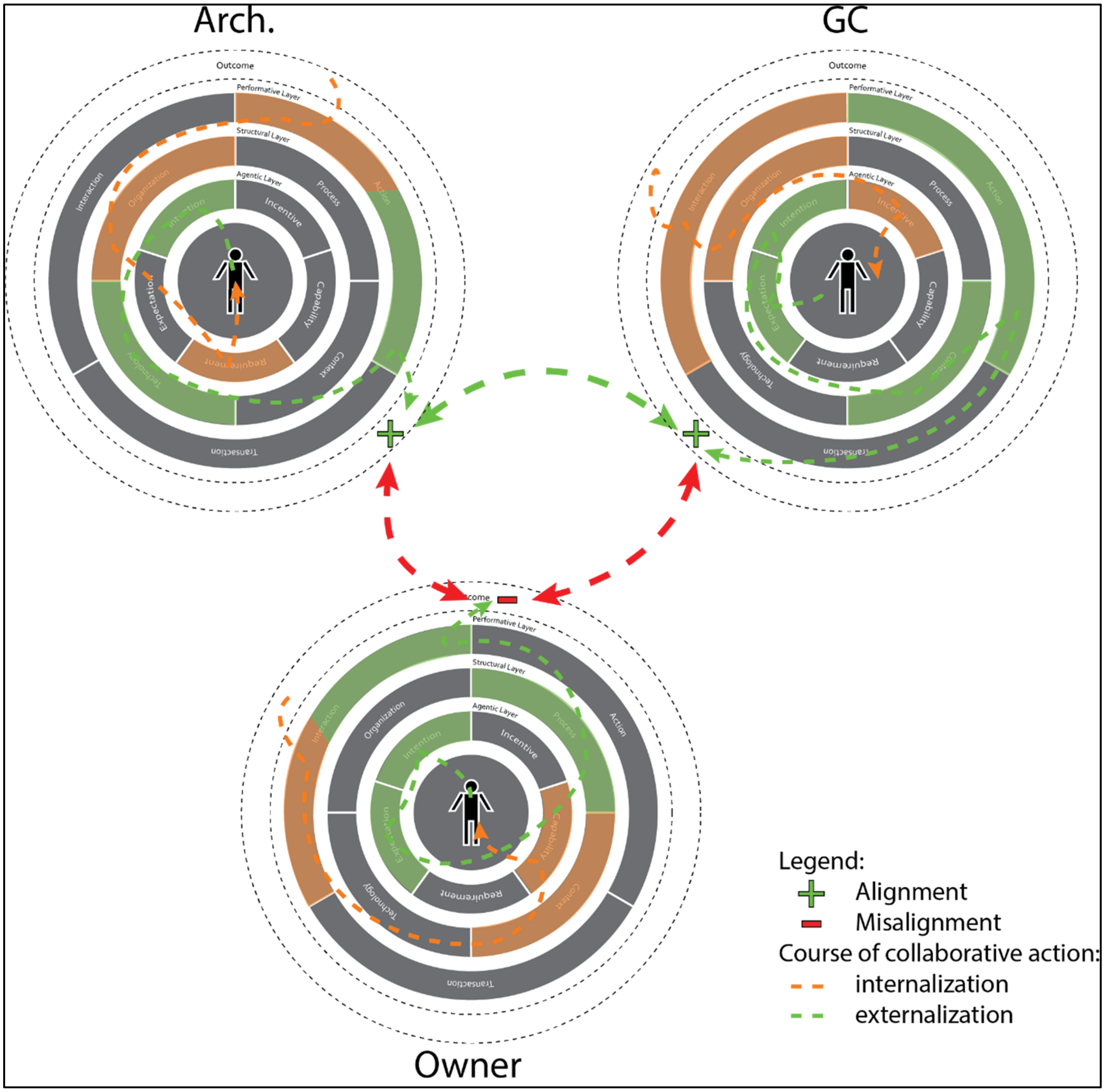

Figure 2.13 Alignment/misalignment between the outcomes of the three 'courses of collaborative action' indicated in vignette 01

> It comes down to schematic vs. 3D. The tools aren't really set up well for electrical because we're the smallest piece of the pie here. So they haven't been well developed for electrical. From an integrated perspective, and a holistic perspective, it's the right direction. It's working through the challenges. (Principal, Electrical engineer (2nd rd))

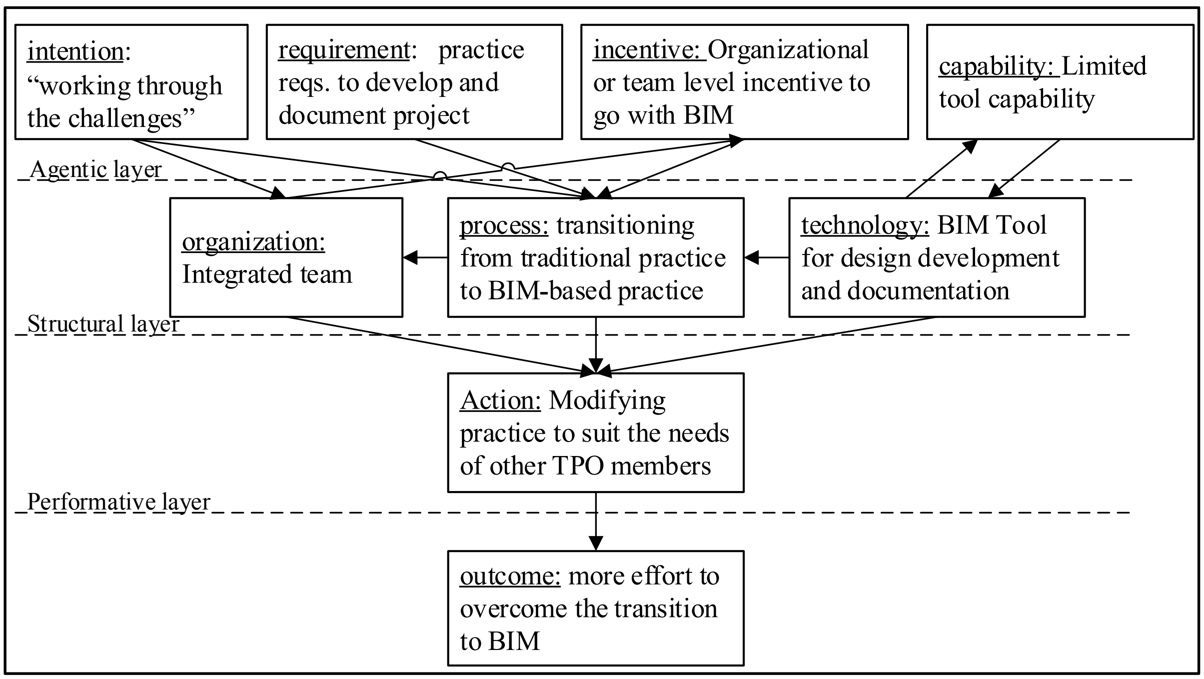

Figure 2.14 Vignette 02a – Electrical engineers perspective on BIM use for project development and documentation

If we reinterpret vignette 02a through the artifact, multiple courses of collaborative action emerge which are subject to two misalignments: (1) within the traditional and novel BIM-based requirements of electrical engineering practice and project delivery processes, and (2) between these novel requirements and the capability of the tools and technologies available. These 'course of collaborative actions', illustrated in Figure 2.15 and translated in are driven by the organization's decision to implement BIM which drove BIM use from an integrated perspective, thus leading the electrical engineer to overcome the BIM tool's deficiencies and put extra effort into developing the design and documenting the project through BIM. This is an example of 'active alignment' through perspective taking on the electrical engineers part. Of course, the vertical integration of the designers in the TPO allow this alignment to happen.

In this case, a little later on in the interview, the electrical engineer mentioned that this was possible to do because the fees could be redistributed across the entire design team to account for any loss in productivity in a specific discipline.

Figure 2.15 Multiple courses of action identified in vignette 02a, leading to a misalignment between practice requirements and tools capabilities

Vignette 2b illustrates how a change in the tool has greatly impacted how her team's work is carried out (Figure 2.16). It illustrates a readjustment of the misalignment illustrated in Figure 2.15 across time simply by having upgraded the software being used and thus unlocking better tool capabilities. The evolution of these alignments across time is at the core of the collaborative episode. The temporal aspect is central to collaboration as it captures the evolution of frames of reference at various levels through learning, negotiation, adaptation and mutual understanding:

> […] We've actually seen a very significant progress in switching over to [a newer version of the software]. Some of the issues that we had been having -- Some of the significant issues, we've been having electrically have been resolved. So, I actually look at it as a functional program now, which I certainly didn't think it was before…It really wasn't a functional program at previous stages. But since we did switch over to [the newer version], we can actually use it, which is a good thing. (Principal, Electrical engineer (4th rd))

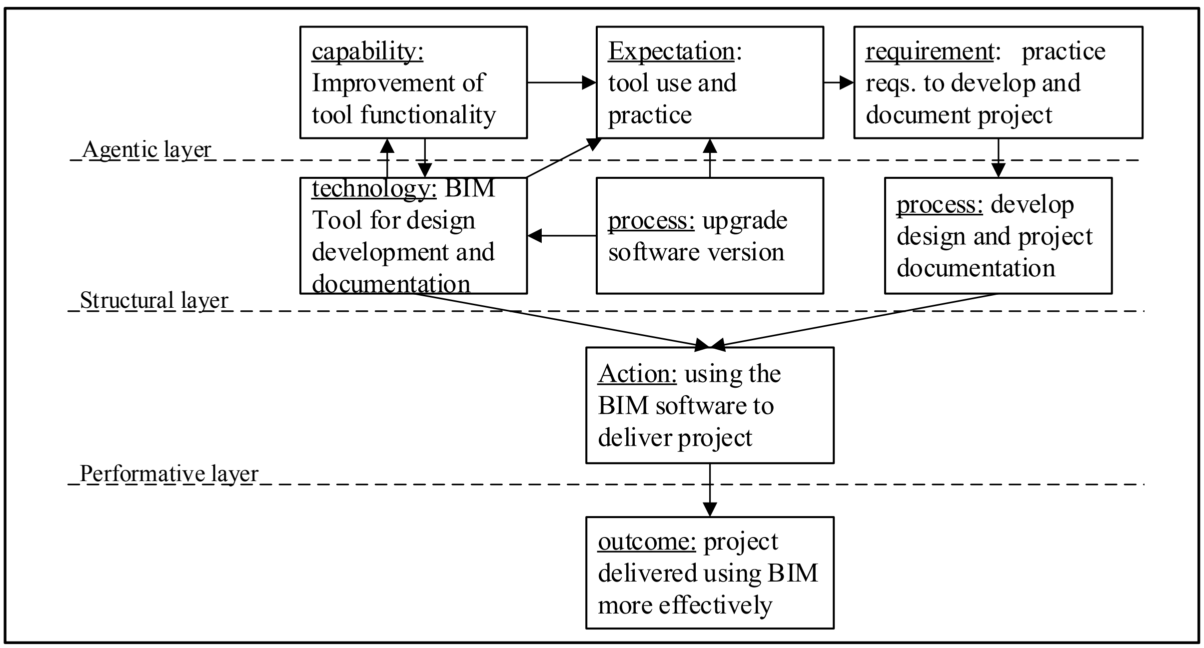

Figure 2.16 Vignette 02b – Electrical engineers perspective on BIM use for project development and documentation

Lastly, vignette 2c illustrates how the electrical engineer has leveraged the tools capabilities within the organizational context to enhance collaboration with the interior designers (Figure 2.17). It illustrates the alignment of process across disciplines. This is in part facilitated through the integrated team setting, through the improvements to the BIM tool being used and through simple innovative practice:

> We figured out a way to work with interiors in [the BIM software] that really helped us a lot on the lighting side of things, in particularly with coordination items. So, they could see what they wanted to see. We could see what we wanted to see. They can move things in line with grids. It doesn't impact our symbology because if you built things as large as our symbols are, all receptacles would be about a foot and a half in diameter, and lights will be about the same size. Interiors doesn't like that very well. So, we found a way with [the BIM software] to actually make that work, which was a really cool thing. (Principal, Electrical engineer (4th rd))

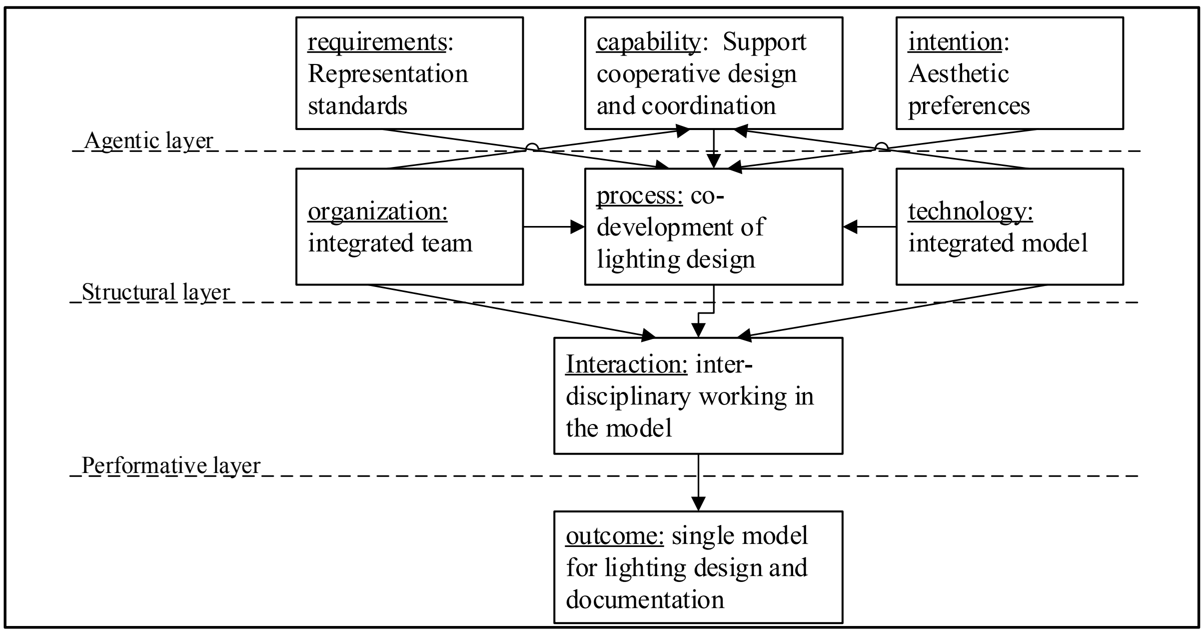

Figure 2.17 Vignette 02c – Electrical engineers perspective on BIM use for project development and documentation – lighting design

These two examples serve to illustrate the discovery of alignments through the artifact's method of operationalization. Throughout the analysis we uncovered many more of these situations which ultimately allowed us to understand the degree of alignment found within the TPOs that were being studied. In answering the first research question, what is the impact of innovative approaches to project delivery, namely BIM, on collaboration in the AECO industry? we can put forth that the emergence of BIM is impacting the frames of references of individual TPO member, not only through a change in the objects of practice as highlighted in other works (Dossick and Neff, 2011; Harty, 2008; Taylor, 2007b; Whyte, 2011), but in the courses of collaborative action that are internalized and externalized within these individuals and specifically through the outcomes of these courses of action and their alignments across networks and time.

2.7 Discussion

This paper presents a highly rationalized and substantive artifact aimed at characterizing collaboration through innovation, which is scalable across levels of analysis and time. The artifact moves beyond the structural aspects of collaboration, which dominate the current discussion in the AECO domain. Indeed, it explores the agentic layer, the individual level, and thus attempts to bridge the gap that appears in the current literature on collaboration in the AECO industry around the scalable interfaces between thought and action in collaborative environments. Being a product of DSR, the artifact is part of an "exploratory and prescriptive" systems which specifically targets collaboration to better inform it, specifically BIM-based in this case.

2.7.1 Alignment with other theories and works

The artifact does not seek to replace any given theory about socio-technical interaction, inter-organizational practices or others. Rather, it leverages and extends concepts into practice put forth in these theories while specifically addressing BIM-based collaboration in the AECO industry. For example, the overall model builds on Emirbayer and Mische (1998) definition of agency, defined as "[…] the temporally constructed engagement by actors of different structural environments—the temporal- relational contexts of action—which, through the interplay of habit, imagination, and judgment, both reproduces and transforms those structures in interactive response to the problems posed by changing historical situations" (Emisbayer and Mishe ,1998, p.970) It explicits these 'structural environments', whereas the mis/alignments within and between categories intimate the 'temporal-relational contexts of action'. Lastly, the 'interactive response to the problems posed' are embodied by the movement across the layers, through externalization and materialization of thought, structured into action when moving from inner to outer layer and learning or the internalization of action, structured into thought when moving back from the outer layer to the inner layer. This reciprocal 'course of collaborative action', a learning process, become central to collaboration in that it produces outcomes, necessary to achieve the goals and in turn those outcomes modify agency as they are structured and reinterpreted. In this movement, the artifact accepts no primacy between agency and structure which reflects a central tenant of Giddens structuration theory (Giddens, 1984). The framework also supports the concept of enactment (Orlikowski, 1992) and appropriation (Hussenot and Missonier, 2010) in its approach to collaboration at the interface between structure and agency in organizational settings. As mentioned it leverages many other theories such as those of motivation, cognition, instrumentality, valence etc which have been developed over the past half-century in the works of Bandura (2001) Feather (1992) Locke and Latham (1994) as well as Vroom (1964). The artifact extends these theories into practice by supporting their operationalization to a certain extent. As such, the main contributing factor of the artifact lies in its potential for practical application to better inform collaboration through novel project delivery strategies and innovations, such as BIM, in the AEC industry. It is built for utility and practice, hence the positioning of the research project in design science research.

2.7.2 Practical application

If we limit our view to the domain of BIM and collaboration, the practical application of the framework extends from the inception of the TPO to its dissolution. By leveraging the framework and the method of operationalization, it allows a clear and precise portrait of BIM-based collaboration through its formalization of determinant categories of collaboration. These categories can be measured at specific intervals to evaluate the progression of collaboration in a TPO. Other works aiming to inform BIM-based collaboration exist, the most notable examples being BIM Project Execution Planning Guide (PxP) (CICRG, 2010) and the BIM Toolkit being developed in the UK by the nbs (nbs, 2015). Both these tools serve a very clear purpose and their utility is reflected through their popularity in the AECO industry (for the BIM PxP guide at least). The proposed framework augments these tools and can serve to inform subsequent iterations by developing categories and interactions, which aren't explicitly accounted for in these tools, such as incentives in the BIM PxP guide and interactions between structuring elements in both tools. It also extends the domain of influence beyond BIM, allowing for different kinds of innovative project delivery methods to be investigated. Seeing as the outcome of collaboration, and not BIM, is the central focus of the framework, it lends itself to a more expansive role than other BIM-specific frameworks.

2.7.3 Discussion on the methodology

The research design for this project was rooted in the design-sciences due to its exploratory and prescriptive nature. The objective was to answer specific research questions which would in turn help to solve a problem in practice. The problem in practice was identified by industry practitioners, a critical element related to DSR. It was further motivated by an apparent gap in the theory. This goal-oriented perspective is central to DSR. To further orient the research design, we adopted a critical realist perspective to frame the epistemic and ontological foundations of the research project. This served to inform the choice of a systematic combining methodology anchored in abductive logic and the overarching mixed method approach to data collection and analysis.

From a DSR perspective, many guidelines and checklists have been developed to help evaluate DSR projects. Using Hevner and Chatterjee (2010, p.20) checklist, we discuss the various considerations applicable to a DSR project. The first question is what is the research question? Clear research questions are seen to impact the reliability, dependability, auditability of a research project (Miles, Huberman and Saldaña, 2013). These questions are laid out in section 2.4. The second question concerns the artifact itself and its representation. This is discussed at length in sections 0 and 2.6.

The third question, which is about the design process used to build the artifact, speaks to the methodology that was employed throughout the research project. The systematic combining process was the principal research and discovery process used in this project. Originally, Dubois and Gadde (2002b) developed this approach for use on single case studies. They were attempting to overcome the prevalent notion in the research domain that single case studies lacked any form of generalizability and transferability. They highlighted the fact that replication across multiple case studies was founded on the positivistic belief in statistical significance and that this was somewhat misguided for case study research. In this research project, data was collected on multiple sites and across multiple case studies. For Van Aken (2005), descriptive relevance or external validity is the most fundamental aim of DSR. We were thus struggling between the appropriateness of a single case study as outlined by Dubois and Gadde (2002b) and the need to develop an artifact that could serve beyond the boundaries of the case study. Therefore, data from multiple sites were used and a form of methodological replication, in the collection and analysis of the data, was used. This is seen as a form of methodological triangulation and supports internal validity, credibility, authenticity of the research. On the other hand, external validity, transferability, fittingness of the research is ensured through transparency of research approach as discussed in the following section (section 2.7.4).

One particular limitation that isn't addressed by Dubois and Gadde (2002b) in their description of systematic combining is the use of the same data source to build and evaluate theory (or artifacts in this case). There is the danger of creating a self-fulfilling prophecy as discussed by Merton (1948) when using the same data to develop and test theories or artifacts or having the same person do the developing and the testing, which also speaks to issues of objectivity and confirmability. In the context of the research project, this was handled in various ways. One approach was through constant reporting and interaction with the project participants. Another way in which this was achieved was through purposeful reflexivity (Mruck and Mey, 2007). Reflexivity is defined as:

> The researcher's scrutiny of his or her research experience, decisions, and interpretations in ways that bring the researcher into the process and allow the reader to assess how and to what extent the researcher's interests, positions, and assumptions influenced inquiry. A reflexive stance informs how the researcher conducts his or her research, relates to the research participants, and represents them in written reports. (Charmaz, 2006, p.188)

Having performed most of data collection and analysis, the first author had to ensure that his training and experience as an architect didn't introduce bias into the research process. For one, he was convinced that BIM is part of the solution to foster collaboration and thus improve the outcomes produced by the industry, hence he had a bias towards BIM over traditional project delivery methods. However, this particular view could not be imparted during interviews, which could potentially introduce bias into the interviewee's response. He also had to take care to not introduce that particular bias into the coding exercise, namely by assigning a negative or positive value to an outcome based on personal belief. To overcome this, the use of the questions outlined in Figure 1.11 and linguistic cues developed as the codes emerged. Each action and outcome that were being coded were constantly being viewed from the interviewee's perspective. Other known biases include cultural biases (race, gender, class) positionality, i.e. being sympathetic to one particular view over another, architect over general contractors for instance or disregarding interview context and situation in the analysis. To further facilitate this 'reflexive action', the first author kept a research journal and annotated directly in the text to keep track of any assumptions that were made.

The fourth and fifth questions, concerning the grounding of the artifact in the knowledge base and its evaluation and evolution, are an inherent part of the systematic combining process. These are discussed in section 0 and 2.7.1. The sixth question, regarding the introduction of the artifact into the application environment and its evaluation are addressed in two ways. The first is the application of the artifact to assess the impact of BIM on collaboration which is discussed in section 2.6. The second is the proposal for future work, as outlined in section 2.7.4, to fully field test the artifact and a description of the methodology and metrics to do so. The seventh question is inherent to this paper, namely adding to the knowledge base through publication. Further to this, a number of reports have been produced and presentations given as part of this research project for dissemination to industry and academic stakeholders. Lastly, the eight question, has the research question been satisfactorily addressed? Is relatively straightforward. Upon reviewing the outcomes of the research presented in this thesis, I let the reader answer the question of whether or not the research question have been satisfactorily addressed or not.

2.7.4 Future work

The principal opportunity for future work is to instantiate the artifact and fully evaluate its usefulness for the management of BIM-based collaboration in a real world setting. While the artifact was evaluated locally in the context of this research project as an integral part of the development and build cycle, there was not the opportunity to fully implement it and test its usefulness in a real project or organizational setting for management. There exists many different methods to evaluate an artifact that has been developed through DSR (Hevner et al., 2004; Järvinen, 2004; March and Smith, 1995; Van Aken, 2005). A real world testing of the artifact should be carried out to demonstrate and assess its utility as a management tool in practice. A hypothetico-deductive experimental research design would allow the development and testing of a hypothesis, informed by the artifact, and its subsequent testing in a real-world setting (Figure 2.18).

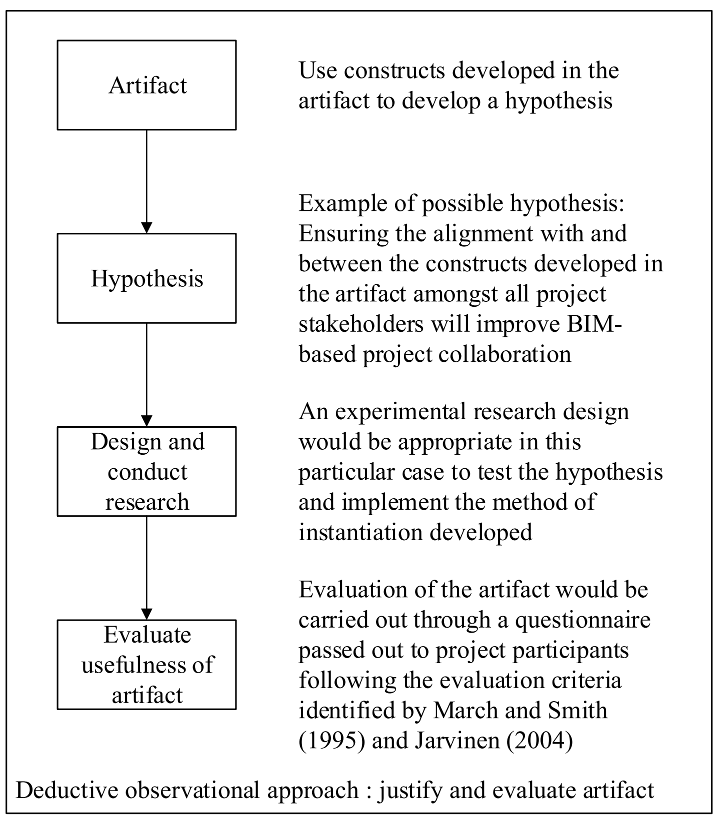

Figure 2.18 Proposed strategy to justify and evaluate the artifact for management and assessment purposes

Other opportunities for future work would be to develop tools to support the artifact's instantiation by providing means to evaluate the degree of alignment, track and assess the measures developed in the method of operationalization (uses, decision, performance indicators, information lifecycle indicators (value, evolution, quality, content) etc.) and provide a dashboard for the measured and perceived outcomes.

Further to this, examples of practical future work include developing an instantiation of the framework in the form of a platform allowing automatic and targeted retrieval of the necessary measures. Future practical application of the framework needs to be further developed, tested and piloted through action-research. This is proposed as a next step in our research agenda. The scope of investigation could be widened to include other innovative project delivery approaches through the lens offered by the artifact. Indeed, the scope of the investigation presented in this thesis was limited to BIM-based collaboration and integration through organizational design (vertically integrated design firm) and design-build. A similar methodology to the one presented here could be used and the artifact could be leveraged to support the analysis. Without falling prey to "theoretical fitting" or "forcing" (Glaser, 1992), the artifact could inform this investigation, which could in turn help extend its theoretical and practical coverage.

Further work could also look into extending the scope of the artifact with regards to personal habits, emotions, moods, etc. Beyond the level of agency discussed, we didn't extend our analysis into the realm of psychology which have been covered by the likes of Bandura (2000); (2001), Bourdieu (1977), Wood, Quinn and Kashy (2002)etc. although the line of inquiry could be opened up in the future. In building the artifact in its current form, we consciously kept to a highly rationalized model of specific behavior within a specific context. However, we did not purposefully ignore elements of behaviour, attitudes and so forth, the data analysis was undertaken with a sensibility to the influence of individual emotions (stress, fatigue, etc.) and their influence in the collaboration process, even if they are not explicitly developed. As mentioned, this could take part as future work.

2.8 Conclusion

This paper has presented the outcomes of a design science research project aimed at investigating the dynamics of BIM-based collaboration in the AECO industry and assessing its impact on project outcomes. Our main premise was the belief that a better understanding of the impact that the transition to BIM is having on the mechanisms through which the AECO industry is delivering projects and the factors modulating this transition, it would allow practitioners to better define and optimize the collaborative environments put forth in a BIM-based project setting. To inform and support this investigation, an artifact was built by developing several constructs which were established through a systematic combining process and a method of operationalizing the artifact was presented. The development of the various constructs and relationships was facilitated by the transition to BIM itself which has allowed a different view of collaboration due to certain issues that were perhaps dormant prior to its emergence being brought to light and exacerbated. The artifact that was developed supports a scalable and targeted assessment of BIM-based collaboration. In this regard, our assessment of the impact of BIM on collaboration highlighted the importance of negotiated alignments not only at the structural level, but also at the agentic level, to ensure successful BIM-based collaboration. Future work is needed to further evaluate the artifact, namely through experimental means to assess its utility as a management tool. Furthermore, the theory developed here remains substantive, built specifically around BIM-based collaboration. Investigating other innovative approaches to project delivery through the lens provided by this artifact could help extend its application domain.

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CHAPTER 3

COLLABORATION THROUGH INNOVATION: IMPLICATIONS FOR EXPERTISE IN THE AECO INDUSTRY

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3.1 Abstract

The current shift in practice brought on by novel project delivery approaches, such as Building Information Modeling, Integrated Project Delivery and Design Process as well as Lean construction, envisions new ways of collaborating throughout a building project's lifecycle. The notion of collaboration however remains an amorphous concept which poses a challenge when attempting to assess, develop and improve expertise in this field. The aim of this paper is to lay the theoretical groundwork to support investigation into collaboration by developing both a process view of the building project and a systemic view of collaboration. A critical realist perspective is adopted to support an investigation into the stratified, emergent and causal nature of these two embedded views. The scope of this theoretical investigation is articulated around the question of expertise and collaboration, specifically attempting to uncover what defines expertise in collaboration and how it can be assessed. By better understanding elements of the collaboration system and the entities that comprise them, modifications to collaborative practices through transition to novel project delivery approaches can be better supported and expertise in this area better defined.

3.2 Introduction

Expertise and collaboration are deeply ingrained in the Architectural, Engineering, Construction and Operations (AECO) industry. Along with the building project, these concepts form the industry's axiomatic basis: collaboration is imperative; it is embodied by temporary project organizations (TPO), i.e. the temporary joining of individuals from different social, mental and object worlds into a functional unit; and it aims to fulfill a common motive – the building project – through pooling and application of individual expertise found within the TPO. This axiomatic framing of the AECO industry is the result of its many notable characteristics which heavily influence the performance and value generated by the industry. For instance, the industry is notoriously fragmented: it is still largely organized around a 'guild structure', a relic of craft production (Koskela, 2000), with associations regulating, managing and protecting their respective bodies of knowledge and sphere of responsibilities (Chiocchio et al., 2011; Forgues and Lejeune, 2013). Relationships within the industry are defined through power and influence which are conferred through expertise (Black, Carlile and Repenning, 2004), i.e. an individual stakeholder's 'cognitive authority' – the mastery of a body of knowledge - and the recognition and legitimization of this authority (Turner, 2001). The industry is also notoriously complex and multifarious due to the nature of the building project : it creates a unique and 'indivisible' (Aldrich and Herker, 1977) or 'wicked' problem domain (Coyne, 2005; Rittel and Webber, 1973) which requires collaboration and expertise to 'tame', evolve and ultimately solve (Franco, Cushman and Rosenhead, 2004). This creates a double-bind of sorts: collaboration is imperative in overcoming the complexity and fulfilling the objectives of the building project, however collaboration introduces and exacerbates this complexity.

Over the past three decades, strategies have been developed to overcome these challenges and help extract the industry from its double-bind. Strategies such as integrated approaches (Elvin, 2007), Building Information Modeling (BIM) (Eastman et al., 2011) and Lean construction (Koskela, 1992) are aimed at fostering and facilitating collaboration in an effort to improve the value generated by and the performance of the AECO industry. BIM has been conceptualized as a set of interacting tools, technologies and processes (Eastman et al., 2011) that are guided by norms and rules (policies) (Succar, 2009) to support AECO practitioners in their development of the building project. A basic premise of BIM is collaboration (NIBS, 2007): On one hand, BIM supports and enables collaboration; on the other, collaboration is required to fully implement BIM. Integrated practices involve the relational side of collaboration. Both Integrated Project Delivery (IPD) and Integrated Design Processes (IDP) aim to foster collaboration and effective project delivery by ensuring that the right expertise is available at the right time by removing organizational, contractual or procedural barriers (American Institute of Architects, 2007; BC Green Building Roundtable, 2007). Lean construction is the application of new production philosophies and mechanisms within the AECO industry (Forbes and Ahmed, 2011; Koskela, 1992). Each of these innovative approaches to project delivery involve a shift in practice: they are redefining the development and application of expertise and collaboration over a building project's lifecycle.

Collaboration remains an amorphous and somewhat ill-defined concept in the AECO industry (Kvan, 2000) although attempts to formally define it have been made (Hughes, Williams and Ren, 2012). This renders it difficult to truly investigate the impact of innovative project delivery approaches on collaboration. Furthermore, a particular field of expertise in collaboration hasn't been developed. This begs the questions as to whether an expertise in collaboration exists independently from disciplinary practice. If it does exist independently, how would an expertise in collaboration be defined? How would the current trend in innovative project delivery approaches impact this collaborative expertise? Lastly, how could this expertise in collaboration be assessed and taught?

The aim of this paper is to explore the notion of expertise in collaboration in the AECO industry and highlight the implications of the transition to novel project delivery approaches on this expertise. The objectives of the paper are to frame the concept of collaboration, to review theory and practices of collaboration within this frame and to investigate the shift in practice and expertise that is being induced by the transition to novel project delivery approaches and its outcomes. A critical realist perspective is adopted due to its bridging of the positivist-interpretivist divide. This perspective is further rooted in the design-sciences, which is characterized by its search for utility and development, as a way to theorize and develop areas of expertise in collaboration. The investigation is informed by the literature and is supported primarily by a systems view and a process view, relating past work such as structuration theory, practice theory, socio-cognitive theory and what is loosely termed “boundary theory”, on collaboration and expertise.

The paper is structured as follows: the ontological and epistemic position adopted with regards to collaboration research is discussed. The concept of collaboration is then defined and the ensuing collaboration system is framed. It is argued that a collaboration system is comprised of four foundational elements: structure, process, agents and artifacts. These elements are interdependent and interact throughout the collaborative episode, the building project, to inform collaborative practice. The outcomes of this collaborative practice is discussed with regards to their assessment and management. Finally, the development of a field of expertise in collaboration is discussed in the context of the AECO industry in light of recent innovative project delivery approaches. The contributions of the paper lie not in the presentation of the collaboration system itself; the foundational elements discussed are supported by decades of organizational studies. Rather, the contribution lies in the juxtaposition of these foundational elements and the uncovering of areas of expertise which can serve to inform an expertise in collaboration for the AECO industry.

3.3 Methodological considerations in collaboration research

The study of collaboration is framed by ontological and epistemic ‘conditions’ that both inform and constrain the varying perspectives through which the phenomenon under study is viewed (Luck, 2010). There appears to be no ‘right way’ to study collaboration although prevailing epistemological, theoretical and methodological currents can be uncovered (Fiedler and Deegan, 2007)), highlighting the fact that there exists no generally accepted approach to study complex phenomena such as collaboration (Nicolini, Mengis and Swan, 2012; Reed and Harvey, 1992). Given that the unit of analysis in the AECO research domain typically revolves around the building project and thus collaboration is assumed, the focus of investigation shifts from explaining why it occurs , as is the case in organizational studies seeking to investigate the motivating factors behind collaboration (e.g.Gray and Wood, 1991), to explaining how it occurs and how to better inform it.

TPOs and collaboration are, in effect, ‘designed’ or ‘fabricated’ phenomena, hence artificial (Nicolini, Mengis and Swan, 2012). This perspective aligns with that of design-science, which is characterized by its constructive and generative nature (Hevner et al., 2004). Being principally prescriptive, the goal of design-science is utility: it attempts to create things that serve human purpose (March and Smith, 1995). Design-science is thus consistent with the practice turn taken in the AECO research domain. This is especially relevant when investigating and developing expertise and reconfiguring practices in light of systemic and disruptive innovations such as BIM and integrated practices. Design-science’s strengths lie in its iterative nature that strikes a balance between the relevance and the rigor of its outcomes. It has become a well-developed domain, with specific guidelines (Hevner et al., 2004; Van Aken, 2005) and evaluation criteria (March and Smith, 1995). Conversely, design-science has been criticised for failing in certain regards, namely for focusing too much on information technologies and failing to consider the organizational and social domains (Drechsler, 2012). More generally speaking, the pragmatic roots of design-science tend to reduce its view of “truth” to a very limited and specific context.

Adopting a critical realist perspective can help address some of these shortcomings. Critical realism assumes that the world exists independently of our knowledge of it, however this knowledge is socially constructed (Sayer, 1992). It attempts to bridge the positivist-interpretivist divide, joining ontological realism and epistemological constructivism (Maxwell, 2012). A critical realist view considers the world in a differentiated and stratified manner – layers defining the realm of real, actual and empirical phenomena - which operate on different time scales (Carlsson, 2003). The realm of the real consists of mechanisms which generate phenomena at the level of the actual, played out through specific events, which may or may not be observed and experienced at the level of the empirical (Sayer, 1992). Through process of retroduction (similar to abduction, which consists in considering all possible theoretical explanations for specific observations in an attempt to formulate hypothesis about the phenomenon under study (Bryant and Charmaz, 2007)), the aim is to discover "the underlying structures that generate particular event patterns" (Carlsson, 2003, p.7) - the generative mechanisms, i.e. the causes of an event, a relationship, etc. In essence, establishing causality is fundamental (Maxwell, 2012). According to (Easton, 2010, p.121) "the most fundamental aim of critical realism is explanation; answers to the question "what caused those events to happen?"". This could seem at odds with the more pragmatic approach underlying the design-sciences, whose fundamental aim would be to answer the question "how can this event be improved?" It is argued here that critical realism's search for "truth" is central to design-science's search for utility. Critical realism supports a wider construction of "truth" which can enable the development of a more robust artifact. Past research in the AECO domain have adopted a critical realist perspective, namely (Smyth and Pryke, 2008) who studied collaborative relationships, trust in particular (Smyth, 2008), and (Fox, 2014) who looked specifically at BIM adoption, however this perspective is still sparse in the AECO domain.

An investigation into collaboration and the concurrent development of expertise adopting a critical realist perspective rooted in the design-sciences should be supported by a mixed-method approach, including both qualitative and quantitative data collection and analysis. On one hand, qualitative research methods are increasingly popular in the AECO industry due to their descriptive and explanatory nature, which allows a deep understanding of the phenomenon under study: they deal with *what* people construct and *how* they construct it, not *why* they do it (Charmaz, 2008, p.397). Critics of qualitative approaches target their subjectivity and interpretative nature as well as their idiographic perspective (Bryant and Charmaz 2007). They also criticize the notion that the descriptions and explanations often lag behind the in-situ application of new constructs or artifacts (March and Smith, 1995). On the other hand, quantitative approaches appear to provide more rigor, reliability and validity (Creswell, 2003). However, attempting to generalize complex phenomena such as collaboration in a highly contextual domain such as the AECO industry is questionable. The emergence of mixed-method approaches has attempted to bridge the divide between qualitative and quantitative methods (Abowitz and Toole, 2010). However, too often mixed-method approaches aren't positioned in an epistemic and ontological framework (Carlsson, 2003). The knowledge uncovered becomes "orphaned", it exists independently and lacks the framing of a coherent constitution of knowledge. Thus the framing of mixed-methods in a critical realist epistemic and ontological framework provides a coherent and consistent foundation to investigate a phenomena as complex and multifarious as collaboration.

3.4 Framing the concept of collaboration

"Collaboration" is a hard term to grasp; it has been overused, becoming a 'catchall to signify just about any type of inter-organizational or inter-personal relationship' (Gajda, 2004, p.66). The very definition of "Collaboration" is elusive and amorphous which renders it difficult to implement and investigate. Past work in various fields, aimed at defining collaboration, has been quasi-cyclical in its recurrence (Appley and Winder, 1977; Gray, 1985; Hartono and Holsapple, 2004; Hughes, Williams and Ren, 2012). Throughout these cycles consensus remains elusive, a fact highlighted by (Hartono and Holsapple, 2004), yet facets of collaboration, developed in these various definitions, can be synthesized into the following definition:

> Collaboration is an interactive, constructive, and knowledge-based process, involving multiple autonomous and voluntary participants employing complementary skills and assets, with a collective objective of achieving an outcome beyond what the participants' capacity and willingness would allow them to individually accomplish (Hartono and Holsapple, 2004, p.20).

This definition highlights the foundational elements of collaboration, which resonate with past work in this field:

1) Collaboration is a socially constructed and purposeful phenomenon (Nicolini, Mengis and Swan, 2012) which involves the interaction between multiple actors from different social, mental and object worlds (Peters et al., 2013);
2) Collaboration is a process involving a specific goal - a motive, a beginning and an end (Thomson and Perry, 2006);

3) Collaboration is structured and set within a given environment (Gray, 1985);
4) Collaboration is supported through artifacts (Boujut and Blanco, 2003).

Structure, process, agents and artifacts, the four foundational elements, frame the concept of collaboration. These four elements interact to define a collaboration system which is developed within the process view of the building project (Figure 3.1). The collaboration system described here goes beyond the techno-centric, information systems support for collaborative that is prevalent in the literature, namely in the field of computer supported cooperative work (CSCW). Instead it leverages the four elements to identify the interdependencies between the well-documented constructs developed in the field of organizational sciences and uncover areas of expertise in collaboration. Furthermore, this model borrows elements from past models such as Leavitt's 'diamond'(Leavitt, 1965), namely, the interrelated and mutually adjusting nature of the components of the organization or in this case the foundational elements of collaboration in TPOs. This view of the building project is completed by the production system (Koskela, 1992) that concurrently exists to support the execution and delivery of the project. Both production and collaboration systems are integral parts of the building project, as are the needs and its outcomes.

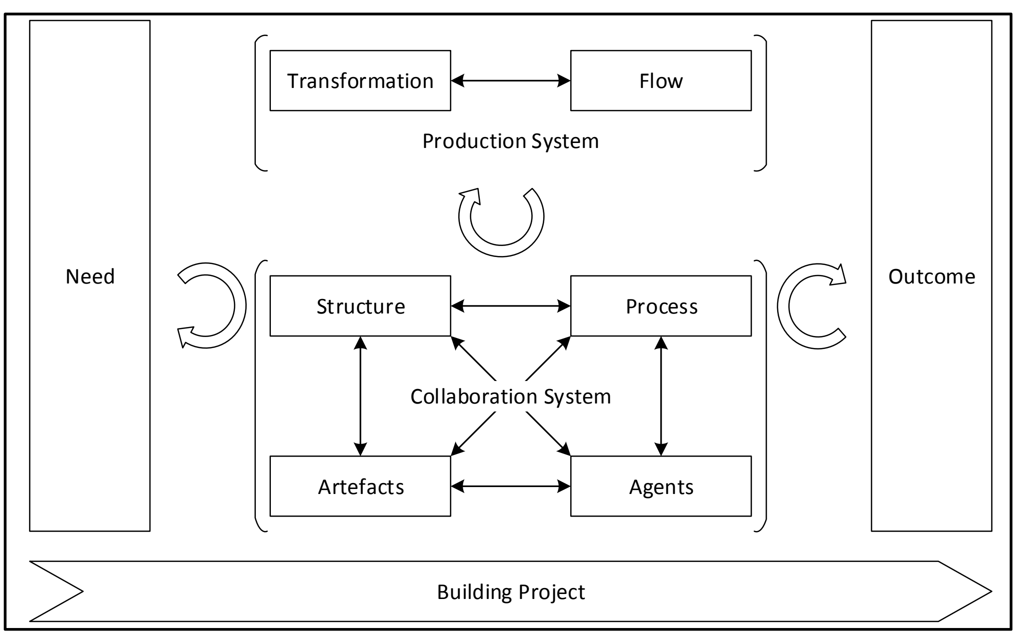

Figure 3.1 Collaboration system within the building project

As mentioned, a defining characteristic of collaboration in the AECO industry is that it is articulated around the building project. A building project can be defined as a "complex, information dependent, prototype production process where conception, design and production phases are compressed or concurrent and highly interdependent, in an environment where there exists an unusually large number of internal and external uncertainties" (Pryke, 2004, p. 790) Building projects have been conceptualized as many different type of systems: open (Ren and Anumba, 2004), activity (Forgues and Koskela, 2009; Hartmann and Bresnen, 2011), emergent (Cicmil and Marshall, 2005), complex adaptive (Aritua, Smith and Bower, 2009; Fellows and Liu, 2012), socio-technical (Higgin and Jessop, 1965), and information processing (Winch, 2010) systems, among others. While these different systems views offer distinct 'units of analysis', they all develop five intrinsic properties, as described by systems thinking (Kaspary, 2014): interaction/relationship, interdependency, autonomy/dependency, and self-production (i.e. autopoiesis, (Maturana and Varela, 1992)). Across these different systems views, building projects are neither the result of rational decision making in that they involve human actors, nor reducible to a common logic in that they involve collective behavior (Coyne, 2005; Marcus and Saka, 2006): building projects are subject to different interpretations, highlighting the need for shared knowledge and representation (Boujut and Blanco, 2003) to support negotiation and mutual understanding amongst individuals (Neff, Fiore-Silfvast and Dossick, 2010; Tryggestad, Georg and Hernes, 2010). They are also subject to competing interests and goals (Anvuur and Kumaraswamy, 2008). Ultimately though, building projects 'are sites of continuously evolving human action' (Cicmil and Gaggiotti, 2013, p.2).

From a critical realist perspective, the notion of collaboration in this systems view is held as an underlying causal mechanism (Mason, Easton and Lenney, 2013). Figure 3.2 applies a stratification, anchored in the critical realist approach, to the building project defined in Figure 3.1 with a specific focus on the collaboration system. For instance, each entity presented in the empirical realm exists in the actual and real realms also and thus can, in their own respect, act as generative mechanisms. However, Figure 3.2 serves to illustrate the overall systemic and emergent view of the building project which, ultimately is experienced through the entities laid out in the empirical realm.

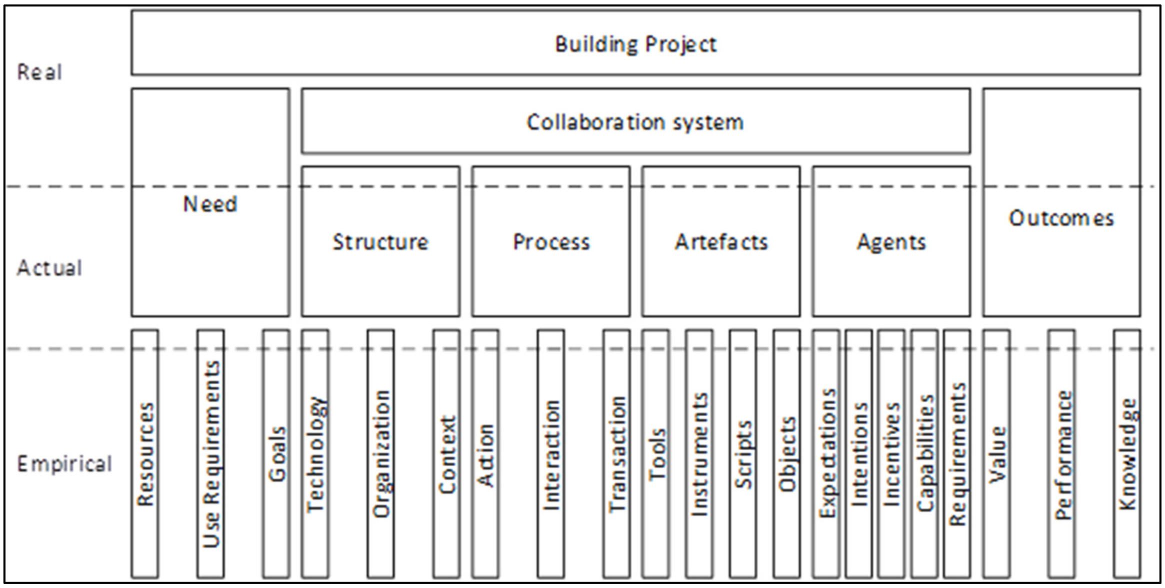

Figure 3.2 A stratified view of the building project centered on the collaboration system

3.4.1 Structure

The structure element of the collaboration system is experienced through its technological, organizational and contextual entities. These three entities are oft-used to structure and describe an organized social group, be it in the organizational sciences (Leavitt, 1965), computer sciences (Tornatzky and Fleischer, 1990), or in the AECO domain (Staub-French and Khanzode, 2007; Succar, 2009), amongst others.

One of the main issues with the notion of context is that too often it is used as a 'underspecified residual category' (Schweber and Harty, 2010, P.672), a 'shell inside of which people behave in certain ways' (Nardi, 1996, p.38). In this case, the contextual entity refers to the problem domain (Warner, Letsky and Cowen, 2005) and the ensuing natural, social, and artificial environments enacted within this domain (Pryke and Smyth, 2012; Simon, 1996; Weick, 1988). The problem domain is framed by what is at stake: the building of a product to meet specific user needs. This product is a result of, and constitutes the motive for, collaboration between the members of the TPO. The nature of the product and its fulfillment, the activity, will determine the TPO's composition, its size and complexity. It will also set the overarching, exogenous and mandated goal: the built asset (Gray, 1985; Nardi, 1996). The finality of the exogenous goal doesn't preclude the emergence of endogenous goals throughout the collaborative episode. Indeed, endogenous goals will emerge, mediated through the project's materiality, and become outputs of collective and collaborative action (Tryggestad, Georg and Hernes, 2010). However, it is the exogenous goals, the needs of the client that provide impetus for the building project.

The shift to novel project delivery approaches in the AECO industry involve modifying the technological, organizational and contextual entities which define the collaboration structure. These innovations - BIM, IPD, IDP and Lean - act as an input, a 'means' to achieve sustainable competitiveness, as opposed to an outcome, an 'end' in themselves (Sexton and Barrett, 2003b) although the relationship becomes recursive within and across projects. They mark a conscious effort to reconfigure work practices, develop new expertise, and reshape the professional identities and roles of project stakeholders (Schweber and Harty, 2010). They are systemic and disruptive, BIM in particular (Lehtinen, 2012; Poirier, Staub-French and Forgues, 2015b). To be effective, they must be adopted and implemented across many different types of boundaries (Harty, 2008) and supported and enacted through networks of relationships (Linderoth, 2010).

Boundaries demarcate one social entity from another; they imply discontinuity at the mental, social and/or physical level (Hernes, 2004; Kerosuo, 2006). Boundaries are conceptualized at the limits of functional, geographic, temporal, hierarchical, social, cultural, technical, historical and professional systems (Lindgren, Andersson and Henfridsson, 2008; Orlikowski, 2002). They are also rooted in practice (Levina and Vaaste, 2004) and exist within and across knowledge domains (Carlile, 2002). Relationships within a TPO serve to cross these boundaries. They lay a latticework of connections that further impact the organizational entity through technical or social means (Solis, Sinfield and Abraham, 2013). These relationships operate at different levels, serving both to structure the collaboration system and render it operational (Pryke and Smyth, 2012, p.23). In their operative function, they are the locus of decision-making, knowledge creation, learning and innovation (Pittaway et al., 2004).

Relationships are influenced by factors such as identity, trust, culture, perceived risk and power (Chiocchio et al., 2011; Phua, 2012; Smyth, 2008)

One of the more explicit boundaries in the AECO industry is imposed through contractual mechanisms (Cox, 1996; Kumaraswamy, Anvuur and Mahesh, 2008). The contracts between parties in a TPO will dictate the location, flexibility and permeability of these boundaries (Fellows and Liu, 2012), while also influencing the strength and type of relationships developed. Novel project delivery approaches target these organizational and contextual boundaries, such as IPD, to provide permeable and flexible structures (Baiden and Price, 2011) supported through common objectives, shared risk and reward, win-win scenarios, mutual benefits and a focus on value (Kumaraswamy et al., 2005).

The third structuring entity in the collaboration system is technology (Orlikowski and Iacono, 2001). There is a long tradition of research into technology, materiality and the organization of work. It's been argued that technology is a product of human action, which in turn, is continuously structured and conditioned in an ongoing and integrative manner (Desanctis and Poole, 1994, Orlikowski, 1992, Orlikowski, 2000). In the AECO industry, as in other industries, collaboration is increasingly becoming technology driven: its use is seen as an inevitable part of everyday practice (Isikdag and Underwood, 2010). Specialized software, collaborative platforms and virtual environments, facilitating team interaction and fostering collaboration, are becoming common practice (Fischer and Kunz, 2004). Technical considerations have been covered at length in the past (Xue et al., 2012). Putting these considerations aside, the increasing reliance on technology, BIM in particular, is fundamentally changing the relationship between agent and information (Crotty, 2011). Within the TPO, the authoring, manipulation, translation, transformation and exchange of information through BIM is subject to the appropriation and enactment of the various BIM technologies by the different TPO stakeholders. This happens outside of the frame of the TPO, within the individual's social, mental and object world, which is then translated to the TPO. This causes misalignments in the deployment and use of technology (Taylor and Levitt, 2007) and leads to the presence of multiple heterogeneous structures which require some form of mutual adaptation and alignment to be effective (Linderoth, 2010; Taylor, 2007b).

3.4.2 Process

The process element of the collaboration system is experienced through the actions, interactions and transactions carried out within the TPO. The process view of the building project resonates within this particular area, as does the process orientation of the production system, which involve transformation, flow and value elements of the building project (Koskela, 1992). In this overarching process view, the building project has a beginning and an end: time becomes its most important resource (Huxham, 1996). It evolves and unfolds through actions, interactions and transactions, across phases and milestones. The emergent and dynamic state of the building project implies an ontology of 'becoming', built around an ever-changing, continually constructed reality as opposed to an ontology of 'being', built around a finite and bounded reality anchored in substance (Cicmil and Marshall, 2005; Koskinen, 2012). This entails that the structure and the artifacts in use are in constant flux as are its agents, constantly being transformed through the actions, interactions and transactions carried-out within the TPO.

The building project is supported by information processes, material processes and business processes (Medina-Mora et al., 1992). The collaboration process exists within and supports all three, though it could be argued that collaboration is principally a business process, especially in the context of computer integrated construction (Teicholz and Fischer, 1994). The actions, interactions and transactions embodied in these processes involve communicating and coordinating (den Otter and Emmitt, 2007; Sonnenwald, 1996), negotiating (Winch, 2010), sensemaking (Weick, 1995), understanding and learning (Koskinen, 2012) as well as problem solving (Franco, Cushman and Rosenhead, 2004) and decision making (Schade, Olofsson and Schreyer, 2011). Every one of these processes exist as bodies of knowledge and fields of expertise in their own right.

The quality of collaboration has been directly attributed to the level of communication and coordination in a project setting (Hoegl and Gemuenden, 2001). The different types of communication, the factors affecting it, its barriers, its enablers, its impacts and its effects comprise a considerable body of knowledge across all domains. Most importantly, communication supports all other entities in the collaboration system. Coordination is a praxis of communication and takes on a specific meaning in the context of the AECO industry: both the product and the process require coordination. This entails different scopes and types of expertise. The transition to BIM and other novel project delivery approaches has specifically targeted better communication and coordination within a TPO. Coordination is now supported through the model which marks a significant shift in practice and presents its own set of challenges as discussed below. It also entails a shift in practices such as coordination meetings and the production of project information requiring new roles and capabilities to manage this coordination and production.

Negotiation serves as structuring mechanisms at the organizational level: this particular transaction sets the boundaries of the collaborative episode (Ring and Van de Ven, 1994). At the project level, negotiation supports decision making though shared understanding to evolve the problem domain (Carlile, 2004). At both levels, negotiation involves human interaction (Turk, 2000) and the ‘spending’ or ‘acquisition’ of capital, be it social, economic, cultural or symbolic (Bourdieu, 1977). In parallel, negotiation is mediated through power and trust, which relate back to expertise and knowledge (Black, Carlile and Repenning, 2004). With regards to novel project delivery approaches, past work has identified their potential in supporting negotiation works (Alin, Iorio and Taylor, 2013). Conversely, the implementation of these novel approaches requires significant negotiation between actors, ‘mutual adjustment’ ((Taylor, 2007b)– speaking of firms) and involves negotiations chiefly around expectations (for example in BIM - how will the model be used; who will do what in the model -(Computer Integrated Construction Research Group, 2010)), interests (who benefits from the implementation –(Schweber and Harty, 2010)) and capabilities (to what extent can these expectations be met -(Succar, Sher and Williams, 2013))This again highlights the duality between the product and the process.

Sensemaking involves identity, experience and interpretation, an agent's mental world, and its enactment in every day practice (Weick, 1995). The building project will trigger and frame sensemaking by providing social cues and feedback which respectively prime and edit the process (Weber and Glynn, 2006). This is crucial as it not only structures the collaborative episode but more importantly it conditions it and lays the ground work for other collaborative processes. Understanding and learning are achieved through the act of translating and transforming knowledge by bridging the boundary between semantic and pragmatic knowledge (Carlile, 2004). These actions occur between heterogeneous knowledge domains, spurred by concurrent information gathering activities and sensemaking activities (Lindgren et al. 2008).

Lastly, problem solving and decision making are the most complex collaborative processes in that they subsume the actions, interactions and transactions mentioned above. They are also the most important in that they are they are guarantor of the project's outcomes. The relationship between both is direct: the act of framing a problem implies that a decision has been made (Coyne, 2005) They also relate back to goal formation, a continuous process which further structures the collaborative episode (Franco, 2007; Tryggestad, Georg and Hernes, 2010). Novel project delivery approaches aim to facilitate and optimize problem solving and decision-making. For instance, BIM allows the development of multiple scenarios to better inform improve transparency in the decision-making process (Schade, Olofsson and Schreyer, 2011). Integrated practices ensure that the right decisions are being made with a product's lifecycle in mind and to optimize the whole rather than its parts (BC Green Building Roundtable, 2007)

3.4.3 Artifacts

The artifactual element of the collaboration system is experienced through the tools, instruments, scripts and objects that are deployed within the TPO. For individuals to interact and shape their environment, a medium that allows conveyance of knowledge through representation is necessary (Bojut and Blanco, 2003, Simon, 1996). Boundary objects (Star and Griesemer, 1989), intermediary objects (Boujut and Blanco, 2003; Vinck and Jeantet, 1995), epistemic objects (Styhre and Gluch, 2010) or collective objects (Zager, 2002) "provide the motives and drive for collaboration to emerge; they allow participants to work across different types of boundaries; and they constitute the fundamental infrastructure of the activity." (Nicolini, Mengis and Swan, 2012, p.3). They exist as a 'translation vehicle between heterogeneous (social) worlds' (Trompette and Vinck, 2009, p.I).These objects materialize action and act at different levels by either providing the infrastructure for collaboration, facilitating work across different types of boundaries, or prompting, sustaining and motivating cross-disciplinary collaboration, reinforcing a 'collective obligation' towards reaching a goal (Nicolini, Mengis and Swan, 2012). Building projects are notoriously document-centric (Isikdag and Underwood 2009). These documents constitute artifacts which are used to foster understanding and shared meaning, support cross-boundary negotiation and learning by structuring knowledge and the negotiation space (Alin, Iorio and Taylor, 2013; Boujut and Blanco, 2003; Forgues, Koskela and Lejeune, 2009). These boundary objects exist in both active and passive forms. In their passive form, they serve as a 'backdrop' to human action and are mobilized during interaction. In their active form, they 'constrain and shape social action' and remain mutable (Bresnen and Harty, 2010, p.551). This speaks to the structuring effects of artifacts in practice.

The technological shift in the AECO industry is being felt in the increasing presence of 'interactive workspaces' (Fruchter, 1999; Leicht, Messner and Anumba, 2009), 'virtual worlds' (Maher et al., 2005; Rosenman et al., 2007) and other immersive infrastructures which support collaboration through technology. These technological objects are modifying and restructuring AECO practitioners 'Object worlds' which are defined by (Berente, Baxter and Lyytinen, 2010, p.574) who expand on Bucarrelli's seminal concept and speaking of the design process, as:

> […] made up of physical artifacts, tools and instruments, as well as abstract formalisms, design principles, methods and associated practices. Object worlds form a fixed background in the sense that they permeate and support all design activity, but while a designer learns, object worlds 'are given new expression

> and show a different nuance from one design task to another" (Berente, Baxter and Lyytinen, 2010, p.574)

Traditionally, the various object worlds in the AECO industry remain fragmented and heterogeneous. The emergence of BIM, IDP and IPD, however support the congruence of the various object worlds found in a TPO. With regards to BIM, the multi-disciplinary model, contingent on aforementioned structural and procedural considerations, is a resource which supports the common information and knowledge space (Eastman et al., 2011)while bounding the negotiation and commitment space (Alin, Iorio and Taylor, 2013). The BIM is both passive, in that it is structuring, and active, in that it is constantly shapes knowledge and influences goals (Tryggestad, Georg and Hernes, 2010). In a period of transition from traditional to BIM enabled project delivery, practices surrounding the use of BIM and project documentation are seen as hybrid (Whyte, 2011; Whyte and Lobo, 2010) in that they are supported both by the digital and physical 3D artifacts and their 2D representations.

The role of BIM tools (software, interface, etc.) as boundary objects is also complex. For instance, with the advent of cloud computing the barriers which hinder the deployment of BIM tools and the model itself as a boundary object are shifting away from being purely technical and highlighting organizational and contextual barriers (Redmond et al., 2012). Questions of interoperability, for instance, are still prevalent, but the technical aspects are giving way to more business and social aspects. In this regard, BIM has yet to really achieve the status of true boundary object (Dossick and Neff, 2011; Neff, Fiore-Silfvast and Dossick, 2010; Whyte, 2013; Whyte and Harty, 2012) due to issues such as limited interpretative flexibility of the model: "As a visualization tool, BIM models have less interpretive flexibility across boundaries, drawing organizational divisions and knowledge distinctions even more clearly" (Neff, Fiore-Silfvast and Dossick, 2010, p. 569) . BIM exacerbates issues such as embedded practices or ingrained knowledge, rather than facilitating their mediation. BIM as an artifact is supposed to span inter-disciplinary (knowledge and practice) boundaries but so far has not due to the fact that BIM renders the interpretation of the building too explicit and 'over determined' due, in part, to technical choices. This over determination has consequences in all aspects of the building project, such as not allowing for interpretative flexibility in the design coordination process (Dossick and Neff, 2011).

3.4.4 Agents

The agentic element of the collaboration system is experienced through the intentions, expectations, requirements, incentives and capabilities of the individual agents making up the TPO. In its most basic form, agency 'concerns events of which an individual is the perpetrator' (Giddens, 1984, p.9). It is characterized by intentionality, forethought, self-regulation and self-reactiveness (Bandura, 2001). Agents "cause events to happen in their vicinity' (Virkkunen, 2006, p.63). Agency is further defined as

> […] the temporally constructed engagement by actors of different structural environments—the temporal- relational contexts of action—which, through the interplay of habit, imagination, and judgment, both reproduces and transforms those structures in interactive response to the problems posed by changing historical situations (Emirbayer and Mische, 1998, p.970)

This definition introduces collectivity and structure to the notion of agency. Collective agency is the shared belief in a group of individuals' collective power to produce desired results (Bandura, 2000).

There exists a long tradition of explaining motivation in agents such as Vroom's expectancy theory (Vroom, 1964), Locke's goal-setting theory (Locke and Latham, 1994) and Bandura's notion of efficacy (Bandura, 2000), amongst many others. These theories articulate intentions, expectations and incentives to justify how and why individuals act in a collective setting. These entities are manageable and attributable to specific tasks or roles, namely through leadership (Bell and Kozlowski, 2002; DeChurch and Marks, 2006). Capabilities and formal requirements also act to influence agency and more specifically practice (Parmigiani and Howard-Grenville, 2011). Practice is characterized by the recursive relationship between the shaping and institutionalization of organizational and social patterns and an accumulation of knowledge and expertise (Bourdieu, 1977; Giddens, 1984; Orlikowski, 1992). This accumulation of knowledge and expertise confers power and influence; the amount of embodied knowledge and expertise confers responsibility and control. An individual's expertise is legitimated through credentials and titles, serving as proxies for 'institutionally legitimated accumulations of knowledge and power' (Black et al. 2004, p.549-550). Furthermore, an individual's relative position in a TPO, his power, status, influence and disposition, will be not only based on accumulated knowledge, his expertise, but also through behavioral traits such as character, personality, and attitude (Pryke and Smyth, 2006, p. 24) This acts to constrain the possible outcomes of the collaborative episode, due to the presence of specific individuals in positions of power, making product and process related decisions, which in turn will influence who accumulates expertise (capabilities) and what outcomes are possible in future interactions.

With regards to novel project delivery approaches in the AECO industry, the alignment between these five entities have been posited to form causal loops which inform action at the agentic level (Poirier, Forgues and Staub-French, 2014). This is supported in other works such as (Taylor and Bernstein, 2009), who develop the notion of practice paradigms in the use of BIM within project networks. These practice paradigms, an embodiment of specific requirements, expectations and intentions towards the use of, evolve through the development of certain capabilities. Merschbrock (2012) further find that lack of formal power and incentives as well as a formal interaction requirements, hinder the full use of BIM in a TPO. In this light, lack of capabilities and incentives further act to constrain and dictate how requirements are formulated and expectations met in the context of BIM (Succar, Sher and Williams, 2013).

3.4.5 Outcomes

The outcomes of collaboration are three-fold: value, performance and knowledge. Desirable outcomes of collaboration are project success, learning and innovation and commitment to future collaboration (Dietrich et al., 2010). Project success is a function of the value generated through the collaborative episode, product success, and its performance, process success. Both concepts are closely related, however value is a subjective concept (De Chernatony, Harris and

Dall'Olmo Riley, 2000) whereas performance is seen as being more tangible through operationalization of its measures. Taken together, value and performance speak to the attainment of goals and their optimization in an efficient manner over the course of the building project.

The first two outcomes – value and performance – are closely tied and relate both to the product of the building project and its process. Value has been defined as "[…] a customer's perceived preference for and evaluation of those product attributes, attribute performances, and consequences arising from use that facilitate (or block) achieving the customer's goal and purposes in use situation" (Woodruff, 1997, p.142). In the AECO industry, value has been defined as a relationship between function, time, cost and quality (Kelly, Male and Graham, 2014), which tie it closely to performance (Atkinson, 1999).The dimensions of performance measurement are multiple. Traditionally in the AECO industry, performance is related to project management outcomes, the aforementioned indicators minus function. Tracking these indicators are seen as critical in order to compel progress in the industry (Bassioni, Price and Hassan, 2004). Measures developed in the UK and in the US also include satisfaction of both product and process as well as profitability among others (Center for Construction Innovation, 2015; Construction Industry Institute, 2013) Additional key performance indicators have been discussed such as measures of innovation and sustainability, which relate back to value generation (Rankin et al., 2008) With the emergence of innovative project delivery approaches the measurement and evaluation of their impact and performance is receiving increasing attention. Work has focused on different areas such as the impact of BIM and IPD at the project level (Ilozor and Kelly, 2012; Khanzode, Fischer and Reed, 2008) and organizational level (Love et al., 2013; Mom and Hsieh, 2012), and measuring return on investment (ROI) (Barlish and Sullivan, 2012; Giel and Issa, 2011). The issue with these measures is that most are lagging (Kagioglou, Cooper and Aouad, 2001) and act as proxies for the assessment of collaboration. Measures, such as capabilities and maturity (Succar, Sher and Williams, 2013; Taylor and Bernstein, 2009; Zutshi, Grilo and Jardim-Goncalves, 2012) as well as the quality of collaboration which is determined through communication, coordination, mutual support, aligned efforts, and cohesion (Hoegl and Gemuenden, 2001) offer a more 'predictive' or leading view on the effectiveness of collaboration. However, these measures still require considerable resources to implement and use efficiently and adequately. They also require considerable knowledge to interpret and act upon correctly.

The third outcome, knowledge (i.e. the application and interpretation of data and information (Ackoff, 1989)), enables and supports both performance and value generation. Learning and innovation, as desirable outcomes of collaboration, involve the collective generation, capture, adaptation and reuse of knowledge, which is subject to well-known and documented difficulties, such as the tacit-explicit divide (Nonaka and Takeuchi, 1995). Knowledge evolves and learning happens through collaboration; the learning process and the capture and integration of knowledge in turn supports innovation (Dietrich et al., 2010). This innovation process is defined as 'the development and implementation of new ideas by people who over time engage in transactions with others within an institutional context' (Van de Ven, 1986, p 591). The institutional context here being the building project, innovation and collaboration become enmeshed, both feeding into and supporting each other in a recursive process. Innovation as an outcome has structuring capabilities. It represents a tension between novelty and habit, stability and emergence. In the network view, innovation happens at the boundaries between knowledge domains, involving the novelty of a situation and consisting in a struggle between embedded knowledge and adaptation to the interests and problem domain of others (Carlile, 2004). Lastly, commitment to future collaboration can be seen as a positive outcome of collaboration. Indeed, it is expected that successful collaboration, translating to value and good performance, will lead to future collaboration. However, the notorious lack of long-term, strategic thinking, exemplified by the lowest bidder mentality, doesn't guarantee this particular outcome. Although, practices such as partnering and alliancing (Bresnen and Marshall, 2000; Ingirige and Sexton, 2006) and other relational contracting approaches (Pryke and Smyth, 2012) have emerged over the past few decades to overcome this particular shortcoming of the industry. These practices and approaches to project delivery act as structuring elements in the collaborative episode, thus reinforcing the outcome/input model of recurring collaboration in the AECO industry, similarly to the innovation process.

3.5 Developing an expertise in collaboration

So far, the concept of collaboration has been framed within a process view of the building project. The collaboration system and its outcomes has been developed through a critical realist lens, uncovering four elements and their respective entities. In addition, the impact of the passage to novel project delivery approaches on each of these elements has been discussed, thus addressing the first part of the objectives of this paper. The latter part of the objectives of this paper, to discuss expertise in collaboration, are addressed in this section which also attempts answers to the questions of whether an expertise in collaboration exists independently from disciplinary practice and expertise. If it does exist independently, how would an expertise in collaboration be defined? And how would the current trend in innovative project delivery approaches impact this collaborative expertise? Lastly, how could this expertise in collaboration be assessed and taught?

The stratified view of the building project, more specifically the collaboration system, supported through a critical realist perspective uncovers a domain of expertise residing in the realm of the empirical, which is consistent with experiential conditions attributed to this particular realm (Easton, 2010). Figure 3.3 illustrates the domain of expertise within the stratified view of the building project. This corresponds to the entities discussed in the previous section which support the collaboration system. From this perspective several competencies and specific areas of expertise are identified which can be developed to support collaborative practices in the AECO industry. In other words, each foundational element intimates a field of expertise and capability which could be developed to constitute an overarching expertise in collaboration. For instance, structural expertise would entail developing capabilities in team formation (boundary identification and setting), goal setting and relationship building and management; relationship management already being a recognized field of expertise (Pryke and Smyth, 2006). Process expertise would entail capabilities in negotiation, translation and knowledge capture as well as in communication; being a “good communicator”. Agentic expertise would entail relational capabilities based around motivating and supporting collaborative behaviors and relationships through leadership. More specifically it would entail being capable of aligning the various intentions, expectations, requirements, incentives and capabilities found within a TPO. Artifactual expertise, i.e. expertise in artifacts such as BIM, entails capabilities in building and using the artifact in a manner that supports its reuse by others. It also entails capabilities in interpreting and leveraging artifacts developed by others. Lastly, expertise relating to outcomes would entail capabilities in identifying value, measuring performance and capturing knowledge.

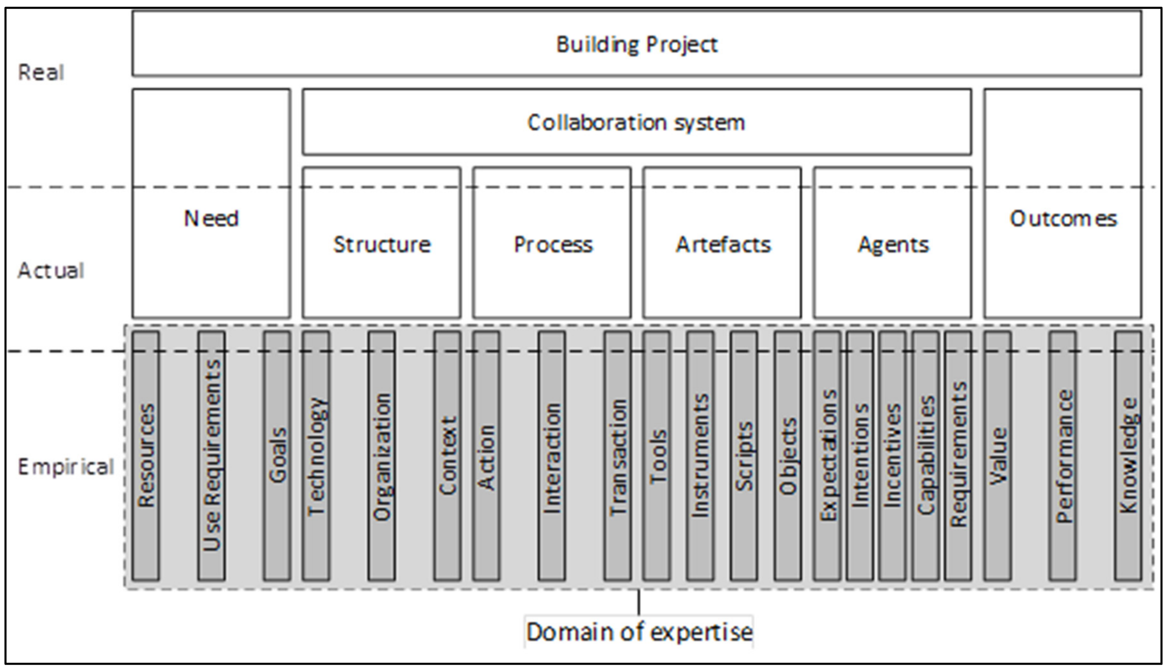

Figure 3.3 Domain of expertise in building projects

Many of the fields of expertise mentioned exist already in their own right. For instance, value management (VM) and value engineering (VE) have received significant attention in the AECO industry, becoming an area of expertise in themselves (Green, 1994; Kelly, Male and Graham, 2014; Male et al., 2007). Value Management "derives its power from being a team-based, process driven methodology using function analysis to examine and deliver a product, service or project at optimum whole life performance and cost without detriment to quality." (Male et al., 2007, p.108) It is a "structured process of dialogue and debate among a team of designers and decision makers […]" (Green, 1994 p.51). Furthermore, the areas of expertise developed within the stratified view of the building project (Figure 3.3), structural, process and relational (agentic), have been identified as areas of value management capability (Maes, De

Haes and Van Grembergen, 2015). However, they have been applied at the enterprise level to enable decision-making.

Knowledge management (KM) has also emerged as a field of expertise, aimed at overcoming the challenge of capturing and diffusing knowledge, in essence mobilizing the intangible knowledge assets within an organization (Egbu and Botterill, 2002) and provide strategies and tools which will assist in retaining organizational memory and knowledge (Al-Ghassani et al., 2002; Kamara et al., 2002; Rezgui, Hopfe and Vorakulpipat, 2010; Styhre and Gluch, 2010). KM is "central to product and process innovation and improvement, to executive decision-making, and to organizational adaptation and renewal" (Earl, 2001, p. 215). It is also central to client satisfaction and improved business performance in the AECO industry (Kamara, Anumba and Carrillo, 2002), supporting valuable and performing outcomes.

The domain of project management and its accompanying body of knowledge (PMBoK, 2000) are concerned with most of the areas described above. However, the adequacy of current project management practices have been questioned (Koskela and Howell, 2002). For one, the relevance of predetermined success criteria has been questioned due to the unfolding and emergent nature of building projects, which further raises questions of control and management mechanisms as well as goal achievement (Cicmil and Marshall, 2005). Calls for adaptive project management, speaking to a novel kind of expertise, have been heard in response to this (Tyggestad et al. 2010)

Expertise in collaboration has been suggested through emerging domains such as 'collaboration engineering' (Briggs, Vreede and Jr, 2003; Kolfschoten et al., 2010), which aims to design and implement "repeatable collaboration processes for recurring high-value collaborative tasks that are executed by practitioners using facilitation techniques and technology" (Kolfschoten et al., 2006, p.612). This approach assumes work practices which are predictable, repeatable and can be designed, an acceptance of intentionally-designed work practices by practitioners and the execution of these work practices in an effective manner (Kolfschoten et al., 2010, p.302). In the AECO industry, certain repeatable and recurring work practices exist, however there are questions about what constitutes high-value. True expertise in collaboration would lie in identifying value and the processes which generate it – otherwise known as value management. Thus, an expertise in collaboration in the AECO industry would lie less in defining protocols and scripts for collaboration which are technology dependent, as these are unstable within and between building projects, becoming even more so in light of the recent aforementioned innovations which are inducing systemic change, and lie instead in core capabilities such as being able to trace value-streams and information flows, which are more stable and recurrent.

A call has been made for new roles, responsibilities and capabilities in light of the recent trends in the AECO industry. For instance the role of Project Information Officer, responsible for the management and integration of information in the new project delivery context has been suggested (Froese, 2004). This role has been formalized in the UK as Information Manager (Construction Industry Council, 2013). The role of Organizational Architect has been discussed to play more of a strategic role in implementing and managing these novel approaches (Forgues and Lejeune, 2013). The overarching intent is to develop an expertise which can support both the collaboration system and the production system. This role should be accompanied with sufficient power to influence and modify courses of action and practices deemed inadequate.

3.6 Conclusions

The subject of collaboration, its characteristics and its outcomes is vast, complex and multifarious. Applying various theoretical, epistemological or ontological lenses will wield differing perspectives on the framing of the concept of collaboration, however a preliminary overview of these different perspectives wields consistency as to its foundational elements. The systems view frames the elements of collaboration systems: the structure, processes, artifacts, agents and their interdependencies. Applying a critical realist lens to this systems view allows stratification of these elements to uncover their underlying entities. In this sense, expertise in collaboration could be acquired in structuring collaborative environments, defining and supporting the processes through which collaboration is carried-out, developing and using artifacts to support collaboration and supervising or supporting agents within the TPO to facilitate their integration and interaction with the collaborative system. Expertise could also be developed in the assessment and evaluation of outcomes of collaboration, namely identification, recognition and management of value, performance measurement and knowledge management. Many of these fields of expertise have been developed, such as the fields of value management and knowledge management. Others have been developed to a lesser extent and carry no clear definition. They are subsumed within disciplinary roles and responsibilities which often leads to lack of development.

From a critical realist perspective, it is important to note that collaboration and the collaboration system are not reducible to these elements and entities, nor conversely does their aggregation imply collaboration: their summation or their reduction does not imply that intervention, in this case particular expertise, on a particular element or entity will wield systemic results. For instance, the focused restructuring of collaboration systems in light of novel project delivery approaches has been deemed insufficient by some to overcome the inherent paradox and complexity of building projects. Indeed, structural change, or 'renewal initiatives' through industrialization, organizational renewal, integration, and re-engineering, among others, have had modest impact so far in the industry due to an apparent neglect of the systemic view of production and consequently, collaboration (Koskela, 2003). This highlights issues with the "assumptions made about the linearity of the unfolding of human action, time–space finality, rational decision-making before the structural intervention […], and the nature of power relationships […]" (Cicmil and Marshall, 2005, p.532). This speaks to the fact that the context of the building project and the TPO is by no means static, a notion that is supported by many authors, and is in fact emergent and dynamic, subject to cycles of order and disorder, which further structure the context of collaboration (Kaspary, 2014); Elements of control, intervention and prediction getting in the way of innovation, creativity and knowledge generation (Cicmil and Marshall, 2005). This speaks to the need for agility, or "learning to learn", in light of the rapidly evolving innovative approaches to project delivery, which will become an asset in this new knowledge economy, an expertise in its own. In this sense, the stratified systems view laid out in this paper uncovers a domain of expertise which can act in an emergent manner to influence events and mechanisms in the realm of the actual and real. It is argued that this is where real expertise lies: in the capability to envision and act upon certain entities or elements in a way which produces lasting results throughout the system and in this case, throughout the building project.

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CHAPTER 4

EMBEDDED CONTEXTS OF INNOVATION: BIM ADOPTION AND IMPLEMENTATION FOR A SPECIALTY CONTRACTING SME

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4.1 Abstract

Purpose - The radical innovation process behind the adoption and implementation of building information modeling (BIM) for a specialty contracting small or medium enterprise (SME) was studied. This paper offers two distinct perspectives on BIM adoption and implementation, which are underrepresented in the current literature: the SME perspective and the specialty contractor perspective. It also attempts to bridge the gap between the growing literature on BIM adoption and implementation and the established literature on innovation by developing the notion of embedded contexts in the innovation process.

Design/methodology/approach - A mixed-method, longitudinal case study approach was employed in this research project to study the evolution of the innovation process and its impact on the Organization over time. The objectives of this research were to investigate and document the different factors mediating the BIM adoption and implementation process for the Organization across various contexts, the mechanisms put in place to facilitate this process, and the perceived impact within the Organization.

Findings - The initial transition to BIM represented a radical innovation for the Organization. Subsequently, a series of incremental innovations took place to further advance the Organization's BIM capabilities. This innovation process is influenced by different layers of embedded contextual factors, which can be mitigated by, among others, a clear strategic approach towards the innovation process. Furthermore, despite a limited sphere of influence, specialty contractors can leverage BIM within their own supply chain to reap significant benefits.

Originality/value - This paper offers an in-depth study of radical innovation within a specialty contracting SME. This study discusses the influence of four embedded contexts on innovation for a specialty contracting SME: (a) the industry context; (b) the institutional context; (c) the Organizational context; and (d) the project context. It also offers insight into the factors, mechanisms and their impact on the innovation process.

4.2 Introduction

Building information modeling (BIM) has been recognised by the Architecture, Engineering and Construction (AEC) industry as having significant potential to positively impact project delivery and outcome. However, both researchers and practitioners alike agree that the adoption and implementation of BIM is a challenging endeavor. Among others, the BIM adoption and implementation process is highly contextual and discipline specific. The importance of this perspective lies in the divergence of 'social worlds' (Taylor, 2007b) within the AEC supply chain. While past research on Organizational innovation has documented the importance of context and environment in the innovation process, this dimension has largely been ignored in the BIM adoption and implementation literature.

This study investigates the contextual nature of innovation through the study of BIM adoption and implementation for a specific industry segment: a specialty contracting SME working in the mechanical contracting field. The motivation behind this study lies in the scarcity of research in this area, particularly within small or medium enterprises (SME). This particular area is important due to the considerable amount of SMEs that form the AEC industry's supply chain. For example, 99.0% of the Canadian construction industry is made up of small (between 5 and 99 employees – 38.5%) and micro (less than 5 employees – 60.5%) businesses (Industry Canada, 2014). Furthermore, the majority of these SMEs are found to not be implementing innovations within their Organizations and invest little in research & development (Statistics Canada, 2011). The need to focus particular attention on SMEs and their capacity to innovate, in this case to adopt and implement BIM, is thus significant. In parallel, the specialty contractor's perspective is of interest due to the potential for significant productivity gains from the use and deployment of BIM in the field, although its adoption and implementation has not yet been fully realised (Boktor, Hanna and Menassa, 2013; Isaac and Navon, 2013; McGraw-Hill, 2009; 2012).

The findings of this study reveal key factors, mechanisms and impacts, developed across four distinct yet embedded contexts: (a) the industry context; (b) the institutional context; (c) the Organizational context; and (d) the project context. The findings stem from the longitudinal case study of a mechanical contracting SME adopting and implementing BIM. The objectives of the research were to investigate and document the various factors mediating the Organization's BIM adoption and implementation process, the mechanisms put in place to facilitate this process and assess its perceived impacts. The first key finding that emerged was that the transition to BIM was a radical innovation for the mechanical contracting SME under study. Once the infrastructure for BIM was in place, a series of incremental innovations took place to further develop the Organization's BIM capabilities. The second key finding that emerged was that the specialty contractor studied had very limited influence on the deployment of BIM throughout a project's lifecycle. While Owners, General Contractors and Architects are in a position to drive BIM at the project level, specialty contractors are dependent on upstream efforts to maximise their work, which limits the opportunities for productivity gains in the field, for the generation of knowledge and for the leveraging of project experience to develop internal BIM capabilities. In contrast, a clear Organizational vision and strategy, combined with a structured approach to the BIM adoption and implementation process was shown to result in positive gains for the Organization, regardless of its external contexts.

4.3 Innovation in the AEC industry

The context of innovation, its process and its outcome has been the subject of much research over the past three decades in the AEC industry. The innovation process has been defined as 'the development and implementation of new ideas by people who over time engage in transactions with others within an institutional context.' (Van de Ven, 1986, p 591). For innovation to occur, the confluence of three elements is required: the generation of an idea (stemming from a need), the opportunity and its diffusion/adoption (Gambatese and Hallowell, 2011; Rogers, 1962; Winch, 1998). Typically innovation types fall into one of the following categories: Technological innovation, encompassing both product and process innovation - new product offerings or product improvements and the creation or improvement of methods of production, service or administrative operations; services innovation - the development of core competencies and products; and Organizational innovation - the development of management initiatives (Oke, Burke and Myers, 2007). Innovation stems from, among others, an Organization's desire to gain competitive advantage, reduce costs, enhance quality, technological opportunity, or institutional requirements. (Mitropoulos and Tatum, 2000; Pries and Janszen, 1995; Rankin and Luther, 2006).

Various models of innovation have been developed for the AEC industry. Slaughter (1998) presents a seminal model of innovation, relating degrees of innovation - incremental to radical innovation, its adoption and its impact. Winch (1998) presents a model of construction innovation, which relates four processes (adoption, implementation, learning and problem solving) across three different environments (external, firm and project). Furthermore, viewing construction as a complex systems industry, the author adapts Miller *et al.* (1995) structural context of innovation management for the construction industry. The innovation superstructure (clients, regulators and professional institutions), the systems integrators (architects, engineers and general contractors) and the innovation infrastructure (trade contractors, specialist consultants and component suppliers) are distinguished. An interesting feature of this model is the apparently secondary or supporting role that trade contractors have in the overall innovation process. This model is further investigated by Rutten, Dorée and Halman (2009), in particular the role of systems integrators in coordinating inter-organizational innovation. This view however is limited to success factors supporting various types of innovation and very little mention of environmental or contextual factors are made.

The body of work of Sexton and Barrett (2003a, 2003b, 2006) has contributed multiple perspectives on the innovation process for SMEs in the construction industry. They propose three models of innovation: a generic model, a 'modes of innovation' model and an Organizational model of innovation. These three models have in common the influence of external environment on innovation process and outcome within SMEs. The authors go on to find that, typically smaller Organizations innovate in an ad-hoc fashion by 'learning on the job' and are motivated by a willingness to survive, which underlies a general lack of strategic vision. They establish a correlation between the size of the network within which SMEs evolve, which dictate exposure to innovative technologies, and willingness to innovate. The authors also find that SMEs are more willing to adopt and implement technologies that have a proven track record and with which they can see immediate benefit, rather than radical technology shifts, such as BIM, which are deemed more risky. This speaks to the lack of strategic approach to innovation, which is symptomatic of SMEs in the AEC industry.

A constant factor underlying these models is the highly contextual nature of innovation (Stewart, Mohamed and M., 2004). For instance, Pries and Janszen (1995) and Mitropoulos and Tatum (2000) draw a clear relationship between innovation, the industry context, the Organizational context and the outcome of innovation. Harty (2005, 2008) adopts a distributed and multi-centered view to innovation across project networks, as opposed to a singular, uniformly driven process view. Accordingly, this enables recognition of the 'complexity of the contexts of construction', orients 'towards inclusiveness rather than simplification' (Harty, 2005, p. 521) and pushes to focus on the process of interactions between innovation and current practice. Taylor and Levitt (2007) look into the alignment of innovation and its implementation within project networks. The authors look into alignments between Organizational, technological and contextual factors, which mediate the rate of innovation deployment. They highlight the mediating force of the geographic and market context on innovation use and diffusion. Bossink (2004) identified a series of Innovation drivers and managerial actions driving these innovations. The author also identified three levels at which innovation drivers are active within the AEC industry: the Organizational level (intrafirm), the project network level (interfirm) and the industry level (transfirm). To summarise, the importance of the environment and context within which innovation occurs is paramount in influencing the course of innovation within an Organization. BIM is one such innovation that is seen as highly context dependent.

4.4 Building Information Modeling

BIM is seen by many as being a disruptive innovation, which is bringing about the reconfiguration of practices in the AEC industry (Crotty, 2011; Eastman et al., 2011). Past research on BIM has looked into the factors affecting BIM adoption and implementation, the mechanisms driving the process and its impact from a variety of perspectives. These factors and mechanisms and their impact have been enquired into at various levels (industry (Becerik-Gerber and Rice, 2010), Organization (Kaner *et al.*, 2008), project (Bryde, Broquetas and Volm, 2013; Fox and Hietanen, 2007)), at various stages in the project lifecycle (design (Manning and Messner, 2008), construction (Akinci and Kiziltas, 2010), operation (Javier *et al.*, 2011)) and for different stakeholders in the supply chain(owners (Giel, Issa and Mayo, 2012), designers (Arayici *et al.*, 2011), contractors(Ku and Taiebat, 2011)). Eastman *et al.* (2011) and Smith and Tardif (2009) offer a comprehensive overview of BIM adoption and implementation different stakeholders by identifying specific factors affecting the adoption and implementation process and their respective benefits. In essence, a lot of ground has been covered in the literature concerning BIM adoption and implementation. However, certain trends emerge when considering this growing body of knowledge such as: the attempt to decontextualize and generalise findings from research projects, the underrepresentation of SMEs and their perspective on BIM adoption and implementation and the focus on BIM from the owners, designers and general contractor’s viewpoint and finally, the specialty contractor perspective is sparse, in particular at the Organizational level.

Past research has identified means and methods for implementing BIM at the project level. Dossick and Neff (2010) performed an ethnographic study of the MEP coordination process for two projects and identified factors which hinder the close collaboration between team members working in a BIM environment, notably Organizational divisions and competing obligations of individual project team members. Staub-French and Khanzode (2007) provide a detailed approach to implementing both 3D and 4D modeling and coordination in a project network from a technological, Organizational and procedural perspective. They go on to discuss the impact of this implementation on project performance and relate the benefits that come from the implementation of BIM in a project setting. Khanzode (2010) presents an Integrated, Virtual Design and Construction and Lean (IVL) method for coordination of MEP systems. The results of four case studies where either Virtual Design and Construction (VDC) or Lean methods (or a combination of both) was implemented for MEP coordination are presented. The author provides empirical evidence of the benefits in increased productivity and reduction of waste for the MEP contractors at the project level. However, little is said about the implications of the adoption and implementation process at the Organizational level.

A recent study by Boktor, Hanna and Menassa (2013) reports that nearly 49% of mechanical contractors in the US are not using BIM. The authors reveal several key factors of BIM adoption for mechanical contractors: There is a correlation between a firm's size and it's usage of BIM, between a project's size and the amount of staff dedicated to BIM as well as the number of years of experience using BIM and the Organization's expertise. In addition, the cost of implementing BIM varies quite significantly, with the average at 1-2% of total project costs (no indication is given as to what is included in the calculations of these costs). Moreover, they note the emergence of two main focus areas for investments: the creation of in-house BIM procedures and the marketing of BIM to customers. This study reveals that there are great expectations within the MEP field concerning the potential benefits of BIM and there is a desire to get involved with BIM in the near future. However, there lacks insight into these specialty contracting SMEs in light of BIM's disruptive nature and the radical transformations that are required to successfully go about adopting and implementing BIM. This study aims to address this gap.

4.5 Research methodology

The objective of this research was to investigate the BIM adoption and implementation process within a specialty contracting SME working in the mechanical contracting field (the Organization). The aim was to uncover and document the factors mediating the BIM adoption and implementation process, the mechanisms that were put in place to facilitate this process and to assess the perceived impact from the Organization's perspective. A mixed-method, longitudinal case study approach, rooted in the interpretivist paradigm, was employed to study the BIM adoption and implementation process and its impact on the Organization over time (Stake, 1995; 2006). This particular research approach was adopted due to its 'inductive development of patterns of meaning' and an emic approach to the understanding of phenomena within the cases under study (Avenier, 2010; Creswell, 2003). This provided the research team with an in-depth viewpoint and allowed them to uncover the various phenomenon brought on by the transition to BIM from the perspective of the organization and its personnel. The case study took place over a period of 18 months, between April 2012 and October 2013.

The Organization studied was founded in 2004 and operates in the Vancouver, British-Colombia area. It has 50 employees and is deployed along a project-based Organizational structure across two divisions: 13 office based employees (project managers, coordinators, estimators as well as administrative staff) who form the project management team and 37 site based employees (superintendents, foremen, journeymen). Since 2004, they have completed over 50 projects ranging from $100k to $12M contract value. The research team studied both the Organization and its supply chain. Under the interpretivist paradigm, the unit of analysis is subsumed by the historical event under observation (George and Benett (2005) in (VanWynsberghe and Khan, 2008)), in this case the adoption and implementation of BIM within the Organization. The units under observation were the personnel involved with the BIM adoption and implementation process within the permanent organization (PO) and within each temporary project organizations (TPO) (Figure 4.1). These units of observation were chosen due to their proximity, involvement and relationship to the BIM adoption and implementation process. Semi-structured interviews, lasting between 30 and 90 minutes, were carried-out on two different occasions with the same personnel over the 18 month period in order to gain insight into the evolution of the adoption and implementation process. The personnel interviewed within the Organization were the president & general manager (who also acts as senior estimator), the construction manager, three project managers, the BIM manager and the principal BIM coordinator. At the project level, the client representative for project 01 (Large institutional (university) district energy project – See Table 4.1) was formally interviewed to gain insight into the client's view of the implementation of BIM by the Organization and its perceived impact on project outcome. Three themes related to BIM adoption and implementation were developed during the interviews: the technology, the Organization and the process. The interviews also touched on both the Organizational as well as the project level adoption and implementation efforts. The interviews were subsequently transcribed and coded in Nvivo (QSR International, 2013). Two coding cycles were performed during the analysis stage (Saldaña, 2013, in Miles, Huberman and Saldaña (2013)). The first cycle of coding allowed the research team to establish the emerging contexts of the adoption and the implementation process. The second cycle allowed the research team to define the various factors, mechanisms and their perceived impact across these different contexts.

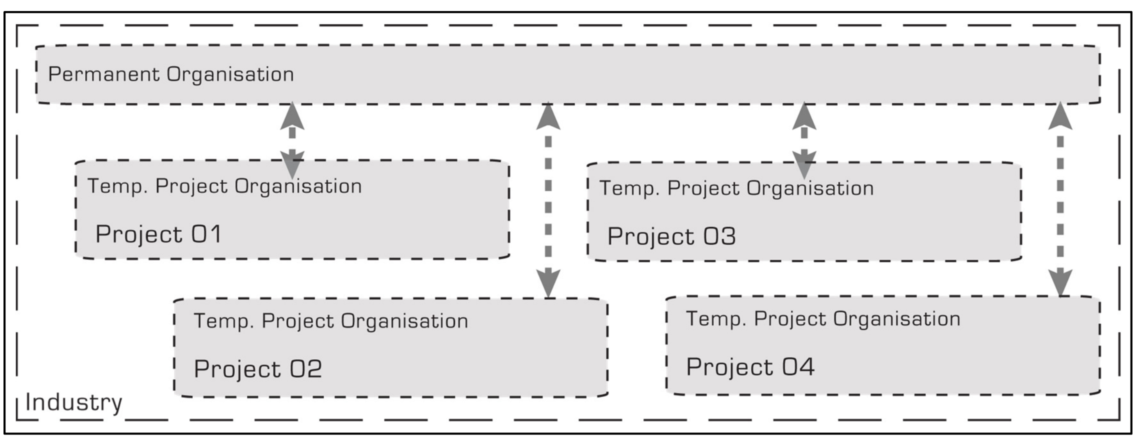

Figure 4.1 Longitudinal Case Study Research Approach

While the interviews constituted the primary source of qualitative data informing the research project, other sources such as: observation of meetings, field notes and informal discussions with project team members were collected and analysed. Furthermore, the monthly BIM steering committee meetings were attended over the course of the research project, field notes were taken during these meetings and the minutes reviewed. The research team also performed direct observation of the personnel, namely the BIM coordinator and site super intendant on a large building renovation project. Quantitative data included project documents such as Request for Information (RFI) and Change Order (CO) logs, budgets and cost reports, schedules, plans and specifications as well as models and employee timesheets.

At the project level, four projects were targeted for data collection. These embedded case studies are described in Table 4.1. The research team attempted to attend as many coordination meetings as possible for these projects, however lack of consent on the part of external project team members on certain projects limited access to these meetings on certain projects. The nature of Projects 01 and 02, mainly the 'lonely' BIM approach, meant that the use of BIM was not formalised in coordination meetings, but was deployed in a more informal fashion, transacting directly with the personnel on site.

Data analysis was approached from two perspectives. The longitudinal data collected within the Organization was analysed to uncover variations through time of the effects of the BIM adoption and implementation process within the Organization. The cross-case analysis of the multiple embedded cases then allowed literal replication across the study for elements pertaining to the project context and its influence in the BIM adoption and implementation process. Furthermore, adopting a mixed-method approach allowed the research team to triangulate data sources. For instance, claims made during the semi-structured interviews were substantiated through document review where possible (i.e. contractual requirements). Some claims were also substantiated through direct observation (i.e. relationships with external stakeholders). Asking multiple interviewees the same questions on document quality, for instance, validated claims pertaining to quality of documentation, which were further confirmed through on-site observations and document review. This was done in an effort to increase both reliability of the findings and construct (internal) validity through 'convergence of evidence' (Yin, 2014).

Table 4.1 Project context and data collection

Project	**01**	**02**	**03**	**04**
Description	Large institutional (university) district energy project	2 story wood-frame institutional (health-care) building	Medium size municipal district energy project	Renovation of a large commercial building
Data Collection	Interviewed 6 project stakeholder Project data	Interviewed 3 project stakeholders Project data	Interviewed 3 project stakeholder Field observations Project data	Interviewed 10 project stakeholders Field observations Project data
Delivery mode	DBB	DB	DBB	CM – Design Assist
Contractual BIM req.	None	None	None	Limited to visualization
BIM Use	Modeled 8 Energy Transfer Stations Clash detection with existing systems On-site prefab. from spool drawings	Modeled all building services to perform clash detection Targeted areas with most potential for conflict	Modeled 4 Energy Transfer Stations Initiated prefabrication in the shop from spool drawings	Obtained models from consultants Targeted areas with most potential for conflict
Capabilities developed	Initial modeling and 3D coordination capabilities Laser scanning On-site pre-fabrication from spool drawings	Better grasp of modeling tools Coordination with other disciplines through self-performed model Used for visualization only	Prefabrication moved off-site Developing expertise in district energy projects	Co-creation and integration of models from other sub-trades Level of development (LOD) of model for fabrication Use of tablets in the field

Project	**01**	**02**	**03**	**04**
Factors	Pilot project No previous drafting or modeling capabilities	'lonely BIM' No contractual requirements for BIM Coordination issues with design professionals Not all specialty contractors on board with BIM	Traditional DBB project so little interaction with design professionals	Need for additional qualified staff for modeling and coordination of BIM Lack of control on supply chain at the consultant level Lack of buy-in from project team on BIM
Impact	Minimized loss and rework due to upstream conflict resolution Rapid resolution of issues due to easy visualization "would have been impossible without BIM" - CM	Organization took a leadership role in the project team Input at the design stage due to DB Resolved a major headroom clearance issue before going to site	Modeling and fabrication of Energy Transfer Stations is becoming streamlined Efficiencies are being perceived in the field	Better integration of sub-trades Reduced conflicts in the field (expected) Reduced re-work (expected)

4.6 Embedded contexts of innovation: the BIM adoption and implementation process

Analysis of the case study data has highlighted four distinct yet embedded contexts mediating the BIM adoption and implementation process for the Organization studied, as illustrated in Figure 4.2. Each context exerts its own influence on this process by introducing specific factors. The Organization has developed mechanisms to counter or enhance these contextual factors according to their impact on the BIM adoption and implementation process. However, not all factors are possible to manage. The interface between the Organizational and project context is characterised by the Organizational push (i.e. opportunities, intent & incentives) and project pull of BIM (i.e. project BIM Requirements & uses, procurement & project incentives) and the Organizational pull with regards to learning and assessment. The following section describes each context in relation to the Organization, the factors inherent to that particular context and their impact on the BIM adoption and implementation process within the Organization.

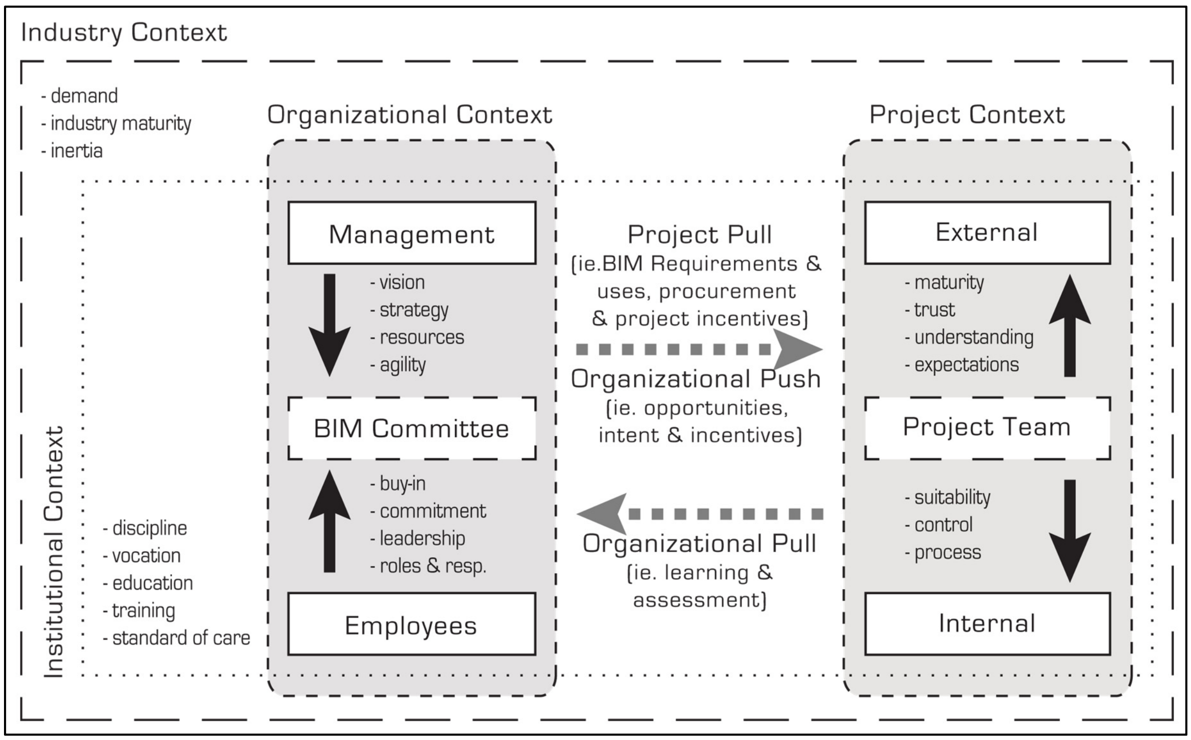

Figure 4.2 Embedded contexts of BIM adoption and implementation

4.6.1 The industry context

The industry context encompasses the geographic and market context, which includes the regulatory and legal contexts. It acts as an external force on the Organization and to a certain degree dictates the relevance of the organizational BIM adoption and implementation process. In this case, the Organization performs most of its work in the medium to large commercial and institutional sectors. In trying to establish relationships with its client base, it caters mostly to larger institutional owners, private owners and larger general contractors (GC) in the Vancouver, British-Colombia, Canada area. The influence of the industry context emerged as one of the biggest challenges to BIM implementation for the Organization.

The main industry level factors which impeded the adoption and implementation process were the lack of demand for BIM from clients (owners and general contractors alike), the low level of maturity within the market segment (mechanical engineering and contracting) and the relative stand still of the adoption of BIM over time within the industry (inertia) as discussed by the general manager:

> The biggest challenge I think has pretty much been being ‘lonely BIM’ on all the jobs we have done. We have yet to be on a fully integrated BIM project. Even ones that we were told would be [fully integrated] during tendering, have not proven to be, such a [project 04], where we are basically driving the bus. We are getting very limited support from anybody else. (General Manager (1^{st} rd))

The proximity to the US market and the lessons learned from the adoption process there as well as the ever-increasing availability of tools and training by vendors is allowing the Organization to push forward with the adoption and implementation process in light of the current limitations highlighted above. In other markets, such as the UK and Singapore, BIM is becoming mandatory. This is not the case within the Canadian context, where industry-level mechanisms have yet to be put forth. Furthermore, in Canada, there lacks this transition to BIM by large public owners seen elsewhere such as in the US and the UK. However, the Organization has noticed an increasing demand for BIM within their market segment. The impact of this has been the slow progress made in overall BIM adoption and implementation. On the other hand, this has provided a considerable opportunity for the Organization to market itself as a leader in the field:

> And so I still think it was a good decision [to adopt BIM]. We’re “leaders of the pack” so to speak and that is bringing us a lot of opportunity. So that was one of my primary motivations in jumping on the BIM band wagon, it was to get ahead of the pack, gain a competitive advantage and I think we have achieved that. (General Manager (2^{nd} rd))

4.6.2 The institutional context

The institutional context is defined by the practices, policies and procedures implemented by the various stakeholders in the AEC supply chain. It is also characterised by the various vocational backgrounds, which comprise the AEC supply chain. In this case, the Organization evolves in a distinct institutional context due to the presence of personnel, coming from various backgrounds, performing concurrent tasks within the organizational context and within the project context. As such, the institutional context intersects both the Organizational and project contexts. This is illustrated by the presence of mechanical engineers within the Organization and consulting engineers within the project team.

Several factors, originating from the institutional context, hinder the BIM adoption and implementation process within the Organization. The practice turn that is required on the mechanical consultant's part when implementing BIM marks a shift in responsibility between the mechanical engineer and the contractor. Indeed, it was observed that the mechanical contractor was either making decisions or prompting them to be made through increased involvement in the modeling process. This phenomenon was seen as being exacerbated by the project delivery mode.

In addition, many interviewees perceived the quality of the drawings obtained from the mechanical consultants as lacking. The Organization thus had to spend time translating these drawings into 3D models and spool drawings, while ensuring the constructability of the design intent:

> BIM is driving us to develop our own engineering capabilities so that we can enhance the design we are getting because they are not very buildable in a lot of cases, or there are serious issues [with the drawings we are receiving from engineers] (Project Manager, project 04 (2nd rd))

The Organization's management observed an internal struggle between office and field personnel in certain instances. This hints at diverging individual priorities within the project delivery setting, even within the same Organization. This was attributed to the increased involvement upstream in the planning process of the field personnel and thus their varying vocational and disciplinary backgrounds. This points to a need to re-evaluate the project delivery process and target the interventions and exchanges between field and office personnel:

> […] office people are just focused on one thing versus a field guy who's focused on a hundred things. They have to learn that they aren't the centre of the universe as far as the field goes. The universe revolves around the site and the guys in the crew, and [the BIM department] is accessory to that. That's a learning curve. I think the part of the timeline we have to get better at we need to get ahead of the curve more. (General Manager (2nd rd))

In terms of institutional mechanisms, the primary means through which these factors could be mitigated, identified during interviews, was education and training as well as the involvement of professional associations in developing specific codes of practice for their members suited to the emerging realities of BIM, such as those developed in the UK (SEC-NSCC, 2013) and Australia (AMCA, 2014). A firm definition of the standard of care and elements such as level of detail, coming from an institutional source, instead of being established on a project basis, could mitigate the aforementioned factors.

The impact of BIM adoption and implementation within the institutional context is the increasingly blurred boundary between the Organization's role as part of the innovation infrastructure and it's increasing role as systems integrator, as presented by Winch (1998). With the transition to BIM, the Organization is seen as evolving in both respects within the supply chain. In addition, the difficulty in finding adequate resources to further the BIM adoption and implementation process within the Organization is seen as stemming from a lack of support and direction from the educational sector.

4.6.3 The Organizational context

The Organizational context is characterised by the permanent nature of its structure. It encompasses the Organization's management, its president and general manager and its construction manager, and the employees, both field and office personnel, who perform daily project delivery tasks. Multiple Organizational factors were identified throughout the case study, most of them consistent with past research, which were determinant in guiding the BIM adoption and implementation process within the Organization. In terms of mechanisms deployed by the Organization to guide the BIM adoption and implementation process, the creation of the BIM Steering Committee as a middle ground where the employees and management could discuss and review this process was seen as key. The impact of the BIM adoption and implementation process within the Organization was mainly perceived in the changing workflows and emerging roles and responsibilities of the personnel involved with BIM.

The size of the Organization adopting and implementing an innovation has long been held as a key success factor (Acar *et al.*, 2005). While large Organizations have considerable resource, SMEs are seen as being much more agile in their capacity to innovate (Oke, Burke and Myers, 2007). The Organization under study displayed agility in navigating the market and choosing which projects to get involved in and to what extent they implemented BIM. Furthermore, as developed in past research (Lehtinen, 2012; Liu, Issa and Olbina, 2010; Won et al., 2013), leadership from the Organization's management was key in driving the adoption process, notably in creating the vision. On the other hand, leadership by key individuals amongst the employees was seen as critical in broadening the implementation process. The Organization's management also created the long-term vision by developing a road map for BIM adoption and implementation:

> That's part of the end product that we are shooting for with BIM, to become a prefabricator. So, we have seen a lot of market opportunity there, not just for our own needs, but to pre-fabricate products for other firms, particularly in the North. We have seen lot of opportunities. So probably in 5-10 years from now we could have a manufacturing business as significant as our contracting business. (General Manager (1st rd))

Buy-in principally came from the personnel's interests and enthusiasm in the potential shown by BIM. As such, natural champions emerged within the Organization. The size of the Organization also played a role in ensuring buy-in from the employees seeing as though individual efforts were more likely to be noticed by management.

The primary mechanism deployed by the Organization to facilitate the BIM adoption and implementation process was to establish a BIM steering committee. Exchanges between managers and employees were facilitated through the committee, which headed the BIM implementation effort by reviewing and selecting the appropriate software and hardware packages, managing the technology and implementing BIM in a pilot project. A substantial part of the decision making process was delegated to the personnel that would be using BIM, in essence empowering them. The venue offered by the BIM committee for management and user base to meet and exchange on issues was critical in establishing and communicating clear expectations, intentions and actions within the Organization. The findings of this study point towards a balance top-down and bottom-up approach to BIM adoption and implementation, over one approach rather than the other (Arayici *et al.*, 2011).

An equally important mechanism was the alignment of the Organization's business strategy and its BIM implementation strategy. This has long been held as a key feature in transforming an Organization's operational context (Venkatraman, 1994). In this case, the Organizational strategy considered three key elements: (1) Increase visibility and market-share, (2) Focus on design-build and design-assist type projects, and (3) increase quality and productivity through modeling and pre-fabrication. This strategy was consistent with the high level of commitment that management showed towards BIM. In light of this, consideration given to BIM on a project basis is now related purely to the scope and extent of modeling to be performed:

> We pretty much mandate it now internally on any significant projects we get, that we are going to "BIM" the mechanical rooms at a minimum. Bigger jobs, we are going to do more, as much as we can, given time and staff but by all means the mechanical rooms. But our intent and our focus is to focus on larger projects. So that would entail typically would be more opportunity for BIM. (General Manager (2^{nd} rd))

Moreover, the steering committee set clear, measurable and attainable goals relating to the BIM adoption and implementation process. These goals were incremental. The short term goals involved the actual adoption and implementation of BIM while the longer term goals involved an overall strategic approach to improving productivity in the field through increased use of technology and pre-fabrication. Two key mechanisms put in place to ensure that these goals be attained were: the allocation of appropriate resources and proper investment in technology, which are seen as key to a successful adoption and implementation process (Won *et al.*, 2013). The training and hiring of additional personnel is also targeted to ensure success. One of the objectives is to train all project coordinators in BIM. However, this is being done on an ad-hoc basis due to availability of personnel and awarding of BIM projects. While this is seen as a key element in ensuring continuity, it is also seen as a challenge:

> We recently (2013) hired a second BIM coordinator, they are harder to find and it's a challenge. Our volume keeps going up, it keeps going up dramatically faster. So we try to keep "irons in the fire", and word is out there we are looking for good BIM people and good project people as well. (General Manager (2nd rd))

The Organization educated and informed their field personnel on the opportunities presented by BIM and its impact on their work. This was done in an effort to garner enthusiasm for BIM across the Organization, and not confine it to the office. Another issue that emerged was that performance assessment and return on investment of BIM are key considerations for the Organization. Isolating the impact of BIM is extremely challenging due to the quantity of factors that influences the project delivery process. BIM plays only a limited part in the overall process. Developing a rigorous and continuous tracking mechanism is a challenge for an SME, as this represents a process, which is as difficult as BIM adoption itself. For the moment, the Organization is motivating the adoption and implementation process mostly based on faith that the transition to BIM will produce a positive outcome:

> We don't know yet. We are doing it on faith so far and this is why questions arise like this costs analysis of the BIM cost versus our labour productivity to see if there is any correlation there. The very first job we did [where we used BIM] we felt we probably would have lost our shirt if we hadn't of 'BIM'ed' it, but that's anecdotal, we don't have any measurement of that, but that's our gut feeling. So our gut feeling is still telling us that this is a smarter way to build and more efficient way to build. We are seeing that our budgets for BIM engineering are not sufficient. It is taking longer than we envisioned and I don't know whether that's because of the models we are getting are poor or whether we are just going up on the learning curve and not as productive yet as we will become hopefully. (General Manager (1st rd.))

The impact of BIM within the Organization was felt in the transformation of workflows, which occurred on three levels: in-house modeling capabilities had to be developed from nothing. Internal information flows and workflows between office and field personnel had to be reworked (Figure 4.3 and Figure 4.4). External Information flows with project stakeholders had to be redefined. In light of this, company standards and templates were developed to ensure consistency in the modeling process. Furthermore, whereas detailed execution was traditionally resolved by the site foreman in the field through trial and error, the introduction of BIM has shifted the detailed execution and conflict resolution process to the office. The information is now being produced in the office and communicated through more precise

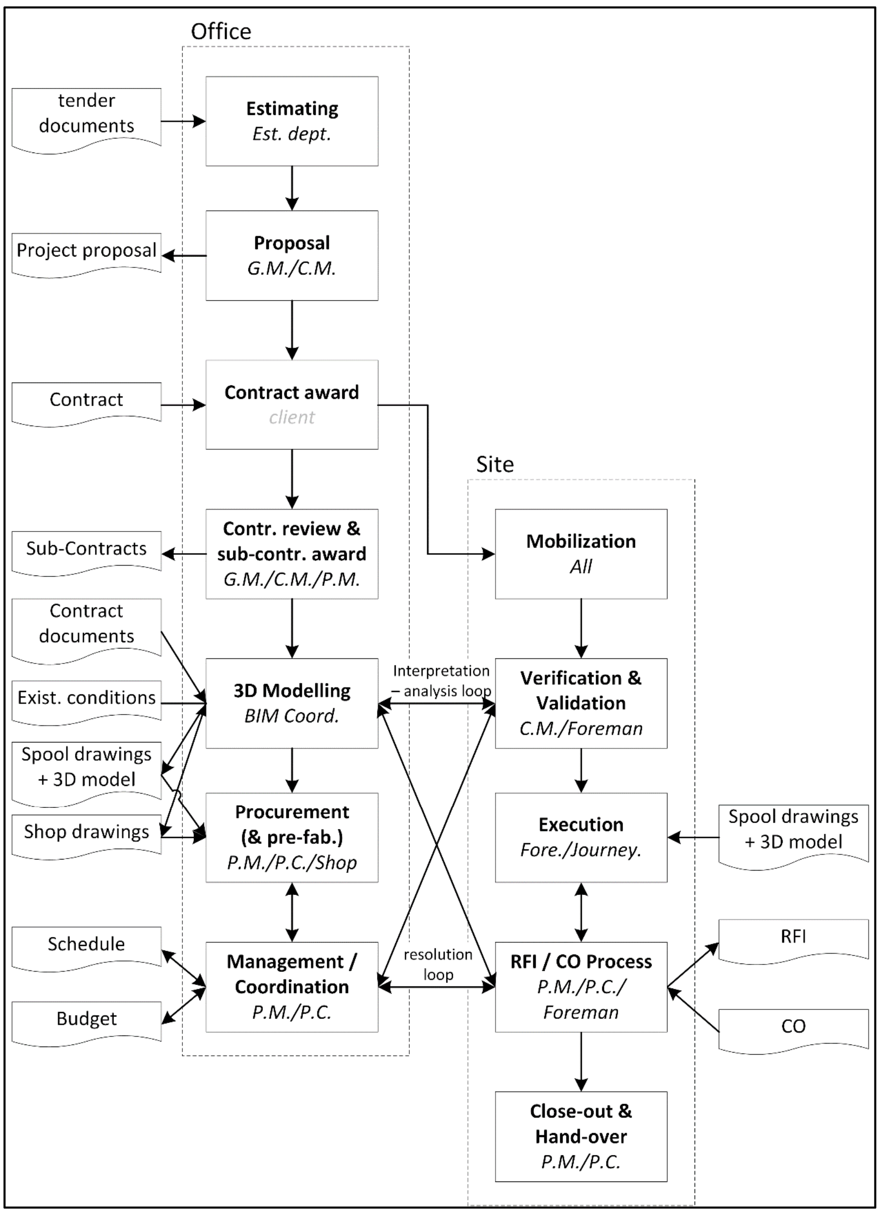

Figure 4.3 Internal workflows (Pre-BIM) – Design-Bid-Build

fabrication and assembly drawings. In light of this, ensuring that the information produced in the office gets to the field and distributed to workers in an efficient manner has become a priority for the Organization. A communication protocol is being established to transfer and diffuse information on site while ensuring feedback to the office personnel to better inform the process through which plans are analysed, models built and validated and finally documentation produced and distributed.

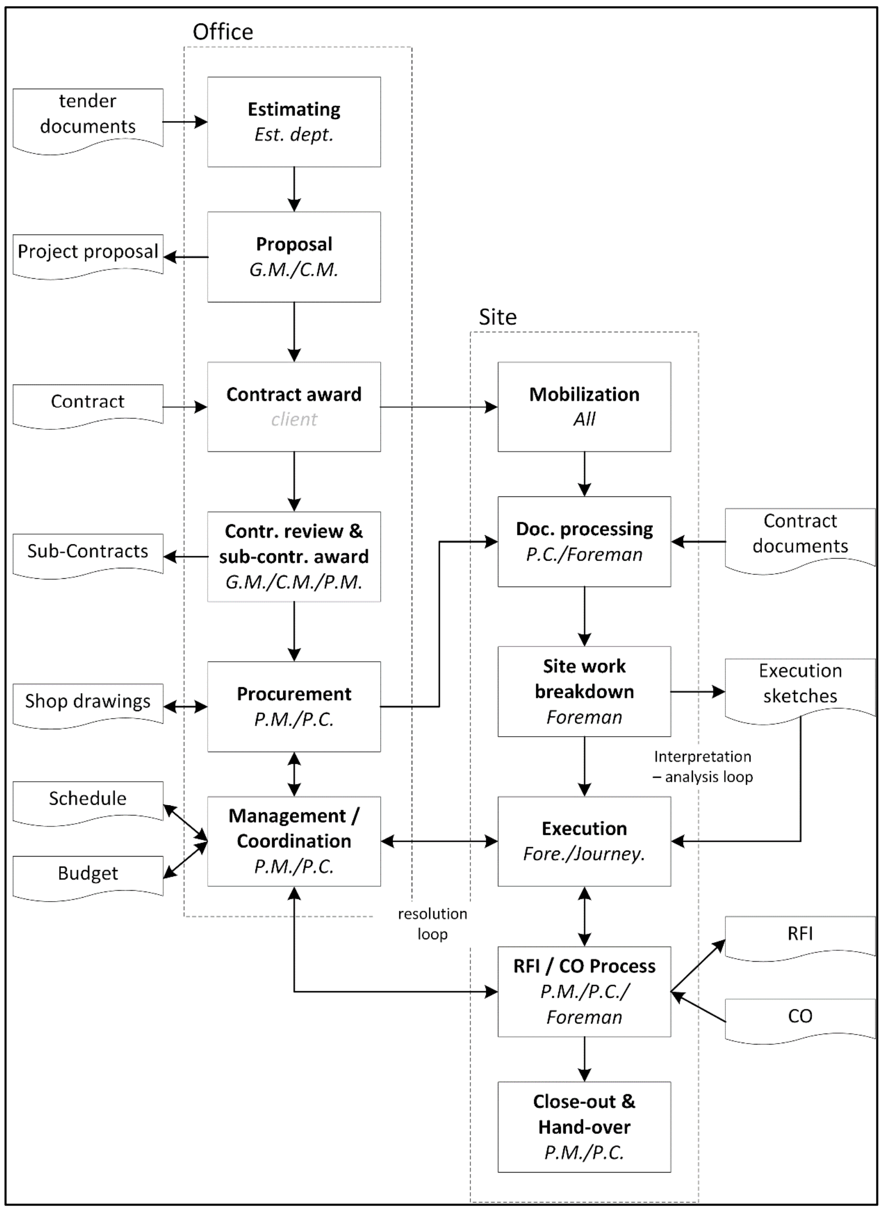

Figure 4.4 Internal workflows (Post-BIM) – Design-Bid-Build

Another impact on the Organization has been the creation of specific BIM roles to take on the new responsibilities and workloads. This develops the need for personnel with a specialised set of skills. For example, the role of BIM coordinator has emerged from the need to perform modeling and additional project coordination tasks introduced by BIM. This is in addition to the traditional role of project coordinator. Ideally, the same person would fill both roles, however, time constraints and capability issues have made it difficult to do so thus far. It is however questionable whether both roles will be completely integrated in the near future due to the sheer effort needed to accomplish both tasks on any job. These new roles and responsibilities are evolving over time, as capabilities are developed and experience is acquired:

> I guess from the beginning my role was fairly, how do I say fairly sparse. I just kind of did this and that and everything in between kind of thing. I don't think my role has developed too much, but it has definitely become a lot more structured. It is more developed in the sense that, my goals are much clearer. In the beginning it was trying to figure out what your goals are. And now it is definitely more developed that way. (BIM Coordinator)

Technology management has also become a considerable endeavor for the Organization. The technology implemented in the past by the Organization was straightforward and worked independently, the transition to BIM requires considerable expertise and investments to upgrade and maintain both hardware and software capabilities. For instance, the choice of the BIM software represents a major commitment due to subsequent issues such as suitability, interoperability, training and support. In this case, the Organization chose a leading software platform, based on its popularity within the market. A second software suite had to be introduced, however, in order to overcome the severe limitations of the first software in respect to fabrication level detailing (Figure 4.5).

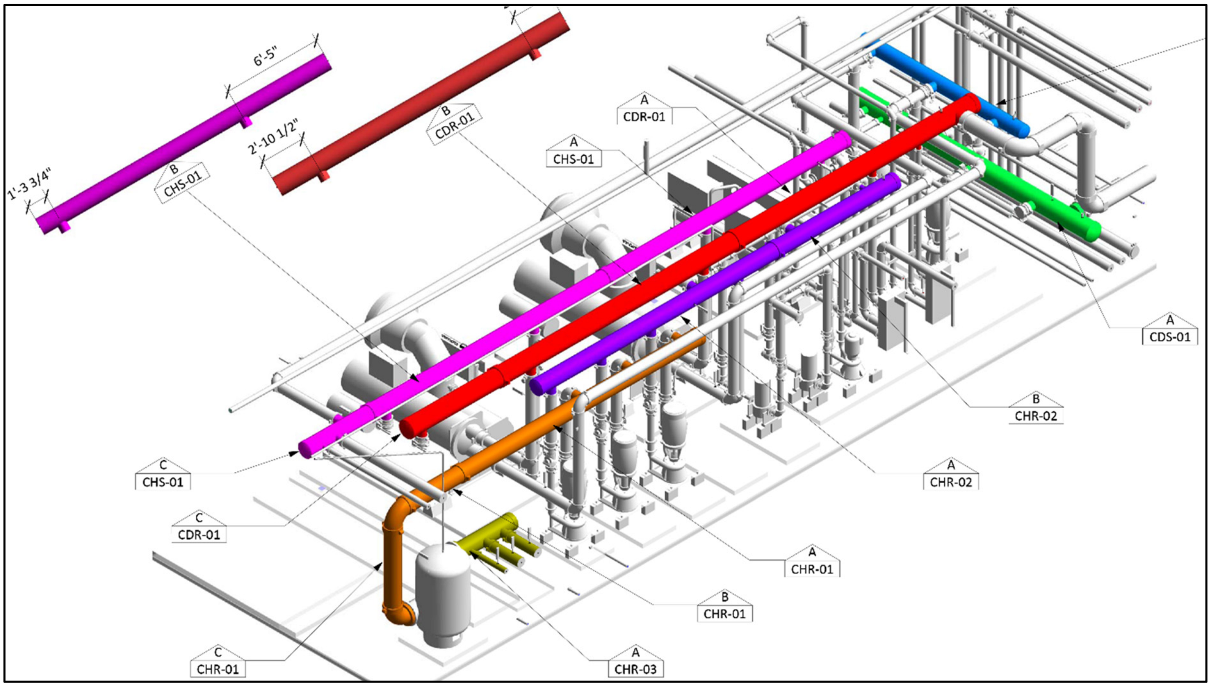

Figure 4.5 Software Outputs

4.6.4 The project context

The project context is characterised by the temporary nature of its structure and the specificity and uniqueness of its setting (requirements, contracts, scope, etc.) (Winch, 2010). Central to the project context is the project team which encompasses the external project team, comprised of the external stakeholders forming the supply chain and the internal project team, comprised of the Organization's office and field personnel working on a given project. While the Organizational context is key to the BIM adoption and implementation process, the project context mediates the extent of this process by influencing the scope to which BIM can be implemented. Furthermore, while the adoption of BIM represents a radical innovation for the Organization, the further development of capabilities related to BIM represent incremental innovations at the project level (Figure 4.6).

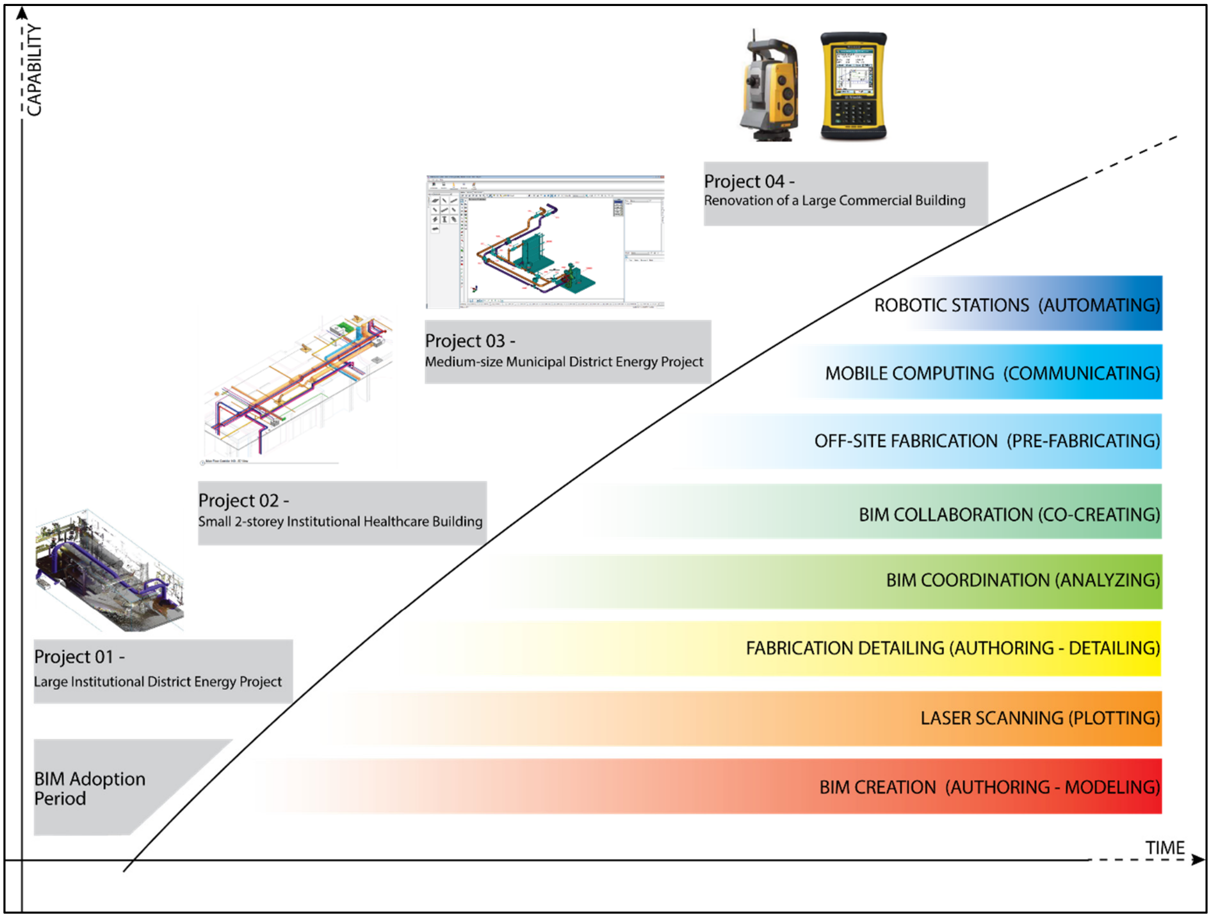

Figure 4.6 Evolution of organizational capabilities

This analysis of the data highlighted factors such as contractual requirements, project delivery modes, maturity levels, project team expectations, etc. which have influenced the extent of collaboration and the establishment of a collaborative BIM environment within the project team, as identified in past research (e.g. Dossick and Neff, 2010). More importantly, contractual requirements dictating specific requirements for BIM implementation, or absence thereof, were seen as a prime factor mediating the level of BIM implementation process at the project level. Of the four projects studied, only one had any mention of BIM in the contract, but no set requirements. Indeed, as BIM is a relatively new process, contractual requirements are often vague and not well defined. This lack of contractual clarity and control over BIM greatly impacts the potential for collaboration and value generation through BIM implementation (Taylor and Bernstein, 2009) and contributes to waste within the project delivery setting (Dubler, Messner and Anumba, 2010). For the Organization, this has resulted in them having to build their own models, instead of benefitting from a model developed up stream:

> It is a bit of little disappointing to be honest with you. We have been given the consultants model to use as the baseline for our model. And their model is, I guess the best word to say "Incomplete" or full of conflicts, and we receive very little support from either [the consultants of the general contractor] to do anything about it. So we have been given a fairly good architectural and structural model to work within, but rather lackluster mechanical model to use as the base for our fabrication model. (Project Manager, project 04 (2nd rd.))

The findings also highlighted a conflict between the use of BIM at the design, construction and operations phases. As such managing the expectations towards BIM, which represent the project team's beliefs and intent towards the model and the process, has emerged as key to successful and effective deployment of BIM within the project context. There still remains, however, a large gap between project expectations and actions:

> Even on jobs like [project 04] that supposedly are all designed, and the rooms are all scanned, we get the models and they aren't. And so instead of being able to get right into BIM design, we are backtracking and going out in field measuring. (General Manager (2nd rd.))

This also highlights a lack of mutual understanding of the BIM process and the time required to develop models and communicate intent is still lacking within the project setting. This leads to scheduling conflicts and tension due to unfulfilled expectations:

> BIM is still not well understood I guess from the perspective of the owners and the general contractors. They all like the beautiful pictures and the 3D models and all that. But they have no appreciation of the lead-time that we need to get it there. (BIM Manager (2nd rd.))

Where specific BIM requirements are lacking, relationships with external project team members were seen as a key factor in the successful implementation of BIM. However, the Organization's increased involvement in the modeling and design validation process has put them in a position to question design decisions upfront, which is creating tension within the project team:

> We are experiencing a lot of resistance from the mechanical consultant to engage us, when we have suggestions or when we point out things that we need clarification on and we are a little bit unsure what that resistant is rooted it in or sourced in, but we are definitely experiencing it as part of trying to get buy in to from all parties to work with us on BIM. I don't know if it is a defensive thing. They don't want to hear that, and us showing them in a very understandable 3D BIM environment than what they have designed is needing to be revised or addressed from a constructability point of view. (Project Manager, project 04 (2nd rd.))

The brings to light the issues of trust within temporary project teams, which has been thoroughly discussed elsewhere (e.g. Emmitt, 2010). Indeed trust has emerged as an important factor in the deployment of BIM within the project context. In this case, the question of trust relates to specific issues such as reliability and accuracy of information input by others, i.e. trustworthiness. In parallel, the question of trust in the capability of external project team members to deliver as per the project requirements plays a central role in establishing the relationships amongst project team members. The Organization has partly dealt with this issue of trust by establishing long-term relationships with a limited number of suppliers and providers.

While BIM is now being implemented by the Organization on almost every project, its extent and scope is being determined on a project-by-project basis. In a lonely setting, this is determined through potential gains. In a more collaborative setting, this will be dictated by the contractual requirements and procurement mode. Within those requirements, the internal project team will establish the level to which BIM is deployed. For the Organization, this question of suitability is being influenced by the potential for pre-fabrication and productivity gains. In spite of the procurement mode dictating the timing of the Organization's integration into the project team, the use of BIM has generally allowed the Organization to play a more predominant role within the project setting. In a more integrative procurement setting, such as Design-Build where the consultants fall within the Organization's supply chain, more control can be asserted on the deployment of BIM across the project team. In a more traditional setting, the Organization will only have control over their own supply chain:

> It has been an opportunity for us on projects to push our sub trades and see them start to develop their BIM capacities. Our sheet metal sub has stepped up in particular. So there are benefits from that. So we are developing our network along with it. (General Manager (1st rd.))

This points to another important mechanism implemented by the Organization which has been to foster the project team's commitment to the BIM effort. To achieve this, the Organization has developed relationships and a network of sub-trades (namely HVAC and fire protection), which have been developing their own BIM capabilities. In that sense, the Organization is creating their own 'constellation of actors' (Linderoth, 2010) with whom they can develop long-term relationships and develop their BIM capabilities concurrently. For example:

> With the [project 04] we did work with our sub-trades that was actually it went fairly smoothly, like with [the sheet metal sub-trade] we managed to work in the same environment and be able to collaborate. (BIM Coordinator, project 04 (2nd rd.))

The impact of BIM adoption and implementation at the project level manifests itself in the transformation of interactions with external project team members, such as owners, design consultants, general contractors and other specialty trades. Interactions now take place through the 3D model and its outputs (Figure 4.5). Furthermore, as a result of the Organization having to rework the models that they had obtained or build their own models from 2D drawings, the Organization has consistently been developing their BIM capabilities. This has resulted in the Organization now being able to offer more services to various client bodies, which is perceived as a positive outcome by the Organization. To continuously develop these BIM capabilities, the Organization has implemented a continuous innovation process within the project context. This process is characterised by the development of specific capabilities, such as pre-fabrication, laser scanning and increased scope of modeling at the project level and at the Organizational level. To do so, a "triggering" process is adopted through which specific projects are targeted to incrementally develop BIM capabilities while maintaining the over-arching strategy towards BIM developed by the steering committee. This presents the

Organization with the opportunity to increase their involvement on a project, which in turn translates to an increase in marketing power for the Organization and their appeal to clients. Figure 4.6 illustrates the project-based evolution and triggering approach taken by the Organization. It is important to note that Figure 4.6 serves for illustration purposes and that it does not represent a teleological view of capability development for the Organization.

4.7 Conclusion

This paper reported the findings of a research project which adopted a longitudinal, mixed-method case study approach, rooted in the interpretivist paradigm. The research project aimed to investigate the BIM adoption and implementation process for a specialty contracting SME in the Canadian AEC industry. Through analysis of the qualitative data collected over the course of the research project the research team uncovered and investigated several factors, mechanisms and their perceived impact, which were seen to influence, either positively or negatively, the adoption and implementation of BIM by the Organization under study. While past work has looked at the innovation process (Barrett and Sexton, 2006) or BIM adoption and implementation within SMEs (Arayici *et al.*, 2011), sparse work has attempted to bridge both research domains. By bridging these domains, this paper distinguishes four distinct yet embedded contexts, which were found to mediate the BIM adoption and implementation process: (a) the industry context; (b) the institutional context; (c) the Organizational context; and (d) the project context. While its importance has been highlighted in the innovation process (Rankin and Luther, 2006; Winch, 1998), this contextual view was seen to be lacking from the literature on BIM adoption and implementation. The paper further identifies several factors, mechanisms and their impacts across these different contexts (Rankin and Luther, 2006; Winch, 1998). Several particularities of the BIM adoption and implementation within the context of a specialty contracting SME were highlighted, namely that it represents a radical change, a drastic departure from traditional project delivery for this SME. Within the Organization studied, this radical change prompted and compounded more incremental innovation. While the findings indicated an overall positive perceived impact on project performance at a high-level, further work is required to validate these findings. In fact, the question of benchmarking and performance assessment is an important one that needs further attention with respects to the BIM adoption process. Work is currently being carried-out to collect data on the performance assessment and evaluation of BIM on project outcomes and return-on-investment (ROI) within the same Organization.

The practical implications of this research point towards two elements: the need for clear policy at the industry level to guide the deployment of BIM and the importance of a strategic approach to the BIM adoption and implementation process at the organizational level. The findings from this study indicate that even if public policy or contractual requirements are lacking, a specialty contracting SME can still reap benefits from BIM if a clear vision and strategy guiding the adoption and implementation process has been put in place. Limitations of this study are found both in the interpretivist paradigm's relativist perspective and in the case study approach adopted. While this approach allows the discovery and emergence of findings grounded in practice, the question of external validity (generalizability) due to the interpretative nature of these findings is always an issue. Through triangulation of data sources, the research team attempted to bolster the robustness of the findings. Further work could be carried out in other geographic and market (industry) contexts to validate these findings. In addition, the specialised nature of the Organization studied (a mechanical contracting SME) raises questions of generalizability of findings to other specialty contracting SMEs in the AEC industry. As such, further work is needed to study other specialty contracting SMEs in the same given industry context. Further work could also look into refining these embedded contexts in light of the various realities facing specialty contracting SMEs. To conclude, a single model of innovation cannot easily explain the adoption and implementation of BIM. It represents a disruptive and radical innovation, yet as it develops, smaller, incremental innovations can take place which support the overall process. Furthermore, this process is seen as highly contextual in that it is industry and discipline specific. This paper takes a step in developing these contextual factors and mechanisms that can be put in place to mediate the BIM adoption and implementation process.

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CHAPTER 5

ASSESSING THE PERFORMANCE OF THE BIM IMPLEMENTATION PROCESS WITHIN A SMALL SPECIALTY CONTRACTING ENTERPRISE

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5.1 Abstract

The current shift to Building Information Modeling (BIM) enabled project delivery in the construction industry is promising important benefits. For small and micro businesses, which represent 99.0% of the employers in the Canadian construction industry, adopting these trends could significantly impact their bottom line. However, this often represents considerable cost and risk. Assessing the performance of BIM implementation therefore becomes an important part of the process, namely in ensuring that it is on track and progressing as required. This article presents the findings from a case study research project conducted over a two year period within a mechanical contracting firm. The objective of this research project was to develop an evolutionary approach, supported by specific measures, to assess the performance of the BIM implementation process within a specialty contracting small enterprise. The findings suggest that BIM has had a positive impact over time on predictability for indicators such as total project cost and labor cost. On the other hand, project scope and quality were not shown to be influenced by BIM in the projects studied. The variability uncovered in the findings reinforces the central tenant of BIM as an enabler for collaboration. Indeed, most of the projects studied were performed in a lonely manner and thus the measured impact of BIM

on project delivery was limited, even if it was perceived as very beneficial. Lastly, the article highlights the need for a parallel reconfiguration of practice: performance assessment and BIM implementation need to be developed conjointly to serve one another.

5.2 Introduction

Building Information Modeling (BIM) enabled project delivery promises significant benefits across the project supply chain and its lifecycle. It also represents considerable risk for organizations due to the many challenges in its adoption and implementation (e.g. Becerik-Gerber and Rice, 2010). BIM implementation can be defined as an ongoing process through which an organization modifies its practices to suit the emerging capabilities offered by the transition to a parametric, information rich, digital representation of a built asset (NIBS, 2007). There are many reported benefits to this transition to BIM, however they remain either anecdotal, intangible or based on conjecture. For organizations, Small or Medium Enterprises (SME) in particular, implementing BIM represents significant risk: anecdotal evidence and faith are insufficient as justification (Gao and Fischer, 2008). The transition to BIM has reinforced the need for organizations to assess their performance to many ends such as evaluating benefits and impact of BIM, measuring capability and maturity and evaluating return on investment (ROI). Attaining these ends carries its own set of distinct challenges, namely determining a consistent assessment process adapted to the contextual nature of the construction industry (Poirier et al., 2015), isolating specific actions or elements and determining their impact on project performance (Andresen et al., 2000) and correctly identifying project dependencies (Sosa et al., 2007). While past work has looked into defining success measures and determining the value of BIM at either the project level or at the organizational levels, little work has been done to bridge the gap between both levels. Many of these studies are survey based, therefore self-reported, and few have objectively looked into the progression of BIM within an organization over an extended period of time.

This article presents the findings of a 2 year research project with a small mechanical contracting enterprise. The objective was to develop an evolutionary approach, supported by specific measures, to assess the performance of the BIM implementation process within the organization and across time. This was done by measuring the predictability of key performance indicators on 8 different projects that were aggregated at the organizational level through a centralized database. The focus of the research project was purposely put on small (between 5 and 99 employees) and micro (less than 5 employees) businesses who, in 2012, made up 99.0% of the Canadian construction industry's workforce (Industry Canada, 2014) and accounted for 72.7% of the total share of nominal GDP in the Canadian construction industry (Leung et al., 2012).

The contribution of this article is the systematic approach taken to the assessment of BIM implementation within a specialty contracting SME through the evaluation of variability of key performance indicators across time. While past research has looked into the performance and impact of BIM at the project level or, through surveys, at the organizational or industry levels, this article bridges the gap between these two levels. Our findings suggest that BIM has helped the Organization improve the predictability of certain cost items, namely total project costs and labor costs. The Organization is also becoming better at evaluating the costs associated to BIM implementation at the project level. On the other hand, the quantity and cost of change orders (CO) and the amount of rework were not seen to be impacted by BIM. The key contributions from this article are three fold: it provides empirical support to the notion of BIM as a collaborative undertaking and the importance of providing a conducive project environment to maximize value. Indeed, the use of BIM in the cases reported in this article were mostly executed in a lonely setting, as such, the organization did not benefit from BIM to the extent that has been reported elsewhere. This speaks to the Organization's lack of influence on decisions made upstream within the project supply chain, namely around the extent and scope of BIM use in a project. It also highlights the parallel courses of the BIM implementation and performance assessment practices: an organization's performance assessment practices should reflect the reconfiguration of practice introduced by BIM. Finally, the article adds to the growing literature relating the quantified benefits of BIM, which can help inform the adoption and implementation of BIM within the Canadian construction industry.

5.3 Background

The well-researched fields of performance assessment and benchmarking in the construction industry highlight the imperative need for consistent evaluation of performance in order to compel progress and innovation (Bassioni et al., 2004). With regards to BIM implementation, multiple perspectives on performance assessment have emerged in the literature. These perspectives focus mainly on evaluating the impact of BIM at the project level (Khanzode et al., 2008), assessing the progression of capabilities and maturity (Succar et al., 2013, Taylor and Bernstein, 2009) and measuring return on investment (ROI) (Barlish and Sullivan, 2012, Giel and Issa, 2011). The use of key performance indicators (KPI) is seen as the most popular method of measuring performance in the construction industry (Robinson et al., 2002) and therefore, considerable work has gone into identifying and implementing frameworks based on these indicators (Kagioglou et al., 2001). Over the past two decades, many KPIs have been identified (Cox et al., 2003, Chan and Chan, 2004) which are typically related to one of 7 categories: Cost, Time, Quality, Safety, Scope, Innovation and Sustainability (Rankin et al., 2008). The emergence of BIM performance assessment as a field of study has benefitted from this work, leveraging it to focus on measuring the impact of BIM. There is, however, a vast discrepancy within the KPIs being tracked to do so (Neelamkavil and Ahamed, 2012). In this regard, BIM shows potential to influence mostly quality control, on-time completion, reducing change orders (COs) and requests for information (RFI) as well as improving labor productivity (Barlish and Sullivan, 2012, Khanzode et al., 2008, Suermann, 2009). Table 5.1 summarizes many of the measures that have been developed in the construction industry and been subsequently used to assess the performance of BIM.

Table 5.1 KPIs and metrics from the literature

Metric	Description	Source
KPI: COST		
Cost predictability	Predictability of budget compared to actual project costs	(CII, 2013), (Egan, 1998), (Khanzode et al., 2008), (Kunz and Fischer, 2012), (Rankin et al., 2008), (Suermann, 2009)
Cost per unit	Average project cost per unit produced (tendered and actual)	(Rankin et al., 2008) (Suermann, 2009)
Cost for defects	Cost of labor and material to rectify defects and rework	(Kunz and Fischer, 2012), (Rankin et al., 2008)
KPI: TIME		
Schedule Predictability	Predictability of planned schedule compared to actual project duration.	(CII, 2013), (Egan, 1998), (Barlish and Sullivan, 2012), (Khanzode et al., 2008), (Kunz and Fischer, 2012), (Rankin et al., 2008), (Suermann, 2009)
Time per unit	Average time per unit produced (tendered and actual)	(Rankin et al., 2008)
Time for defects	Time spent to rectify defects and rework	(Rankin et al., 2008)
KPI: PRODUCTIVITY		
Direct & indirect Labor	Dollars per unit and units per hour performed of direct & indirect labor	(CII, 2013), (Forbes and Ahmed, 2011), (Khanzode et al, 2008), (Thomas and Završki, 1999), (Suermann, 2009)
Prefabrication	Amount of off-site prefabrication performed	(Barlish and Sullivan, 2012), (Khanzode et al, 2008),
KPI : QUALITY		
Deficiencies	Total number of deficiencies (also related to cost and time)	(Rankin et al., 2008), (Suermann, 2009)

Metric	Description	Source
KPI : SAFETY		
Reportable incidents	"The number of reported incidents measured against the hours worked during construction" (Rankin et al., 2008)	(Egan, 1998), (Rankin et al., 2008)
Lost Time	"The amount of time lost to incidents measured against the hours worked during Construction" (Rankin et al., 2008)	(Egan, 1998), (Rankin et al., 2008), (Suermann, 2009)
KPI: SCOPE		
RFI - Quantity	Quantity of RFIs	(Barlish and Sullivan, 2012), (Giel and Issa, 2011) (Khanzode et al., 2008)
CO cost and quantity	Quantity and cost of COs as a % of project costs	(Barlish and Sullivan, 2012), (Giel and Issa, 2011) (Khanzode et al., 2008)
RFI - Response Latency	Average response latency for RFI in a project	(Kunz and Fischer, 2012)
Avoidance costs	Estimated cost of conflict resolution and avoidance through BIM	(Giel and Issa, 2011)
KPI: ORGANIZATIONAL		
Profit	Profit margin on projects	(Coats et al., 2010)
Client Satisfaction	Level of Client satisfaction with services	(Egan, 1998), (Rankin et al., 2008), (Suermann, 2009)
Repeat Business	Number of contracts obtained from the same client	(Coats et al., 2010)

Some studies have used cost growth as a measure of performance, namely Kelly and Ilozor (2013) who find that BIM has a negative impact on cost growth on the projects studied, which is contrary to general themes in the literature. This notion of predictability holds much potential in serving as a true indicator of performance (Koskela, 1992, Forbes and Ahmed, 2011) and was one of the measures developed by Rankin et al. (2008). Indeed, better predictability indicates lower risk and while the seven areas of measurement (Cost, Time, Quality, Safety, Scope, Innovation and Sustainability) offer quantifiable and finite indicators, the true measure of performance lies in their predictability over time. While, the literature pertaining to BIM performance assessment has mainly focused on individual projects at specific points in time, some work has supported an organizational perspective of BIM performance assessment, namely Coates et al. (2010) who argue that "KPIs should be measures of risk to annual goals and strategic objectives" (Coates et al., 2010, p.6).

From this perspective, some work has looked at evaluating ROI as a measure of expenditure (risk) in relation to quantifiable benefits (achieving strategic goals and objectives). It leverages the KPIs that have been identified elsewhere to justify the cost of BIM within an organization. The literature on ROI differs from that on impact assessment by identifying the various costs associated to BIM such as hardware, software, training, recruitment and contingencies (Olatunji, 2011). Some take a simpler approach to the ROI calculation where expenditures are uniquely attributed to cost of modeling on a project and return is defined by elements such as avoidance of issues in the field through early resolution. For instance, Giel and Issa (2011) provide a model for estimating BIM ROI, calculating an ROI of BIM ranging from 16% to 1,645% on the projects they studied. This method, however, remains highly hypothetical since it assumes that the issues avoided through the model would not have been avoided using traditional coordination methods. Moreover, frameworks have been developed to further systematize the ROI evaluation process both from the purely quantitative perspective, providing investment and return metrics, comparing BIM to non-BIM projects (Barlish and Sullivan, 2012) and balancing both the quantitative and the qualitative perspectives (Love et al., 2013). To date, the operationalization of these frameworks provides insight into the beneficial impact of BIM at the project level, however, these findings remain inconclusive due to the underdeveloped use of BIM in many of the projects studied (Barlish and Sullivan, 2012). There is great interest in developing this field.

The third area of enquiry is that of capability and maturity assessment. Several frameworks and tools to evaluate the BIM capabilities and maturity levels of an organization have been developed over the past years such as, among others, the BIM Maturity Index (BIMMI) (Succar, 2010), the Computer Integrated Construction research program's organizational maturity assessment matrix (CIC, 2013), the National Institute of Building Science's Interactive BIM Capability Maturity Model (NIST, 2007) and the VDC/BIM Scorecard (CIFE, 2013). Commercial tools have also been developed such as BIM quickscan (Sebastian and van Berlo, 2010) and bimScore (Kam et al., 2012). The focus is mainly around the evolutionary nature of BIM within the organization (e.g.Taylor and Bernstein, 2009). These models are, however, often based on conjecture and require an objective introspection on the part of the organization performing the assessment.

Some authors have tried to overcome this subjective approach to assessment, such as Mom and Hsieh (2012) who propose a BIM Performance Assessment Framework (BIMPA). This BIMPA is operationalized "at the corporate level, which attempts to identify, control, predict, measure, and improve the critical factors that affect construction business performance" (p.2). The issue lies in that the framework intimates a "clean" and linear BIM implementation process at the organizational level while not factoring in the importance and the influence of project level BIM implementation nor the context of the implementation. Du et al. (2014) have developed the BIM Cloud Score to benchmark the modeling process. The authors hope that through this approach organizations can benchmark their "BIM performance". The BIM Cloud Score seeks to measure the outcome of the modeling process, but it doesn't look into the project delivery and the various inputs that guide the modeling process; the metrics developed also lack grounding.

In essence, there lacks a way to systematically assess the evolutionary nature of the BIM implementation process within an organization. Indeed, many of the models or frameworks that set out to assess the performance of BIM, either its impact, its return or its evolution, disregard the interactions between the project, the organizational, the institutional and the industry contexts, which are highly interrelated and influence the BIM implementation process (Poirier et al., 2015a). Some of the assessment methods that are being proposed also tend to ignore existing organizational measurement processes and tools, which is problematic. Indeed, organizations adopting and implementing BIM are confronted with multiple parallel processes: not only do they have to transform their practices around BIM, they have to reconfigure how they evaluate and track their performance in light of this transformation.

5.4 Research Methodology

A mixed-method, longitudinal case study research approach (Fellows and Liu, 2008; Yin, 2014) was employed to investigate the performance assessment practices for a specialty contracting SME evaluating its BIM implementation process. This was done across multiple projects by developing specific KPIs and metrics that were based on the organization's current performance assessment capabilities and practices. This research project was part of a larger, multi-pronged research project aimed at studying the adoption and implementation of BIM within SMEs in the Canadian construction industry (Forgues et al., 2014, Poirier et al., 2013). The scope of this particular research project was conducted over a 2 year period. Its objectives were to (1) investigate the current performance assessment practices of the organization and (2) to develop an approach, supported by specific measures, to assess the performance of the BIM implementation process within the organization from an evolutionary perspective. The research team was working with the hypothesis that, over time, the implementation of BIM would improve predictability of project scope (less RFIs and Change Orders), of project budget (actual vs. estimated cost), of project schedule (actual vs. estimated duration), of project quality (less rework) and of labor productivity within the organization. In parallel, the cost of BIM at the project level would either be constant or diminish slightly as the organization increased its capabilities in the field of modeling and prefabrication.

To test this hypothesis, eight projects were targeted within the organization for an in-depth analysis: six where BIM was used in a significant manner and two projects which did not involve the use of BIM to serve as baseline comparison cases. Table 5.2 presents the four DES projects while Table 5.3 presents the four building mechanical projects that were analyzed. The projects are presented in a chronological order. Qualitative data was collected through semi-structured interviews and direct observation. The interviews lasted between 30 and 90 minutes. The personnel interviewed within the Organization were: the president-general manager (who also acts as senior estimator), the construction manager, three project managers, the BIM manager and the principal BIM coordinator. This personnel was involved in all eight projects in one form or another. Cases 01-A, 02-A and 02-B were retrospective, whereas the remaining cases were on-going over the course of the research project. Through direct observation, we identified the estimating and project management practices, notably to determine how the organization estimated, scheduled and managed their projects. We also identified the organization's performance assessment practices, including the existing infrastructure used to collect and aggregate the data, the measures being tracked, the data collection mechanisms and the data analysis methods.

The quantitative data that were collected for these projects were: Request for Information (RFI) and Change Order (CO) logs, budgets and cost reports, schedules, plans and specifications as well as digital models and employee timesheets for all eight cases These artifacts were evaluated to identify the current KPIs and metrics being tracked as well as to determine the current status of data available for analysis. The research team reviewed the available data through the organization's project management software as well as the level of detail to which it could be extracted for each of these projects.

Table 5.2 Description of selected DES projects

	Project 01-A	**Project 01-B**	**Project 01-C**	**Project 01-D**
Description	Small municipal DES project	Large institutional (university) DES project - Phase 2	Medium municipal DES project	Large institutional (university) DES project - Phase 3
Timeframe	12/2010 – 04/2011	10/2011 – 02/2012	09/2012 – 03/2014	08/2014 – 09/2015
Delivery mode	DBB	DBB	DBB	DBB
Role	Prime contr.	Prime contr.	Prime contr.	Prime contr.
Contractual BIM requirements	None	None	None	None
Unit	4 ETS	8 ETS	11 ETS	21 ETS
Contract amount	$200k	$2,7M	$1M	$4,7M
BIM Use	None	• Modeled all Energy Transfer Stations • Laser-scanned all mechanical rooms • Clash detection with existing mechanical systems within rooms • On-site prefab. from spool drawings	• Modeled all Energy Transfer Stations • Initiated off-site prefab.	• Modeled all Energy Transfer Stations • Laser-scanned all mechanical rooms • Clash detection with existing mechanical systems within rooms • Off-site prefab.

Table 5.3 Description of selected building mechanical projects

	Project 02-A	Project 02-B	Project 02-C	Project 02-D
Description	6 story institutional (health-care) building	2 story wood-frame institutional (health-care) building	Renovation of large mixed-used commercial building	3 story industrial building
Timeframe	08/2008 – 11/2009	09/2012 – 07/2014	06/2013 – 02/2015	01/2014 – 03/2015
Delivery mode	DBB	DB	CM - DA	DB
Role	Mech. contr.	Mech. contr.	Mech. contr. Design Assist role	Mech. contr.
Contractual BIM requirements	None	None	None	None
Unit	60,000 sq.ft.	56,425 sq.ft.	676,050 sq.ft.	92,850 sq.ft
Contract amount	$1,35M	$1,4M	$12,6M	$5,3M
BIM Use	None	• Modeled all building services (HVAC, Fire Protection, Plumbing, Electrical, etc.) to perform clash detection • Targeted areas with most potential for conflict (shafts, ceiling spaces, etc.)	• Obtained design models • Performed detailed modeling of mechanical penthouse • Full prefabrication of mechanical penthouse • Used as a coordination tool with sub-supply chain (HVAC and Electrical)	• Modeled all mechanical rooms • Off-site prefabrication from spool drawings

Figure 5.1 illustrates the systematic and evolutionary approach to benchmarking and performance assessment that was developed and formalized from the direct observation in the early stages of the research process. It bridges the gap between the project level and organizational level by identifying processes belonging to each level and where they intersect. It is evolutionary in that it intimates an iterative approach to the assessment process by continually reassessing the performance assessment strategy as capabilities are developed within an organization, which will in turn modify the scope of the performance assessment process by introducing new measures or data collection points.

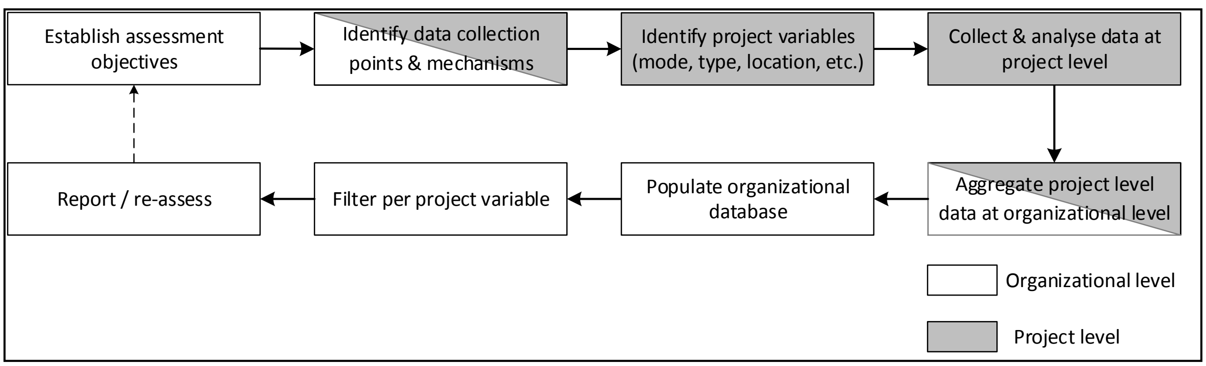


Figure 5.1 Benchmarking and performance assessment approach

5.5 The Organizational Context

The Organization we studied was founded in 2004 and operates in the Vancouver, British-Colombia area. It has 67 employees and is deployed along a project-based organizational structure across two divisions: 24 office based employees (project managers, coordinators, estimators as well as administrative staff) who form the project management team and 43 site based employees (superintendents, foremen, journeymen). Since 2004, they have completed over 50 projects ranging from $100k to $14M in contract value. The Organization delivers projects concurrently across two project streams. Project stream 01 involves the delivery of District Energy (DES) projects including fabrication and installation of Energy Transfer Stations (ETS). Project stream 02 involves the delivery of traditional building mechanical systems including HVAC, fire protection, plumbing, etc. Within both project streams, the organization will typically sub-contract all sheet metal and ducting work, fire protection, pipe insulation and refrigeration while plumbing, HVAC piping and equipment installation will be self-performed work. The organization moved forward with the adoption of BIM in 2010. To date, it has completed 11 projects using BIM, mostly in a lonely setting, meaning that they are the only stakeholder using BIM in the design or construction phase. Six of those projects were targeted in this study due to the considerable scope of BIM use in these cases. The organization has been developing its BIM capabilities in the following areas: on-site and off-site prefabrication, laser scanning, pre-planning, trade coordination, visualization, constructability review, and clash detection.

The Organization has consistently spent 0.8% of their yearly sales volume on BIM implementation. These costs represent the cost of: software licenses (40%), hardware (4%), training (2%) and the overhead salaries and burden of employees dedicated to BIM in the organization who aren't working on billable work (such as developing libraries, standards, etc.) (54%). Consequently, the organization was seeking a way to justify these overhead costs related to BIM adoption, the project costs of BIM and the concurrent development of capabilities (laser scanning, off-site pre-fabrication, etc.). In fact, the need to consistently measure, evaluate and benchmark the organization's performance as a key to sustaining the BIM adoption and implementation process was highlighted as one of the main challenges faced by SMEs adopting and implementing BIM (Forgues et al., 2014, Poirier et al. 2013), which is consistent with past work in the field of organizational innovation (Rankin and Luther, 2006). The main motivation behind initiating this portion of the research project was therefore to assess the performance of the BIM implementation process within the organization. This was stressed by the Organization's general manager during an interview, which, when asked about justifying the costs associated to BIM responded:

> We don't know yet. We are doing it [the implementation of BIM] on faith so far and this is why questions arise like this costs analysis of the BIM cost versus our labor productivity to see if there is any correlation there. The very first job we did [where we used BIM] we felt we probably would have lost our shirt if we hadn't of 'BIM'ed' it, but that's anecdotal, we don't have any measurement of that, but that's our gut feeling. So our gut feeling is still telling us that this is a smarter way to build and more efficient way to build. (General Manager (1st rd.))

5.5.1 Estimating and Project Management Practices

In order to use predictability of costs as one of the indicators, the estimating practices must first be well understood. The organization's estimating and management practices relies on the way the project is being procured and delivered. Typically the organization will be involved in design-bid-build (DBB), design-build (DB) or construction management (CM) projects and may be involved in a design assist (DA) role.

DBB is seen as the least desirable delivery mode by the organization, according to our interviews. In the case of a DBB, the estimating and tender process is very short (2-3 weeks) and wrought with uncertainties. The evaluation of project cost is largely based on the experience and knowledge of the personnel who are involved in the estimation process. Estimations are based on a set of 2D drawings and specifications provided by a team of consultants, at varying levels of detail. Estimations are compiled on a software platform that includes a third party costing database. The software allows the estimator to input quantities of specific elements and the software will automatically provide a cost unit and a labor unit. Typically, the estimators will work with the organization's General Manager and Construction Manager to process the documents and outline the project scope. In addition, on certain projects, they might involve key personnel (Project Managers, Foremen, etc.) to impart additional knowledge and refine the bid. The "estimating team" will generally go over the project documents and attempt to quantify each element and attach a cost to it's procurement or fabrication, installation, commissioning and servicing/warranty. Attributing a cost factor to elements is based on quantity with several factors linked to each particular element such as difficulty, schedule, labor, and several other extraneous factors such as weather and market conditions which are compounded into the final estimate. Furthermore, it was stated during one interview that additional provisions are sometimes made depending on the consulting firm that produced the design based on past experience with these consultants. In essence, outside of the actual count and measure of elements as represented on the plans, there is a considerable amount of factors which are taken into account that rely on the experience of the estimating team.

During the tender process, the estimating team and the subcontractors who are pricing out the work will submit RFIs to refine the design intent and get as much information as possible. Clarifications of plans will be produced under the form of addendum by the design consultants. It is at the tender phase that equivalency requests are usually submitted. Estimating in this context is a highly punctual and rigid process with a distinct input (tender documents + RFIs) and a distinct output (bid). Once confirmation is given and the contract is awarded, the team that prepared and submitted the bid will generally review the entire package, involving the Project Manager more closely this time, to comb over the project once more, go into greater detail and ensure that no major elements have been overlooked or errors committed during the tender phase that could impact project delivery. At this time, the project team will be assembled, including project coordinator and field staff. Contracts will be awarded to sub-contractors based on negotiations involving all those that have produced a bid. One interviewee said that it was at this point, during negotiations with sub-contractors, that any errors or omissions that were made during tender would be negotiated and "patched-over", risk being essentially transferred to the sub-contractors as much as possible. In the DBB delivery mode, BIM will usually be deployed once the contract has been awarded and its scope will be restrained to a specific area where clear value can be obtained, in mechanical rooms for example. DBB does not provide the opportunity for the organization to use BIM during the tender stage due to the short timeframe and the cost of modeling.

In the DB/CM/DA project delivery mode, more work goes into obtaining the contract as there is a longer proposal and qualification phase, however this form or delivery mode allows the organization to develop a relationship with other project stakeholders which is seen as beneficial by the organization. Estimating plays a large part in obtaining a contract, as the contractor must submit a gross maximum price (GMP). The estimation process is an iterative one. As design is being refined, so is the estimate becoming more and more precise. This allows for a tighter control over the budget as well as presents opportunities to optimize certain design decisions. These design decisions can be rapidly priced via the estimating team and informed decisions can be made as to how to proceed. Estimating in this context is an evolving and iterative process with many inputs and many outputs. However, once the Organization has submitted their GMP, they are responsible for delivering the project within the agreed price, which carries the risks similarly to a DBB delivery mode. Mobilization happens once contracts are awarded and the project has sufficiently been detailed in order to obtain permits and begin construction. Since the project team has been working together for a longer period of time and essentially all stakeholders have a good overall grasp of the project, the project start-up phase was noted as being much smoother than in the DBB mode due to many issues having been resolved during design. In the DB/CM/DA project delivery mode BIM will be deployed as early as possible to help inform design decisions. To date however, BIM has not been used to inform quantity take offs. The Organization is in the process of developing those capabilities.

5.5.2 Performance Assessment Practices

The Organization's performance assessment practices aim to track cost, schedule and quality as KPIs. These KPIs are tracked at the project level and used to evaluate project progress. The Organization has implemented a centralized project management and enterprise resource planning (ERP) software (Timberline® (Sage, 2013)), which allowed easy access to and reporting of project measures (for instance total time allotted for a specific cost code). The data made available through this software are: project estimates, cost reports, schedules, request for information (RFI) logs, change order (CO) logs, and employee timesheets.

Our observations allowed us to identify that the data collection mechanisms in place at the project level were reliant on the individual efforts of certain key personnel. Data collection was distributed across a limited number of project team members, namely the project manager, the project coordinator, the site superintendent and foreman. The project manager is mainly involved in aggregating and tracking the high-level key performance indicators such as cost and schedule. He maintains the associated elements in the project management software such as billings, work orders and material orders. He also tracks milestones and schedule items. The project coordinator tracks all project related communications – RFIs, COs, SIs, Shop Drawings, etc. – and maintains the associated logs within the project management software. The site superintendent and the foremen are responsible for the collection of data on a daily basis - activity planning and tracking, material tracking, quality assurance, and issue tracking. We also observed that although the organization had established a practice of tracking data and performance at the project level, this data wasn't being aggregated at the organizational level to detect trends in the BIM implementation process. In addition, data collection by the site personnel was seen as a challenge due to their multiple responsibilities, namely work execution, planning, tracking and issue resolution. A lot of time was spent on issue resolution, which didn't allow much time for other activities - BIM could potentially allay this particular issue.

5.6 Findings

The analysis of the quantitative data provides an empirical view of the performance of the Organization's BIM implementation process. The quantitative data, collected on the 8 projects indicated in Table 5.2 and Table 5.3 were analyzed. Projects 01-A and 02-A are non-BIM projects serving as a basis for comparison with the other BIM projects. The following KPIs were operationalized to assess the performance of the BIM implementation process across time within the organization:

- Project cost predictability,
- Project scope predictability,
- Productivity indicator predictability,
- Project schedule predictability,
- Project quality.

5.6.1 Project Cost Predictability

The first measure we assessed was predictability of cost data. The formula used to calculate this was taken from Rankin et al. (2008):

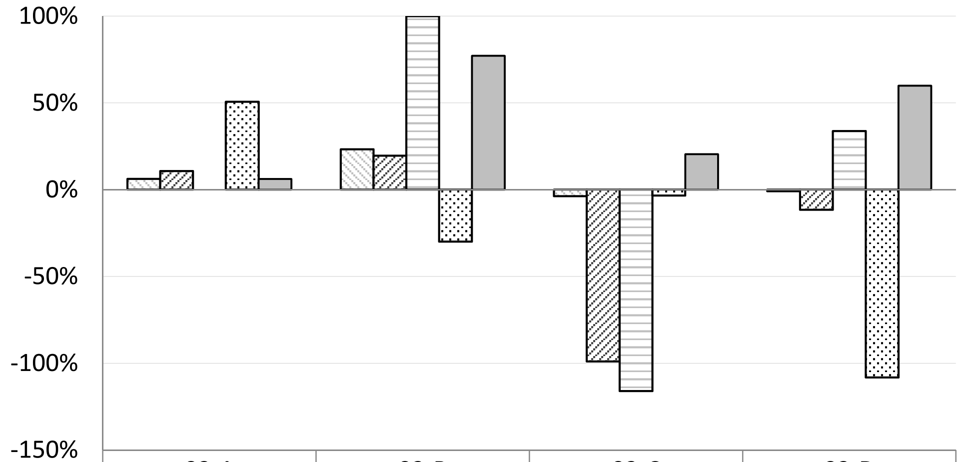
$$Cost\ predictability = \frac{actual\ cost - tendered\ cost}{actual\ cost}\ x\ 100 \tag{5.1}$$

Taken from Rankin et al. (2008)

A null value (0%) is desirable as it indicates complete predictability. A positive value indicates an actual cost that is superior to the tendered cost, i.e. over-budget. A negative value indicates a tendered cost that is superior to the actual cost, i.e. under-budget. The maximum positive value is 100%; there is no negative value limit. While percentage error, or the measure of predictability, is typically an absolute value (Rankin et al. 2008), the use of negative value allows to see where projects are under budget. We performed the analysis of cost predictability for 5 budget items: total cost of work (excluding profit), direct labor, BIM costs (cost of modeling), site supervision and project management (Figure 5.2 and Figure 5.3). These 5 budget items were selected as they involve the Organization's direct/indirect labor, which is seen as an area where BIM can potentially have significant impact (Khanzode et al. 2008)

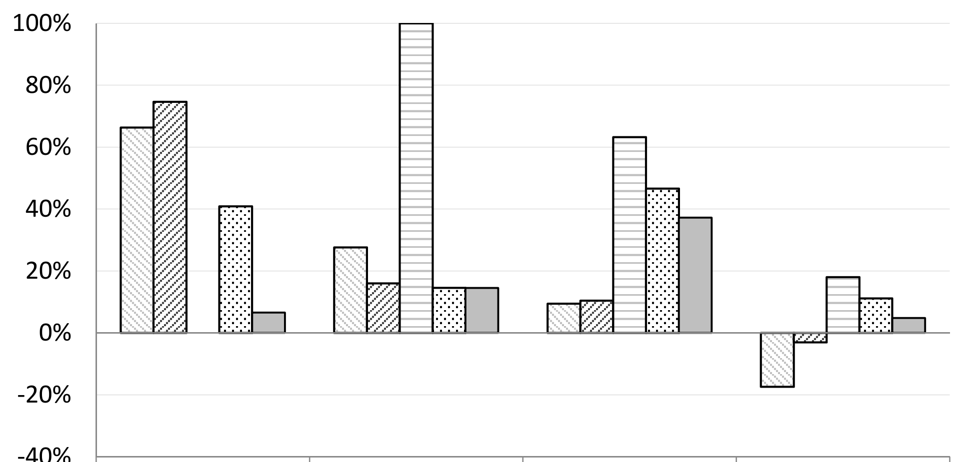
Figure 5.2 illustrates positive values for all cost items across the selected DES projects except total project costs and labor costs for project 01-D. Actual costs for the selected items are thus consistently higher than budgeted costs regardless of BIM implementation except for the aforementioned elements. BIM costs are consistently under estimated with project 01-B showing 100% variability, indicating that no costs were carried for BIM at tender. They are tending towards 0% however, which could indicate a better grasp of costs associated to BIM by the Organization as it gains experience with BIM on DES projects. Furthermore, the three projects where BIM was implemented show an improvement in cost predictability for total project costs and labor costs. This can be interpreted as BIM potentially having a positive effect on ensuring better cost predictability on these budget items. Moreover, the Organization is developing an expertise in DES projects, supported by BIM, which could explain the overall trend towards better predictability across time for the cost items discussed.

Figure 5.3 illustrates significant variance for many cost items across the selected Bldg. projects. Site supervision is consistently under budget for projects having deployed BIM. On the other hand, project management is consistently over budget for all projects. Project 02-B shows 100% BIM cost variability, indicating that no costs were carried for BIM at tender, while project 02-C shows -116% BIM cost variability, indicating that BIM costs came significantly under budget. This is due to the fact that the scope of BIM was significantly pulled



	02-A	02-B	02-C	02-D
Total Project Cost	6%	23%	-4%	-1%
Labor	11%	20%	-99%	-12%
BIM	0%	100%	-116%	34%
Site Supervision	51%	-30%	-3%	-108%
Project Management	6%	77%	20%	60%

Figure 5.2 Cost - Cost predictability - DES projects



	01-A	01-B	01-C	01-D
Total Project Cost	66%	28%	9%	-17%
Labor	75%	16%	10%	-3%
BIM	0%	100%	63%	18%
Site Supervision	41%	15%	47%	11%
Project Management	7%	15%	37%	5%

Figure 5.3 Cost - Cost predictability - Bldg. projects

back during the project and limited to a very small, yet highly complex area. Total project cost predictability for projects 02-C and 02-D as well as site supervision cost predictability for project 02-C are very good. That being said, it is difficult to draw a clear causal link between the use of BIM and cost predictability in the case of building mechanical projects due to the many variables that come into play. However, by maintaining the database, a clear trend could emerge that highlights the impact of BIM over time on this indicator.

Figure 5.4 illustrates the variability between actual and estimated cost of BIM as a percentage of total labor cost; it is an attempt to establish a clear benchmark relating to the cost of BIM. The average actual cost of BIM is 6.2% of actual labor costs on DES projects while it is 2.5% on Bldg. projects. These values are highly dependent on the scope of modeling and the context in which BIM is deployed, however it gives a sense of scale for the cost of BIM in relation to the cost of labor. The difference between the tendered and actual costs tend towards 0%, with projects 01-D, 02-C and 02-D showing a difference of 1.5% or less. It can be interpreted that as the Organization gains experience with deploying BIM in their projects, they are rapidly becoming better at evaluating the cost of BIM. As the Organization progresses in its BIM

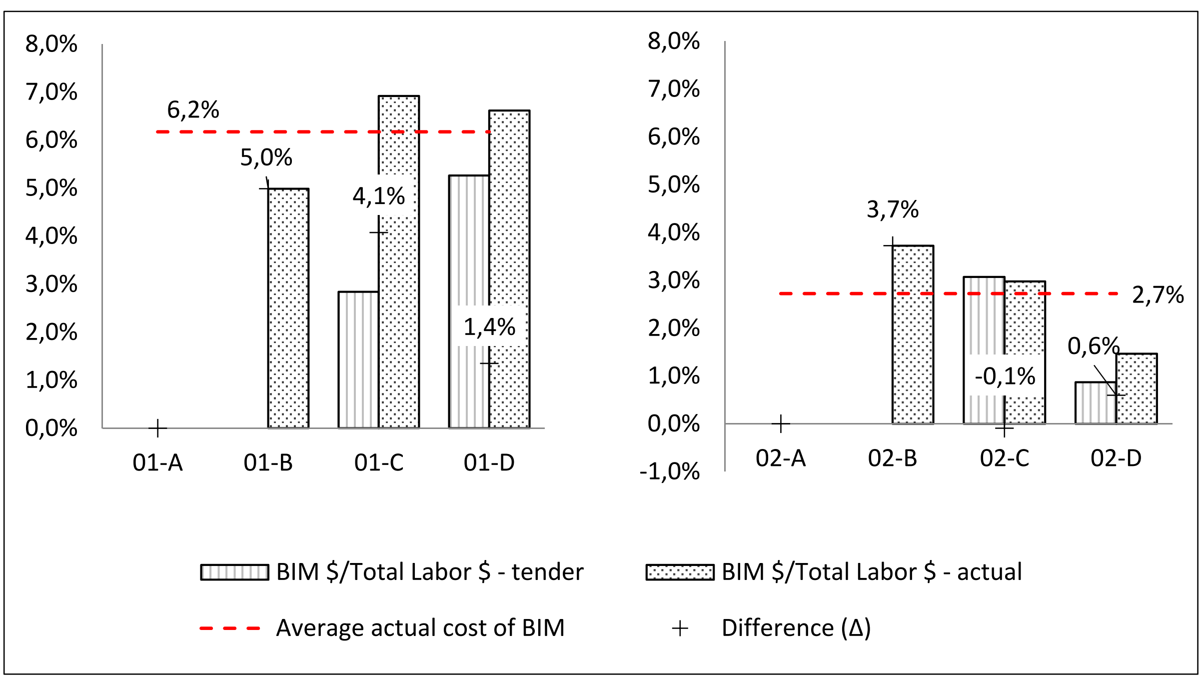


Figure 5.4 Cost - Cost of BIM / Total cost of labor

implementation process, the expectation would be that for the DES projects, due to repetition and the similar nature of project settings, the percentage of BIM costs compared to labor costs would decrease over time, i.e. BIM would become less expensive. For the building mechanical projects, this decrease could be expected between similar projects and as the Organization gains experience in the modeling and coordination of mechanical models. However, this trend may be less clear due to the multitude of factors influencing building mechanical projects.

5.6.2 Project scope predictability

Figure 5.2 and Figure 5.3 suggests relatively low cost predictability for certain budget items across both project streams. This could suggest many things. For one, it could suggest that a lot of changes were issued during the construction phase. This is confirmed to a certain extent by Figure 5.5, which indicates the total cost of change order (CO) as a percentage of total cost of work. Furthermore, contrary to past research, Figure 5.5 suggests no clear impact of BIM

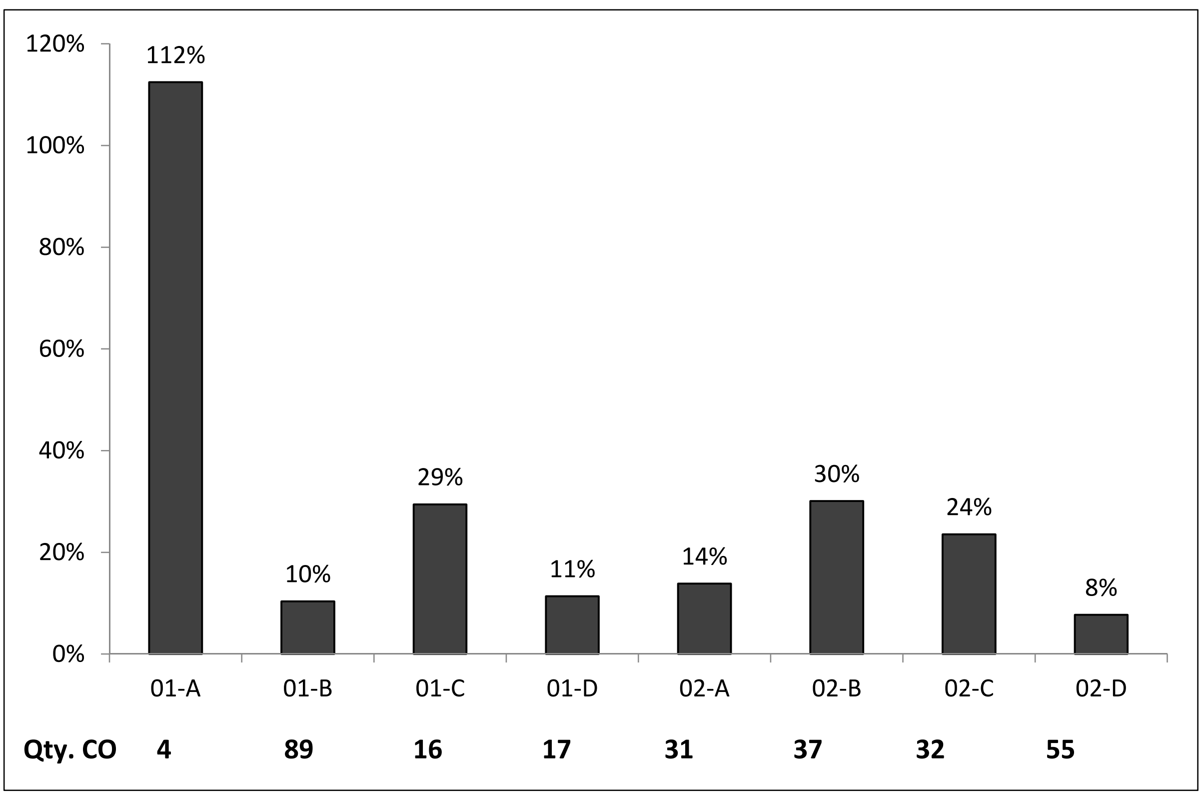


Figure 5.5 Scope - Total Cost of CO / Total cost of work and Qty. of COs

on the number of COs in either DES project or building mechanical projects. This could be caused in part by the lonely setting in which BIM was implemented and the limited influence the Organization has over project delivery in the supply chain – i.e. being “the last to BIM” doesn’t allow the Organization to influence upstream decision making and thus impact the quantity and scope of COs.

5.6.3 Productivity indicator Predictability

One of the measures of productivity is that of input (time, cost, etc.) per unit of output produced taken from Durdyev and Mbachu (2011):

$$productivity = \frac{input}{output} \tag{5.2}$$

Taken from Durdyev and Mbachu (2011)

In this case, cost per unit produced, both for labor and for BIM, were analyzed as an indicator of productivity. For the DES projects the unit used was dollar ($) per ETS. For the building mechanical projects, the unit used was dollar ($) per square foot of total project area. Figure 5.6 illustrates the variations between tendered labor costs and actual labor costs per unit for all eight projects (also illustrated in Figure 5.2 and Figure 5.3). While the labor cost per unit is difficult to compare between projects, due to the variable contexts, its predictability across all projects nevertheless constitutes a considerable risk for the organization. For the DES projects, predictability trends towards a null value, whereas this is not the case for building mechanical projects. Furthermore, a major difference is noted between non-BIM and BIM projects for the DES projects, which, along with increasing overall expertise in this particular area, potentially indicates a positive impact of BIM on the predictability of labor productivity. The data are inconclusive for the building mechanical projects. Furthermore, the use of gross floor area as a productivity unit is questionable and is addressed in Poirier et al (CHAPTER 6)

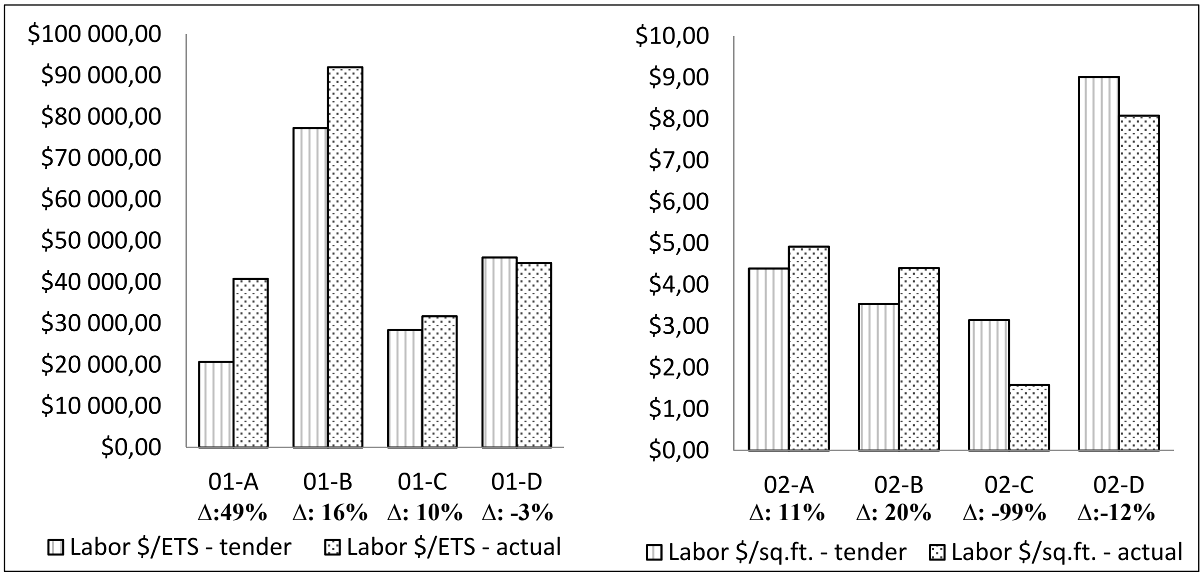


Figure 5.6 Productivity - Labor cost per unit

Figure 5.7 illustrates productivity rate – units performed per unit of time (output/input). This is different from cost per unit performed (Figure 5.6) since the measure doesn't include the pay grades and burden of the employees. It is an indication of direct time required to perform a task. For the DES projects, the units performed represent the quantity of ETS' (or fraction thereof) performed per hour. The secondary axis represents the number of hours it takes to complete one ETS. For building mechanical projects the units performed represent project area performed per hour. The predictability of productivity rate in both streams is highly variable across projects, with projects 01-B, 02-A and 02-B having a lower actual productivity rate than estimated, while actual productivity rates for projects 01-A, 01-C, 01-D, 02-C and 02-D are superior to estimated productivity rates. On the DES projects where BIM was used, a significant increase in field productivity rate is noted for projects 01-C and 01-D. The use of BIM driven, off-site prefabrication for these projects could potentially explain this increased productivity. The baseline project 01-A also shows better actual productivity. As such, the comparison to non-BIM project offers no ground to state that BIM was beneficial in this case. For the building mechanical projects, both projects 02-C and 02-D show better actual productivity, which can be attributed also to BIM driven, off-site prefabrication, especially for the mechanical rooms. Again project context is crucial in this case, as the organization's productivity is greatly reliant on the overall management of the project by the general contractor (i.e. crowding, sequencing, etc.) as well as many other project specific factors. This particular measure of the impact of BIM on labor productivity is further investigated in Poirier et al (CHAPTER 6). That being said, as the Organization build's its database, trends could emerge per project type, procurement mode and level or BIM implementation.

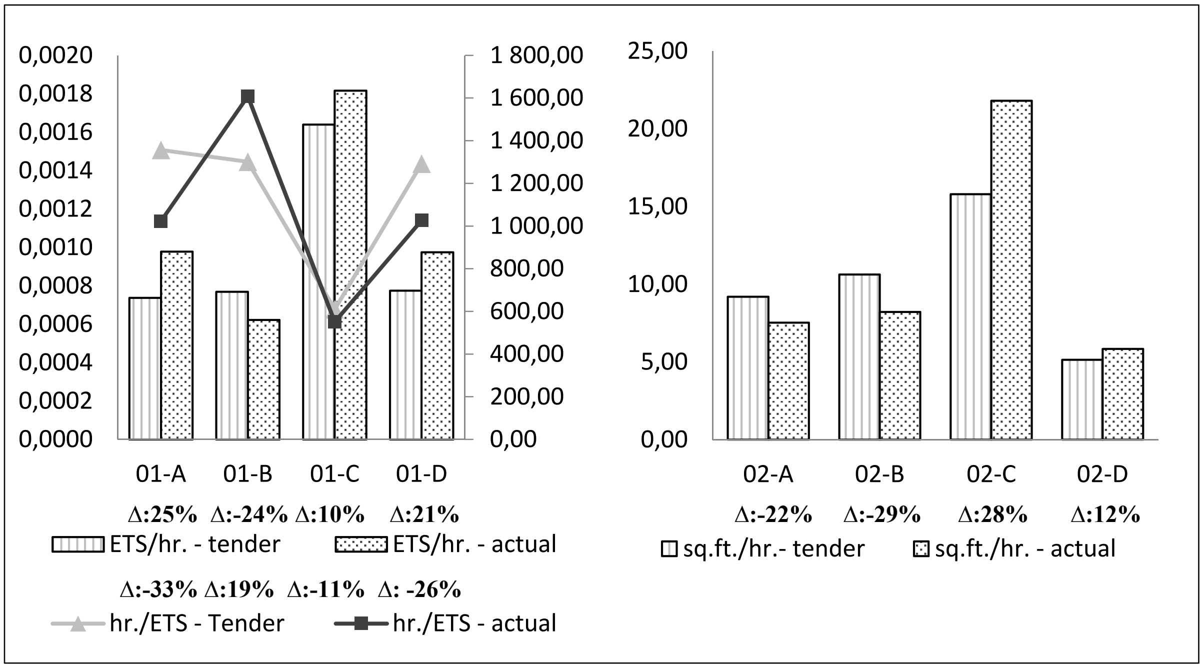


Figure 5.7 Productivity - unit per time

Figure 5.8 illustrates the variations between tendered BIM costs and actual BIM costs per unit for all eight projects (also illustrated in Figure 5.2 and Figure 5.3). Except for project 02-C, all other BIM projects studied had an actual cost of BIM that was superior to the tendered cost. This speaks to BIM costs being underestimated. The average actual cost of BIM per unit for the DES projects is approximately $3,500.00 per ETS while it is $0.11 per sq.ft of total project area. This indicator serves as a baseline to compare future projects against. Indeed, as the Organization gains experience, it is expected that this average cost per unit should remain stable or decrease. Again, this is highly dependent on project context and scope of modeling, however it can serve as a way to assess the efficiency of BIM use and progress of implementation.

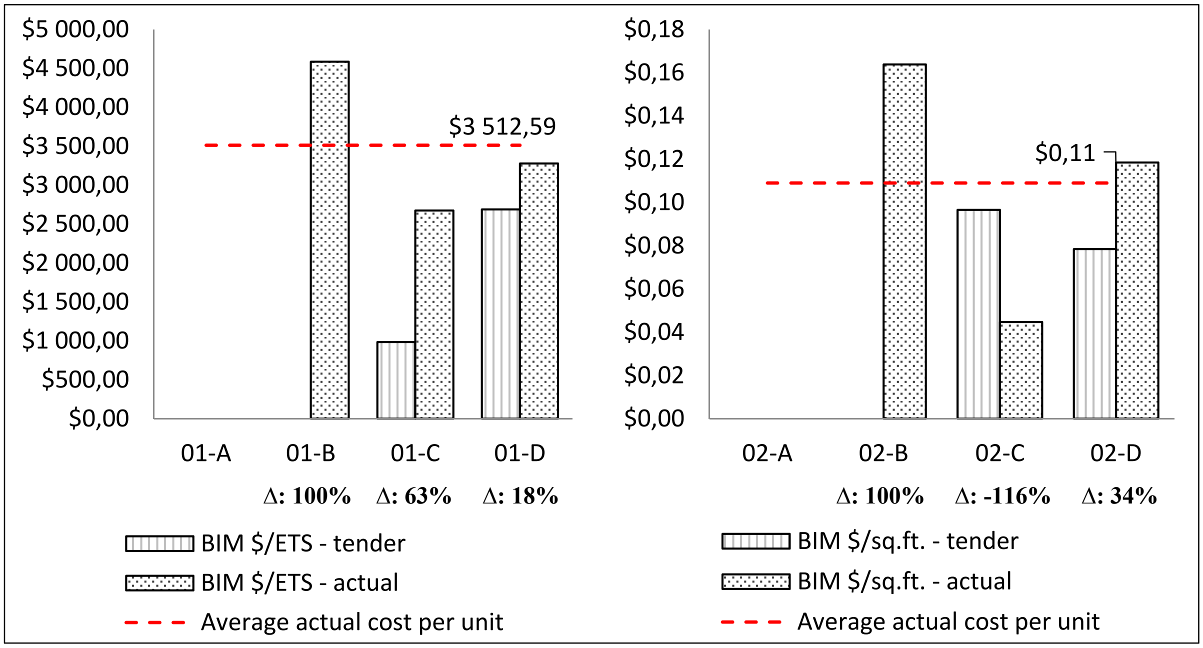


Figure 5.8 Productivity - BIM cost per unit

5.6.4 Project Schedule Predictability

Figure 5.9 illustrates the predictability of labor duration across the projects studied. The formula used to calculate this was taken from Rankin et al. (2008):

$$Schedule\ predict. = \frac{actual\ duration - tendered\ duration}{actual\ duration}\ x\ 100 \tag{5.3}$$

Taken from Rankin et al. (2008)

As per cost predictability, a positive value indicates an actual duration that is superior to the tendered duration and vice-versa. The wide variation across all projects and the misalignment between schedule predictability and cost predictability could be due to the estimating process utilized by the Organization (refer to section 5.5), whereby labor units are associated with quantities, thus duration is a factored by-product of estimated quantities. It could also be due to changes issued during the construction project. It is important to note that this particular measure is not representative of overall schedule predictability. The durations shown in Figure 5.9 are direct durations taken from each project's timesheets and estimates provided by the organization, not the scheduled durations established by the project management team. While they are typically correlated, i.e. the estimated labor units inform the duration of an activity, the sequencing of work is left to project managers who can optimize the schedule and adapt it to the General Contractors master schedule. In this case, BIM is not shown to have an impact on scheduled duration across the projects studied.

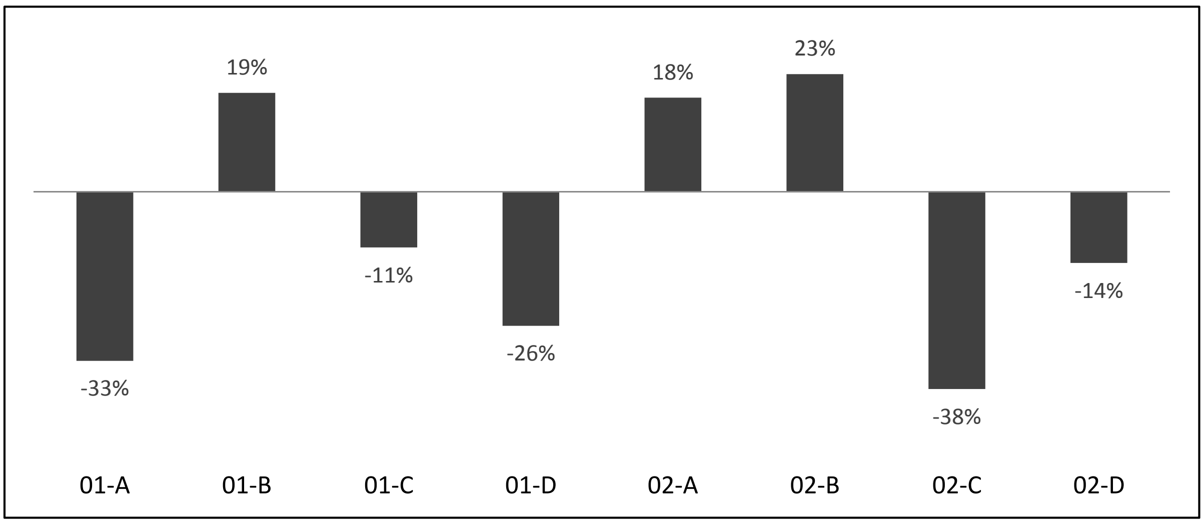


Figure 5.9 Schedule - Predictability of Labor duration

5.6.5 Project Quality

We analyzed the cost of rework and deficiency repair as an indicator of project quality. For the building mechanical projects, either data was missing or the actual rework performed very limited, totaling less than 0.001% of total project costs. For the DES projects no clear trend was discernable regarding a decrease in rework for projects where BIM was implemented.

5.7 Discussion

5.7.1 Analysis of the findings

Our observations and analysis confirm the considerable challenges associated with assessing the performance of BIM implementation at both the organizational and project level; dissociating the use and impact of BIM from the project context is a significant, if not impossible, challenge. Thus, for the KPIs that were targeted and their respective metrics, it is challenging to draw clear conclusions concerning the performance of BIM within the projects studied and its evolution within the Organization. By formulating and testing the hypothesis that the implementation of BIM within the Organization would improve predictability of project costs, schedule, scope, productivity and quality of projects, we were attempting to identify trends in the behavior of the metrics with regards to BIM use and evolution across time. Our findings suggest that indicators such as predictability of total project costs and labor costs for DES projects (Figure 5.2) as well as cost of BIM as a percentage of total cost of labor (Figure 5.4) show an improvement across time on projects where BIM was implemented by the Organization. However, for other indicators, such as cost conformance for building mechanical projects (Figure 5.3) or schedule conformance (Figure 5.9) there is no clear trend marking a positive evolution of BIM within the Organization. In addition, indicators, such as cost of BIM as a percentage of total cost of labor (Figure 5.4) and BIM costs per unit (Figure 5.8) have a lot of potential in serving as a benchmark within the Organization. In accordance with the main hypothesis that was formulated, it could be put forth that the cost of BIM for the Organization will remain stable or decrease over time as they gain experience. The same can be said for labor productivity (Figure 5.6 and Figure 5.7) which should tend to improve as the Organization moves towards pre-fabrication. This was confirmed to a certain extent in Figure 5.7.

These measures are, however, extremely reliant on project context, which includes project type and scope, delivery mode, position of the organization within the supply chain as well as the level and scope of BIM implementation. This is supported by the apparent lack of influence of BIM on the predictability of project scope, namely the quantity and cost impact of change orders (Figure 5.5). This particular metric has been reported elsewhere as an indicator of the positive impact of BIM on project outcome (e.g. Barlish and Sullivan, 2012, Khanzode et al., 2008). Therefore, this apparent disconnect between the findings of this project and those presented elsewhere reinforces the notion of BIM as a collaborative undertaking, where true value is obtained when BIM is implemented across the project supply chain (NIBS, 2007). In this light, the approach and measures presented here can provide targets for the organization to reach and help inform the implementation process.

5.7.2 Transforming practice

While we observed and analyzed the performance of BIM implementation within the Organization, we also observed the shift in practice that was required to develop the benchmarking and performance measurement capabilities. Indeed, we observed many shortcomings with the Organization's current performance assessment capabilities. For example, performing project post-mortems as well as extracting project data to maintain a database to benchmark and track project performance was not a common practice. This was explained as being a symptom of the fast paced and unpredictable nature of the construction industry, which requires that project personnel be involved on many projects at once and jump from one project to the next with little time to perform a post-mortem analysis of completed projects. This step is crucial in the benchmarking and performance assessment process to bridge the gap between the project level data and its aggregation at the organizational level (Figure 5.1). The research project attempted to facilitate this aggregation by identifying which data points should be aggregated to populate the database.

Furthermore, if predictability is to become a longitudinal measure of performance at the organizational level, there is a need for more precision in establishing budgets and schedules as well as determining what an acceptable variance (delta) is. Indeed, it was confirmed during discussions with estimators that labor units are often adjusted during the estimating process and that it is heavily reliant on heuristic methods. This is explained in part by the short time frame estimators have to estimate a project in a DBB setting. The Organization should look into leveraging BIM to assist in establishing the project budgets and tenders.

The benchmarking process requires a lot of data, captured over a long period of time, in order to establish clear trends in the performance assessment that can be filtered according to project type, procurement and delivery mode, level of BIM use, etc. It also requires a lot of time and effort to set-up and maintain a working database. For the Organization, allocating time to the benchmarking process was seen as problematic. It currently has only one financial controller who is involved in compiling and producing various progress reports for all projects. Additional responsibilities to track and maintain a benchmarking database would be too onerous for him alone. The Organization would therefore have to commit or hire additional personnel to maintain and update this database. In benchmarking performance, the DES projects would be better suited as their contexts are similar. For building mechanical projects, building type, budget and scope, procurement mode and other contextual factors would have to be included in order to compare similar projects. This speaks to the need for a large pool of data, which is rigorously acquired over time

Lastly, in developing additional metrics to assess the performance of BIM implementation, there is a need to establish metrics that are directly related to the organization's type, position in the supply chain and sphere of influence. By evaluating the predictability of these metrics the performance of BIM implementation could be better evaluated. This can complement maturity models, which rely on more qualitative measures to evaluate capability evolution within an organization.

5.8 Conclusion

The emergence of BIM has exacerbated the need to holistically consider the benchmarking and performance assessment process within the construction industry. Performance, impact, ROI, capabilities and maturity all need to be taken into account when assessing the BIM implementation process. While increasing evidence of BIM's perceived and measured impact on project delivery is fueling its growth across the construction industry, many issues remain around establishing non-spurious relationships in its assessment. Past work has attempted to establish some relationships between capabilities, the use of BIM and its impact on performance, such as productivity, cost, schedule and quality. However, the scope of analysis of these works have been limited to the project context (Khanzode et al, 2007; Giel and Issa, 2011; Barlish and Sullivan, 2012) or to the organizational context (Coates et al, 2010).

This article has presented an evolutionary approach, supported by specific metrics, to benchmarking and performance assessment that bridges both the project and the organizational contexts to help an organization evaluate the performance of and inform its BIM implementation process. It has specifically looked at the predictability of KPIs across time as an indicator of performance. By evaluating the evolution of predictability of certain metrics across eight different projects, the research team laid the ground work for the assessment of the BIM implementation process from a quantitative perspective, which could support maturity modeling and capability assessment. While limited, the analysis of the data sample has allowed us to highlight that indicators, such as BIM costs and labor productivity, were seen as becoming more predictable across time. Other indicators, such as scope and quality were inconclusive, mainly due to the lonely setting in which BIM was implemented by the Organization. This speaks to the need to establish collaborative BIM environments to fully benefit from the improvements in project performance highlighted elsewhere. Future work could look into refining the approach presented here, evaluating the interactions between the various KPIs and investigating other KPIs to support this process.

This article does not attempt to establish a clear causal relationship between the use of BIM and project performance. Indeed, the limitations of this work lie in controlling for all variables that define the project context. Creating a set of generalizable metrics is near impossible and it is why no causation is infirmed between BIM use and project outcome. In parallel, the productivity measures used in this research require further investigation, namely in refining the units of measurement and limiting them to the actual scope of modeling. The specific field of mechanical contracting was studied in the development of KPIs, however further work should look into establishing metrics for other fields of work. Lastly, the extent to which BIM was implemented in the projects studied represents a limitation. Indeed, all the projects studied were performed in a lonely setting. This speaks to the current state of the market in Canada and the difficulty the Organization is having in working in an integrated environment.

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CHAPTER 6

MEASURING THE IMPACT OF BIM ON LABOR PRODUCTIVITY IN A SMALL SPECIALTY CONTRACTING ENTERPRISE THROUGH ACTION-RESEARCH

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6.1 Abstract

Productivity in the construction industry is a well-documented and expansive field of research. It benefits from over four decades of research that have developed models and methods for evaluation and identified multiple factors that influence it. In parallel, Building information modeling (BIM) has emerged as a disruptive innovation, showing great potential to mitigate many of the factors negatively affecting construction productivity. Indeed, studies are increasingly looking into the impact of BIM on project performance. Improving construction productivity, labor productivity in particular, is one of the widely reported benefits. For organizations looking to transition to BIM, being able to grasp these benefits and quantify their impact is extremely important to ensure the viability of the BIM implementation process. This article presents the findings of an action-research project undertaken with a small mechanical contractor which investigates the impact of BIM on labor productivity on a large commercial project. The objective of the action-research was to assist the organization in reconfiguring its performance measurement practices in light of the transition to BIM and prefabrication. The article discusses the challenges of this reconfiguration and presents the findings from the performance measurement process which was put in place. The findings suggest a clear

positive impact of BIM on labor productivity on the project studied: the areas that were modeled and prefabricated showed an increase in productivity ranging from 75% to 240% over the areas that were not modeled. More importantly, however, the article presents a strategy allowing organizations to consistently assess their performance relating to labor productivity.

6.2 Introduction

Many instances of best practice and innovation involving building information modeling (BIM) implementation have been reported in the literature (Eastman et al., 2011). Experience tells us, however, that there remains a considerable gap between the leading edge (i.e. early adopters) and the majority in the construction industry (Boktor, Hanna and Menassa, 2014). Considering that implementing BIM represents considerable financial risk, especially for SMEs, clear benefits need to emerge and be quantifiable in order for these SMEs to move forward with implementation. The promise of increased labor productivity is one of such benefits that is stimulating the adoption and implementation of BIM in the construction industry. Indeed, this novel approach to project delivery is presented as a solution to overcome the apparent stagnation and even decline of labor productivity in the construction industry (Teicholz, 2004; 2013) While questions surrounding this macroeconomic view of labor productivity is debated (Allmon et al., 2000; Rojas and Aramvareekul, 2003a),it remains that there is a general consensus around the need for significant improvement in the construction industry. Several strategies have been developed that touch on the potential of BIM to improve labor productivity, namely through project coordination (Staub-French and Khanzode, 2007) and prefabrication (Nawari, 2012) amongst others. Many of these benefits have been reported (Neelamkavil and Ahamed, 2012) and attempts to quantify the impact of BIM on labor productivity have been recorded (Khanzode, Fischer and Reed, 2008). Additional work, however, is required to study, and more importantly to allow organizations to evaluate, the impact of BIM on labor productivity in the construction industry if it is to become grounds for justification of BIM adoption. In particular, the way in which they go about to measure this impact is often unreliable due to the sheer complexity of measuring labor productivity, which requires considerable effort in collecting and analyzing data in the field (Thomas, 2012). This represents a major barrier to developing this particular measure as a valid way to justify an organization's transition to BIM.

This article presents the findings of an action-research project undertaken with a specialty contracting small enterprise who adopted and has been implementing BIM since 2010. The Organization with whom we were performing the action-research project was founded in 2004 and operates in the Vancouver, British-Colombia area. It has 67 employees and is deployed along a project-based organizational structure across two divisions. It counts 24 office based employees (project managers, coordinators, estimators as well as administrative staff) who form the project management team and 43 site based employees (superintendents, foremen, journeymen). The objective of this action-research project was to assist the organization in reconfiguring its performance assessment practices in order to allow it to effectively evaluate the impact of BIM on labour productivity. Working with the data that were made available through the organization project management software and by reconfiguring part of their project performance measurement practices, the research team was able to develop a strategy for the organization that would allow them to benchmark and track their labor productivity on BIM projects. The key contribution of this article lies in the action-research approach taken to the reconfiguration of performance measurement practices within a small specialty contractor. The article focuses on labor productivity and BIM, a field of research which, while gaining popularity, is still relatively sparse, especially given the fact that labor productivity is seen as one of many measures benefitting the most from BIM. Lastly, the article develops a strategy aimed at measuring labor productivity in an effective manner which isn't too onerous for small organizations.

6.3 Background

6.3.1 Measuring labor productivity

There exist different perspectives on what constitutes a measurement of labor productivity in the construction industry. These differences lie in the methods through which data are collected and analyzed, the quality of the data being analyzed and most importantly the scale at which the data are being collected. Indeed, there are two distinct perspectives on labor productivity in the construction industry: the macro perspective and the micro perspective (Dozzi and AbouRisk, 1993). There is some controversy surrounding the macro perspective due to, among others, inconsistencies in measurement methods and lack of consensus on what should be measured (Allmon et al., 2000; Goodrum and Haas, 2002). The macro perspective does allow the identification of long term trends at the industry level, for instance having identified stagnation or decrease in the US industry (Teicholz, 2004; 2013) or growth in the Canadian industry (Nasir et al., 2013) and other countries such as the UK and Denmark (Pekuri, Haapasalo and Herrala, 2011) . Several studies have found that multifactor productivity, a combination of labor and capital costs producing an output, best suited for this perspective (Tran and Tookey, 2011). For organizations however, the usefulness of this perspective is questionable as it doesn't provide a basis for consistent comparison and interpretation of the data can be misleading (Goodrum and Haas, 2002). The micro perspective, which is focused on the task, is seen as a more suitable approach for organizations to benchmark their own labor productivity (Dozzi and AbouRisk, 1993). From this perspective, productivity is measured in terms of input and output at the individual work task level (Halligan et al., 1994; Park, Thomas and Tucker, 2005). Durdyev and Mbachu (2011) provide an operational definition of productivity as:

> the amount or quantity of output of a process per unit of resource input […] where: Output could be in units or dollar value of product or service, revenue generated or value added; resource input could be in units or dollar value relating to manpower (i.e. man-hour), machinery (i.e. machine hour), materials (i.e. quantity), or money (i.e. dollar value). (Durdyev and Mbachu, 2011, p.19)

That being said, construction productivity is often taken to mean labor productivity. According to Halligan et al. (1994)

> this measure of productivity has several advantages: the meaning of the term labor productivity is relatively well understood; labor productivity is often the greatest source of variation in overall construction productivity; and the productivity of other inputs can often be measured with respect to labor productivity. (Halligan et al., 1994, p. 48)

Park, Thomas and Tucker (2005) discuss the lack of a standardized definition for productivity in the construction industry. They choose to define labor productivity per the following equation:

$$labor\ productivity = \frac{input\ (work\ hour)}{output\ (quantity)} \tag{6.1}$$

Taken from Park, Thomas et Tucker (2005)

On the other hand, Halligan et al. (1994) and many others after (e.g. El-Gohary and Aziz, 2014; Freeman, 2008)), indicate that construction labor productivity should reflect units or work placed or produced per man-hour, per the following equation (also called the unit rate):

$$labor\ productivity\ (unit\ rate) = \frac{output\ (quantity)}{input\ (work\ hour)} \tag{6.2}$$

Taken from Halligan et al. (1994)

The labor productivity performance factor is also seen as a way to measure productivity (Thomas et al., 1990):

$$performance\ factor = \frac{estimated\ unit\ rate}{actual\ unit\ rate} \tag{6.3}$$

Taken from Thomas et al. (1990)

Lastly, the performance ratio has also been presented as a measure of productivity in, amongst others, Yi and Chan (2014) where expected productivity, similarly to baseline productivity in Thomas and Završki (1999) is calculated as the base rate of productivity when there are no disruptions to work :

$$performance\ ratio = \frac{actual\ productivity}{expected\ productivity} \tag{6.4}$$

Taken from Thomas and Završki (1999)

There exists many approaches to measuring and evaluating labor productivity in the field. The key is in its comparison across time or across systems. Indeed, productivity is a relative concept, which must be contextualized to be a valuable indicator of performance (Bernolak, 1997). Methods such as field rating, work sampling, five-minute rating, field surveys and models such as the Method Productivity Delay Model (Dozzi and AbouRisk, 1993), the

Construction Productivity Management Model (Motwani, Kumar and Novakoski, 1995) or factor-based models (Thomas et al., 1990) are aimed at identifying and mitigating factors that negatively impact productivity. Other models such as Baseline Productivity Analysis (Thomas and Završki, 1999) and Measured Mile Analysis (Schwartzkopf, 1995) are used as tools to quantify and evaluate variability of productivity, a useful measure of project success (Menches and Hanna, 2006), which can act as an indicator of overall project performance and justify claims for lost productivity (Ibbs, Nguyen and Lee, 2007).

6.3.2 Factors affecting construction labor productivity

The field of research studying the various factors affecting construction labor productivity is a very well documented and expansive one. Considerable work over the past four decades has gone into identifying the factors that affect construction labor productivity (Yi and Chan, 2014). While construction productivity and construction labor productivity have been taken as synonymous by some authors (Halligan et al., 1994), there is an important distinction to be made between factors affecting both as they are not compiled at the same level: construction labor productivity is a subset of construction productivity (Herbsman and Ellis, 1990). Most studies categorize factors using a two tiered system. For example, Kazaz, Manisali and Ulubeyli (2008) develop four categories of factors affecting construction labor productivity: Organizational, Economic, Physical, Socio-psychological. The authors go on to identify 36 underlying factors within those categories. Rojas and Aramvareekul (2003b) also develop four categories which are: Industry Environment, Manpower, Management system and strategies, External conditions and identify 18 underlying factors within those categories. Dozzi and AbouRisk (1993) identify 9 categories and 44 underlying factors. Enshassi et al. (2007) identify 10 categories and 45 underlying factors. Dai, Goodrum and Maloney (2009, citing CII, 2006), identify 12 categories and 83 underlying factors, and so forth. Several factors have been developed interchangeably as both a category and as an underlying factor. For instance, motivation as a factor influencing labor productivity has been presented as a category by Dozzi and AbouRisk (1993), Enshassi et al. (2007) and Rivas et al. (2011), among others, who then go on to develop underlying factors that affect worker motivation. On the other hand, motivation has been presented as an underlying factor among many others such as Dai, Goodrum and Maloney (2009), Rojas and Aramvareekul (2003b), and Adrian (2004). It becomes apparent that while there is relative consensus surrounding the factors that affect construction labor productivity in the literature, the categorization of these factors has been inconsistent (Rivas et al., 2011; Yi and Chan, 2014). A trend does emerge from the literature in which factors are related to a certain level of granularity – Environment, Industry, Organization, Project or Individual (Yi and Chan, 2014). At the individual level, these factors are further related to specific individual skills or attributes (i.e. human factors) - management, supervision and labor. The table presented in Appendix VIII (Table-A VIII-1) summarizes a series of factors affecting construction labor productivity found in the literature across these levels of granularity and based on (Yi and Chan, 2014) analysis framework.

Several studies have tried to work out different ways to increase productivity at the task level by addressing these factors. These opportunities can be classified in four categories: management systems, manpower, technology, and new techniques (Jergeas, 2009). However, according to Rojas and Aramvareekul (2003b), improving productivity is a management issue, therefore the introduction of new techniques or technologies may be necessary, but not sufficient to improve productivity. The introduction of BIM into the project delivery process challenges these findings as it represents a solution encompassing both the managerial and technological aspects mentioned. Moreover, according to the CII(2008), economic research has shown technology trends have a greater impact on labour productivity than on multi-factor productivity measures. In light of this, investments in new equipment and technology may improve an Organization’s labour productivity, but its productivity factors may actually decline if the relative increase in the cost of the equipment outweighs the relative saving in labour cost and gains in output. The implementation of BIM faces these challenges whereas investments in BIM have the potential to outweigh any gains made by its implementation.

6.3.3 The impact of BIM on labor productivity

For the purpose of this article, a Building Information Model is defined as:

> [...] a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward. (National Institute of Building Science, 2007)

Building Information Modeling is defined as "[...] a technology and associated set of processes to produce, communicate, and analyze building models." (Eastman et al., 2011) BIM is thus conceptualized to be a tool, a technology and a process, which enables the digital construction of a building, or prototyping, prior to its physical construction. As such, BIM serves as a shared information resource for all project stakeholders across a project's lifecycle (Eastman et al., 2011).

There is much anecdotal evidence of the successes of BIM and its positive impact on project performance. Empirical evidence is more difficult to come by, however over the past decade studies have increasingly attempted to quantify the impact of BIM on project performance. For example, Bryde et al. (2013) look into the reported benefits of BIM across 35 construction projects having utilized BIM. They find that the most reported benefits of BIM are related to cost reduction and control as well as time savings. They also discuss potential benefits of BIM for project managers and how BIM can improve coordination and communication, among others. They do not discuss, however, the potential impact of BIM on productivity which lies at the root of these improvements. Giel and Issa (2011) focus on the return on investment (ROI) of BIM, namely the avoidance of extra costs due to conflict detection. This implies productivity improvements through less rework and design changes, however it is not discussed as such in the article. Moreover, studies have increasingly looked into defining what organizations should be measuring to evaluate the impact of BIM on project performance. For example, Suermann (2009) studied the impact of BIM on the 6 KPI identified as being the most useful for the construction industry by Cox et al. (2003): quality control (rework), on-time completion, cost, safety (lost man-hours), dollars/unit performed, and units per man hour. He concludes that

BIM has the potential to have the most influence on quality control, on-time completion and productivity (units/man hr.). Khanzode et al. (2008) identify the challenges and benefits of using BIM for mechanical, electrical and plumbing (MEP) coordination on the Camino Medical Healthcare Center. The authors first lay out the process and set guidelines for implementing BIM for MEP coordination. They then specify and use a series of measures in their evaluation of the project to evaluate the impact of BIM. These measures are: better project understanding, field productivity rate increase between 5 and 25%, on-time completion, quantity of off-site prefabrication and amount of rework reduced to 0.2% of total hours of field work. Sacks and Barak (2008) measure the impact of BIM on productivity for structural engineering practices. They estimate between 15 and 41% gains in productivity, which translates to fewer hours spent on drawing production. Coats et al. (2010) propose several KPIs through action-research with a small design firm in the UK to evaluate the BIM implementation process. The authors allude to productivity in the form of man hours spent per project and speed of development. In his dissertation, Chelson (2010) identifies the key indicators of BIM's impact on productivity as being: quantity of request for information (RFI), amount of rework, schedule compliance and change orders due to plan conflicts. According to him, the positive impact of BIM on field productivity is related to human factors rather that technical factors. However, he is faced with significant limitations such as the absence of historical data due to the newness of BIM, the uniqueness of construction projects and the difficulty for most organizations to identify their own productivity rates. This limits the possibility of establishing cause-effect relations between the use of BIM and labor productivity, let alone in relation to management types and project delivery modes. This is a challenge that most if not all studies, let alone organizations, face in attempting to quantify the impact of BIM. It becomes apparent that BIM has much potential to positively impact labor productivity for all construction industry practitioners be it more efficient design and documentation process for professionals, better access to relevant information for managers or creating favorable conditions in the field through fewer conflicts and less rework. Work is still needed, however to further investigate the impact of BIM on specific measures such as labor productivity.

6.4 Research Methodology

Based on past work performed over a two year period with the Organization in question, we initiated an action-research project to evaluate the impact of BIM implementation on their labour productivity. An action-research approach was employed due to it's cyclical, iterative approach, it's interventionist emphasis within the research setting (Lewin, 1946) and it's grounding in the pragmatist epistemological paradigm (Azhar, Ahmad and Sein, 2010). This interventionist approach was deemed necessary as the Organization's need to reconfigure and rethink how they collected and analyzed labour performance data around the novel project delivery practices introduced by BIM had emerged over the course of this two year longitudinal case study. During this time, we observed and documented the Organization's BIM adoption and implementation process (Poirier, Staub-French and Forgues, 2015b). We also attempted to benchmark and assess the performance of the implementation process (Poirier, Staub-French and Forgues, 2015a). A clear gap was identified with regards to assessing labor productivity and how this particular measure could reflect the value and the impact of the BIM implementation process. We therefore decided to focus on labor productivity as a specific measure of the impact of BIM. We thus formulated the following research questions: What is the impact of BIM on labor productivity for a mechanical contracting enterprise? and how do you measure this impact? The objective of the action-research project was thus to assist the organization in reconfiguring its performance assessment practices in order to allow it to effectively evaluate the impact of BIM on labour productivity.

Action-research aims to solve a problem in practice while contributing to knowledge through joint collaboration between academia and industry (Susman and Evered, 1978). The characteristics of action-research are: (1) it is future oriented in that it aims to create a more desirable future for practitioners, (2) it is collaborative due to the close relationship between researcher and subject, (3) it implies system development by aiming to " build appropriate structures, to build necessary systems and competencies, and to modify the relationship of the system to its relevant environment" (p.589), (4) it generates theory grounded in action, (5) it is agnostic in that it recognizes that action and theory are closely related and embedded in process, and (6) it is situational in that it recognizes that action is informed by the context in which it takes place (Susman and Evered, 1978). Action-Research is a cyclical process comprised of 5 distinct phases as discussed by Azhar et al. (2010) and Baskerville and Pries-Heje (1999) (Figure 6.1):

1) Diagnosing: The first step consists in diagnosing the current situation and identifying the primary problem that prompted the organization's desire to change;
2) Action Planning: The action planning step consists in planning the intervention by establishing the target and the approach to change;
3) Action Taking: The action taking step consists in implementing the planned action;
4) Evaluating: This step consists in evaluating the outcomes of the planned actions carried out in the action taking step. The evaluation step must determine whether the change was successful or not and whether this success was directly related to the actions that were taken in the action-research;
5) Specifying learning: consists in the creation of new knowledge from the continuous reflection and increased understanding that takes place during the research project. It is an ongoing process throughout the action-research and it is formalized between cycles.

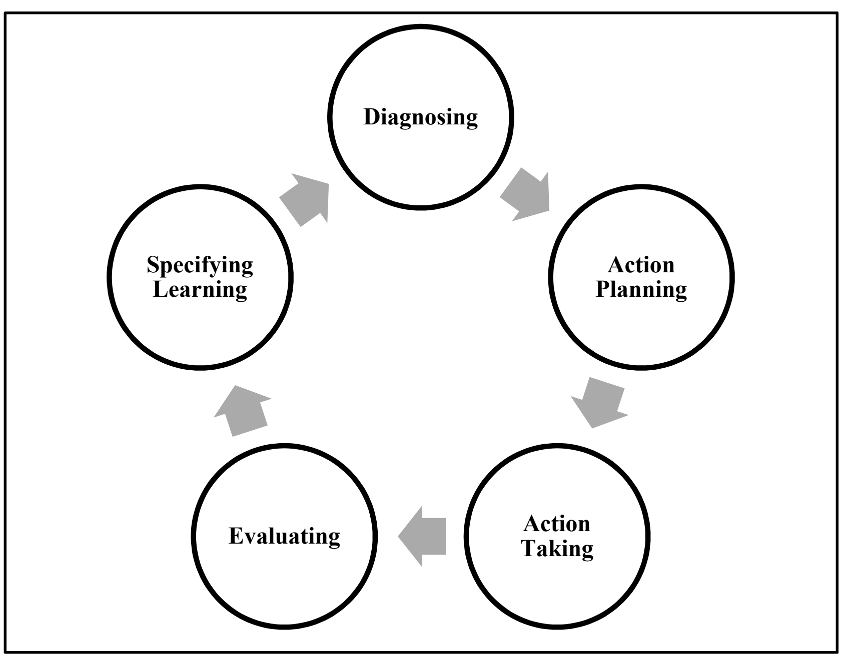

Figure 6.1 Action-Research Cycle
Adapted from Susman and Evered (1978)

The research team and the organization performed one action-research cycle over a 12 month period, between august 2013 and august 2014. Both qualitative and quantitative data were collected and analyzed over this period. Qualitative data were collected through semi-structured interviews, informal discussions and direct observation in the field. The semi-structured interviews and informal discussion involved the president-general manager, the construction manager, the project manager, the project super intendant, the project foremen, the project coordinator, the BIM manager and the principal BIM coordinator. The interviews were transcribed and analyzed in a computer assisted qualitative data analysis software, Nvivo 10 (QSR International, 2013). We performed broad brush coding to simply uncover the themes relating to productivity, BIM implementation and performance assessment (Miles, Huberman and Saldaña, 2013) We performed direct observation of the personnel, namely the BIM coordinator, site super intendant and the foreman on the project.. We took field notes and marked-up the IFC plans in digital format on a mobile tablet. We noted any factors or occurrences that detracted from the planned project execution process. The qualitative data served to gain an in-depth understanding of the current practices regarding productivity measurement within the Organization. It allowed us also to qualitatively assess the evolution and impact of BIM on the project that was under study, namely by capturing issues surrounding the use of BIM on site by the personnel.

The quantitative data collected on this project were: Request for Information (RFI) and Change Order (CO) logs, estimates, budgets and cost reports, schedules, plans and specifications as well as digital models and employee timesheets. We performed a post-mortem survey to identify the perceptions of the project team with regards to BIM and its impact on labor productivity. The survey was carried out with the project manager, the project coordinator, the superintendent and the project foreman. We tracked units produced on a daily basis. This was done to establish a baseline productivity rate for the project. All areas were tracked, including the non-modeled areas. The intent was to track productivity in areas where pre-fabrication and BIM were used to resolve issues beforehand and areas where BIM wasn't used. We also kept a project log and noted any issues or items that would hinder productivity, scope or flow of work. We met regularly with the site superintendent and foremen to get a sense for how the project was going and what the daily challenges were. We tracked the evolution of work on a mobile tablet. The mobile tablet had a PDF annotation and revue application, which allowed us to identify the work completed directly on the drawings. We annotated the issued for construction drawings (IFC) for the non-modeled areas, snapshots from the model for modeled areas and spool drawings for the areas that were modeled and prefabricated. We also performed a laser scan of the modeled area to compare it to the model when work was completed.

6.5 Project Context

The action-research project was carried out on the major renovation of a 7 storey, 650,000 sq.ft. commercial building located in downtown Vancouver, British-Colombia. The total project budget was approximately $66 million and was scheduled to last 20 months. The original budget for the mechanical portion of the project totaled approximately $13.1 million. Figure 6.2 illustrates the total cost breakdown for the mechanical portion of the project (profit excluded). The project was procured under a construction management contract (CM) with a large general contractor. The Organization was acting as a design assist trade to the mechanical engineers and provided a gross maximum price (GMP) upon completion of design. The Organization sub-contracted all sheet metal and ducting work, fire protection, pipe insulation and refrigeration as well as controls. Plumbing, HVAC piping and equipment installation was self-performed.

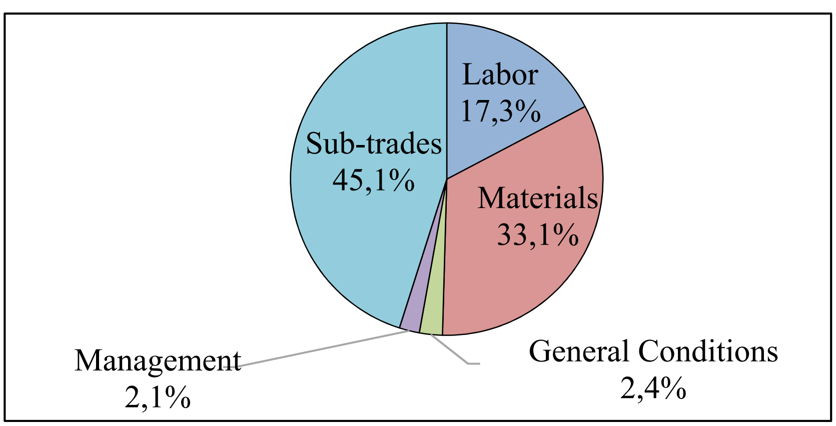

Figure 6.2 Total Project Cost Breakdown (excluding profit) for building mechanical and plumbing scope of work

Being a major renovation for commercial use (office and retail), the project faced a lot of uncertainties from the onset. As with other commercial projects, the design team was given a short timeframe for design and a lot of changes during construction, due to tenants signing leases among others, led to major redesigns of the floor plans. This impacted the Organization's work mainly in having to wait for design changes to be issued (up to three months in one case) and having to remove certain elements that had already been installed once design changes were issued. Work carried-on during the re-design process, however at a much slower pace. Moreover, as with other major renovation, many unforeseeable conditions impacted the workflow. For instance, the original steel structure required many more upgrades than initially planned, namely to the mechanical penthouse area and other core areas. Furthermore, the structural steel contractor experienced delays in completing his scope of work. Both these issues caused significant delays for the Organization and other sub-contractors, as the structural steel was on the critical path. Another issue was that a lot of the mechanical and plumbing work, such as ducts and vents, had be worked around existing conditions while respecting design intent, such as commercial office ceiling heights. In this respect the site super-intendants experience played a major role as he had to make critical decisions in the field in order to not hold up progress.

The Organization's work flow and schedule was dictated by the master schedule defined by the construction manager/general contractor. As the Organization was not prioritized as a trade they had to make way for other trades, specifically structural steel and building envelope. This created congestion and meant that the organization was constantly getting relocated to allow others to work. Lastly, the project was located in a downtown area with high traffic volumes and limited storage and lay-down space. Furthermore, due to site conditions, only one tower crane was installed. Material delivery to site and material handling on-site was thus a major challenge. According to the Organization's super-intendant, crane time had to be booked up to two weeks in advance.

In terms of BIM use, the original intent was to have a fully coordinated multi-disciplinary model used for visualization, clash detection, conflict resolution, coordination and prefabrication for certain areas. The initial agreement had the mechanical engineers develop the model to a level of detail which would define major project elements such as duct routs and piping and the Organization bring that to a level of detail to allow detailed coordination and fabrication. As the project progressed however, the scope of BIM was scaled back for many reasons. Chiefly among them was the mechanical engineers' reluctance to modify and update the models to reflect the design changes taking place due to the short turn-around time that was allowed for the issuance of the drawings. Figure 6.3 is a snapshot of the complete model that was provided by the mechanical engineer. The Organization, on the other hand, didn't have time to update their fabrication level drawings to reflect the changes. Therefore, the organization decided to scale back their BIM use and focus on the mechanical penthouse, which they could prefabricate in large part. In this regard, only the mechanical penthouse was modeled and prefabricated. The rest of the project was performed in a traditional manner. Figure 6.4 shows the mechanical penthouse as modeled by the engineer, the Organization and as-built. Since this was a design assist, there was an agreement that the Organization completely model this scope of work. The sheet metal sub-contractor also performed some modeling on this project as a visualization and coordination tool. That being said, the final extent of BIM use was much less than what was initially intended. For the purpose of the action-research however this gave us the opportunity to compare productivity rates within a same project, for areas modeled and areas not modeled.

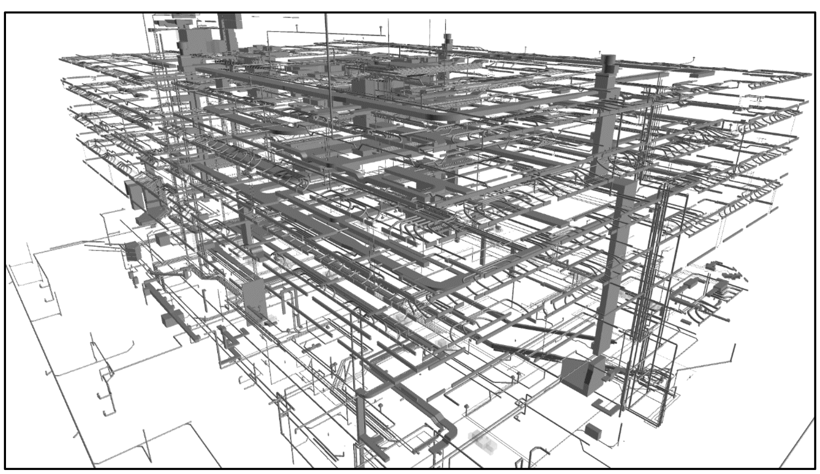

Figure 6.3 Snapshot of complete Mechanical Model provided
to the Organization by the Engineer

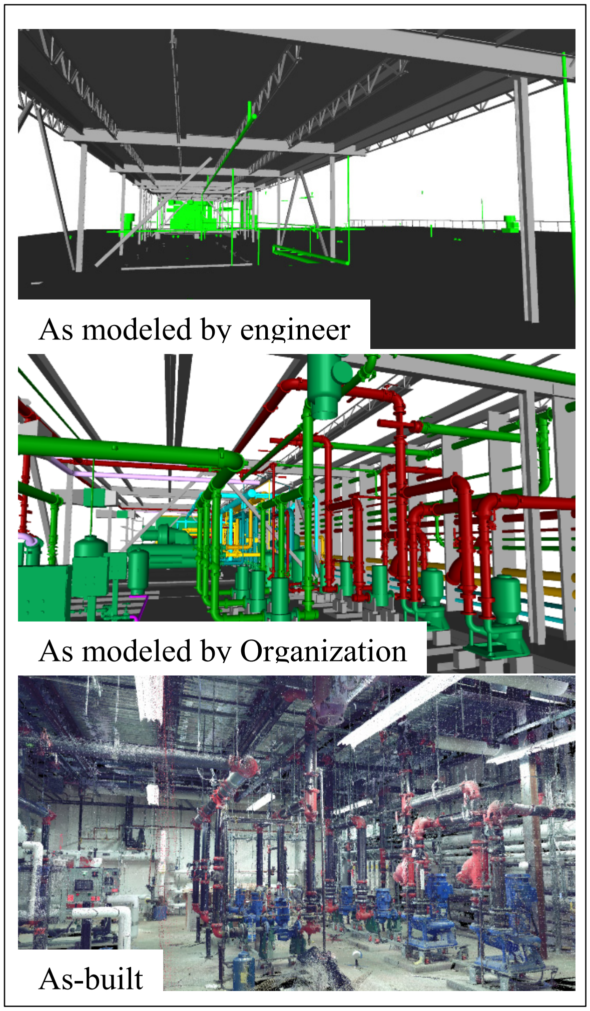

Figure 6.4 Mechanical penthouse as modeled by the engineer, the Organization and as-built

6.6 Findings

The diagnosis phase consisted in investigating and reviewing the Organizations current practices both regarding BIM use and performance assessment. The findings from this phase are reported in part elsewhere(Poirier, Staub-French and Forgues, 2015a) and CHAPTER 5. The following elements were highlighted:

- The Organization was collecting insufficient data at the project level to allow for rigorous, longitudinal performance assessment at the organizational level. Namely, cost codes were deemed insufficient to allow a retrospective analysis which could breakdown the project to a sufficient level of detail to extract valuable information;

- The personnel tasked with capturing the performance data in the field had other responsibilities, which often took precedence;
- There lacked a person responsible for benchmarking and aggregating all the data within the organization. The Organization's financial controller was very busy in his day-to-day task and didn't necessarily have the time to perform a regular update of all data analysis points;
- The Organization's position in the supply chain didn't allow them much influence on establishing the scale and scope of BIM on a project. They mostly had to implement BIM in a lonely setting, which limited the extent to which the benefits of BIM could be reaped by the entire project team;
- While we found that the implementation of BIM did influence the predictability of total project costs and labor costs across time, the impact of BIM on labor productivity required further investigation.

Assessing the impact of BIM on labor productivity was therefore targeted for the action-research, since BIM has been seen to enhance field productivity for specialty contractors elsewhere (Khanzode, Fischer and Reed, 2008). The importance of this particular indicator for the Organization was highlighted during our interviews:

> For us the next big step is to prove that [BIM] is enhancing our productivity. We keep looking when we are closing big jobs, we are looking at our estimates and our budgets for BIM and we are starting to carry significant money, fifty to a hundred thousand dollars, right now for the big job for the BIM engineering they need. So then we start looking at our labor factors and we say OK are we at a point where we can start improving our labor factors. And we don't have that confidence yet. We don't have the data to back it either. (General Manager (1st rd.))

In the action planning and action taking stages, based on the diagnosis carried out over the course of the longitudinal case study (Poirier, Staub-French and Forgues, 2015a; 2015b) (CHAPTER 4 and CHAPTER 5) we aimed the intervention towards allowing the organization to quantify the impact of BIM on productivity. Having established an overall benchmarking and performance assessment strategy in CHAPTER 5, the research team met with the Organization's project team to plan the labor productivity assessment strategy. We identified the data collection points and data collection mechanisms, the project variables (refer to section 6.5) and laid out the plan to execute the data collection and analysis. We also discussed the reporting and aggregation methods. This formed the basis for the labor productivity assessment strategy which is presented in Figure 6.5.

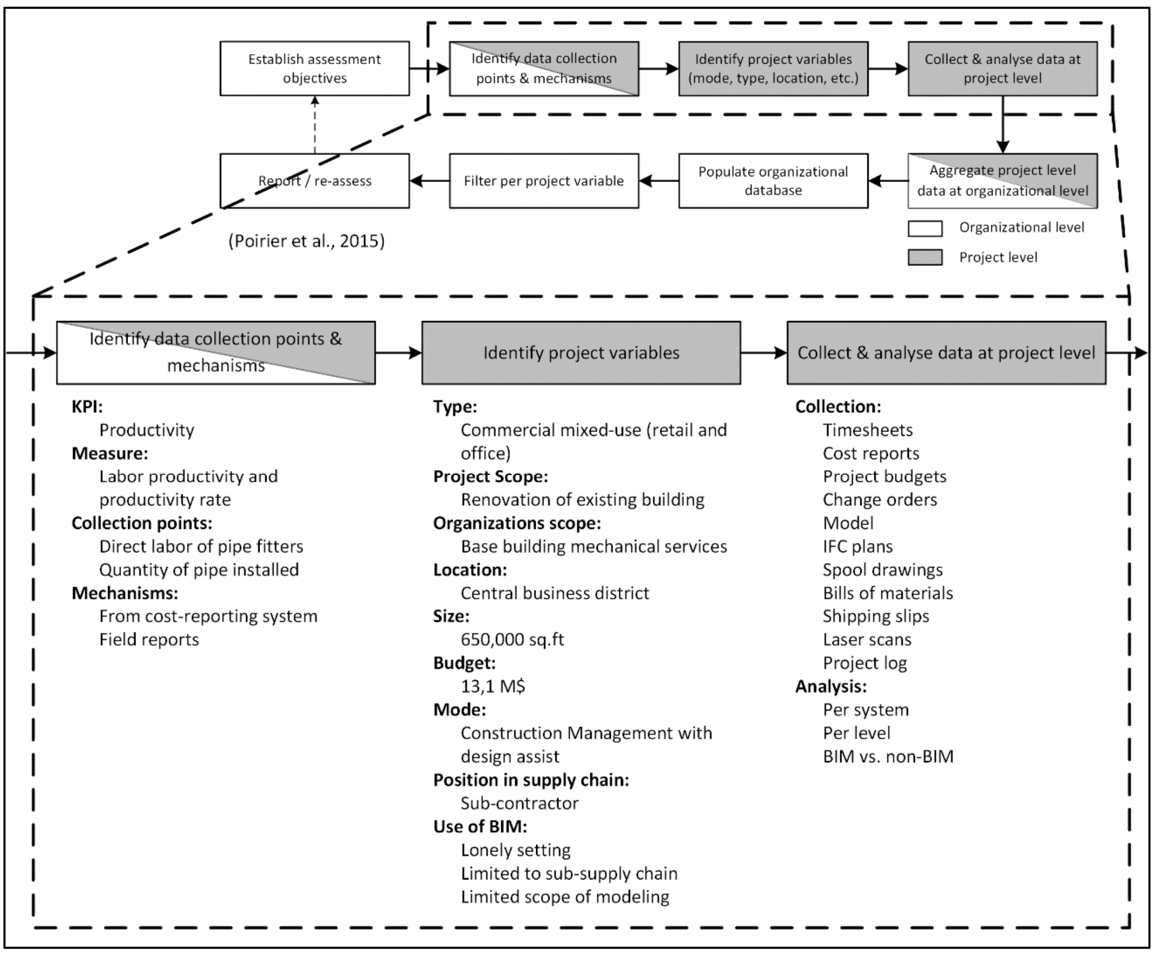

Figure 6.5 Benchmarking and performance assessment strategy targeting labor productivity
Adapted from Figure 5.1

Typically, the organization tracks between 30 and 45 cost codes on a building project. These cost codes are broken out into type of activities – rough-in, piping, HVAC and indirect labor

– and then further into the type of system – storm, sanitary, domestic water, heating and cooling water, equipment installation, gas, steam and plumbing fixtures. As mentioned, we found during our diagnosis that these cost codes were insufficient to allow rigorous performance assessment to take place. We therefore had to revise what data were being collected through reconfiguring the cost codes. The principal challenge in establishing the data points was finding the right balance between sufficient precision and limiting the onus of data collection: too many data points would likely hinder the site personnel's tracking of time and result in lack of precision. We also had to think in terms of project planning; the data points had to fit activities that were easily planned and tracked.

In establishing the cost codes for the research project, the organization went from tracking between 30 and 45 cost codes to tracking 113. Another level of precision was added to the cost codes: location. The cost codes were therefore broken out by type of activity, type of system and location, for example, #6082 - Chill Water Piping Level 4_Mechanical Room. By adding location to the cost codes we could establish a measure of labor productivity more easily by tracking units performed in a specific location at a specific time and track movement of personnel. Both time and cost components were tracked and reported through the organization's project management software. Actual quantities were measured in two ways. The first way was by visually inspecting on-site and marking up the issued for construction (IFC) drawings. We indicated where changes were made and adjusted the quantities that were taken off from the IFC drawings. The second way was by performing a laser scan of the mechanical penthouse and remodeling the as-built conditions.

The estimated productivity rates came from the Organization's centralized database maintained by a 3rd party (Trimble Accubid). During the estimation process these productivity rates were factored for various elements, such as project complexity. The estimated productivity rates were thus assumed to be reliable. Given the project context discussed before, these rates were somewhat, if not significantly, impacted.

The units that we tracked were length of pipe and weight of final assembly. While length of pipe is the traditional unit of measurement for plumbing and mechanical piping (Park, Thomas and Tucker, 2005), it doesn't account for diameter of pipe, material nor complexity of assembly, which is a critical factor of labor productivity. Indeed, as design becomes more complex, productivity worsens (Thomas and Završki, 1999). Therefore we calculated the weight of each component going into an assembly to calculate total weight installed. While this was an onerous task for the bulk of the project, it was greatly facilitated for the scope of work that was modeled as component weight could be added as a parameter in the BIM and automatically extracted. For future consideration the organization could look into including unit weights in their cost database which would be extracted in their estimates.

To perform the actual labor productivity calculations, we employed a variation on the technique put forth in Dozzi and AbouRisk (1993) for measuring productivity from the Cost-Reporting system. Labor productivity was evaluated in two ways: (1) actual labor productivity was compared to estimated labor productivity and (2) labor productivity was compared between similar systems for areas where BIM was used and were BIM wasn't used on the project. We investigated the measures of productivity presented in Table 6.1 along with the productivity ratio presented in eq. 6.4. We ultimately decided on utilizing the productivity rate as it is more intuitive for the organization. We also utilized weight as the output variable since it was suggested by the organization and after analysis, there is stronger correlation between the input variables and weight than between the input variables and length (Table 6.2)

Table 6.1 Productivity measures investigated

		output		**input**	
		length	weight	time	cost
output	length			hr./ft.	hr./lbs.
	weight			$/ft.	$/lbs.
input	time	ft./hr.	lbs./hr.		
	cost	ft./$	lbs./$		

Table 6.2 Correlation coefficient of labor productivity input and output variables

	length (ft.)	weight (lbs.)	time (hr.)	cost ($)
length (ft.)	1.0000			
weight (lbs.)	0.5360	1.0000		
time (hr.)	0.6698	0.7890	1.0000	
cost ($)	0.7526	0.8222	0.9175	1.0000

The first measure we looked at was actual labor productivity compared to tendered labor productivity for the entire project (Figure 6.6 and Figure 6.7). Figure 6.6 illustrates the productivity rate per system type while Figure 6.7 illustrates the productivity rate per level for the entire project. The distinction of system type is important due to, as mentioned, the type of material that is being manipulated and the complexity of the system (i.e. copper piping vs. cast iron or welded vs. grooved couplings). The findings suggest an actual productivity rate that is superior to the estimated productivity rate across all systems and on all levels with the penthouse, where BIM was used, having the greatest productivity ratio.

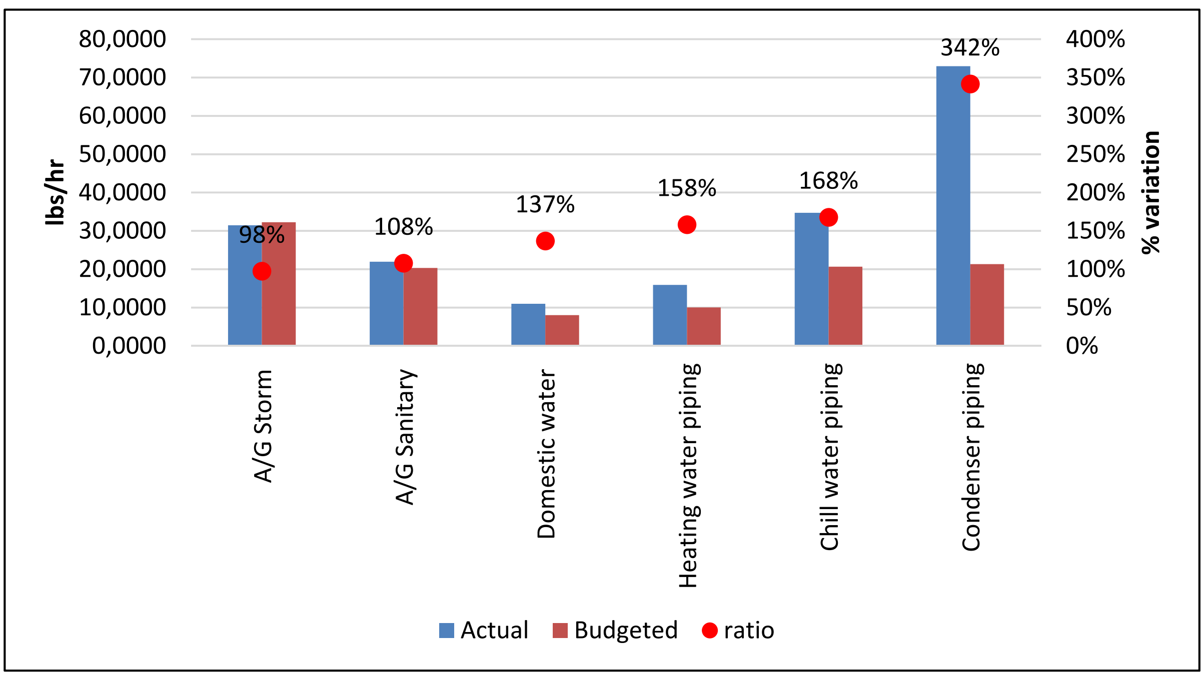

Figure 6.6 Productivity rate per system - entire project

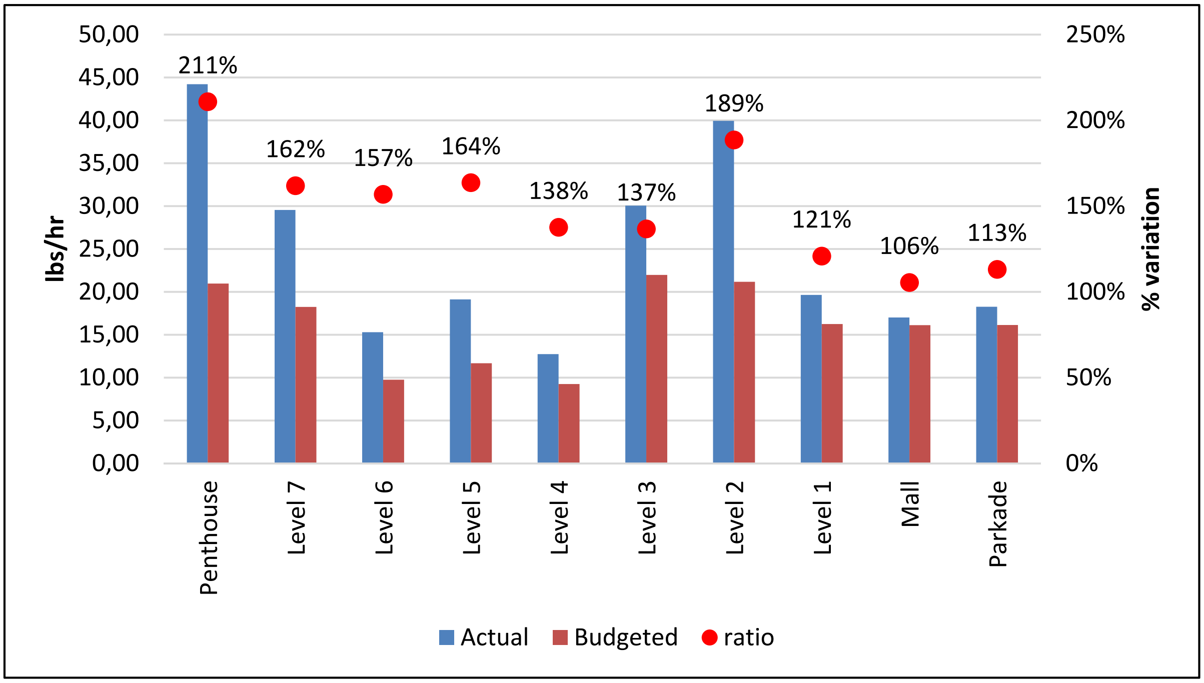

Figure 6.7 Productivity rate per level

Once we established general measures of productivity for the entire project we then compared the areas where BIM and prefabrication was used (the mechanical penthouse) to where BIM wasn't used (the rest of the project) (Figure 6.8). Three piping systems in particular were targeted since they had been modeled and prefabricated: heating water, chilled water and condenser. We included the time and costs of prefabrication into the calculation. Across the three systems studied, labor productivity both in terms of time and cost was systematically higher for areas that were modeled compared to areas which weren't modeled. For labor productivity with time as the input, the areas that were modeled and prefabricated showed an increase in productivity ranging from 75% to 241% over the areas that were not modeled.

6.7 Discussion

The evaluation stage of this AR cycle considers the change in the practice of assessing the performance of labor productivity and the impact this change has had on the organization. Informal discussions with the project team involved in the pilot project allowed us to identify challenges in the new approach to performance assessment. First, the addition of cost codes

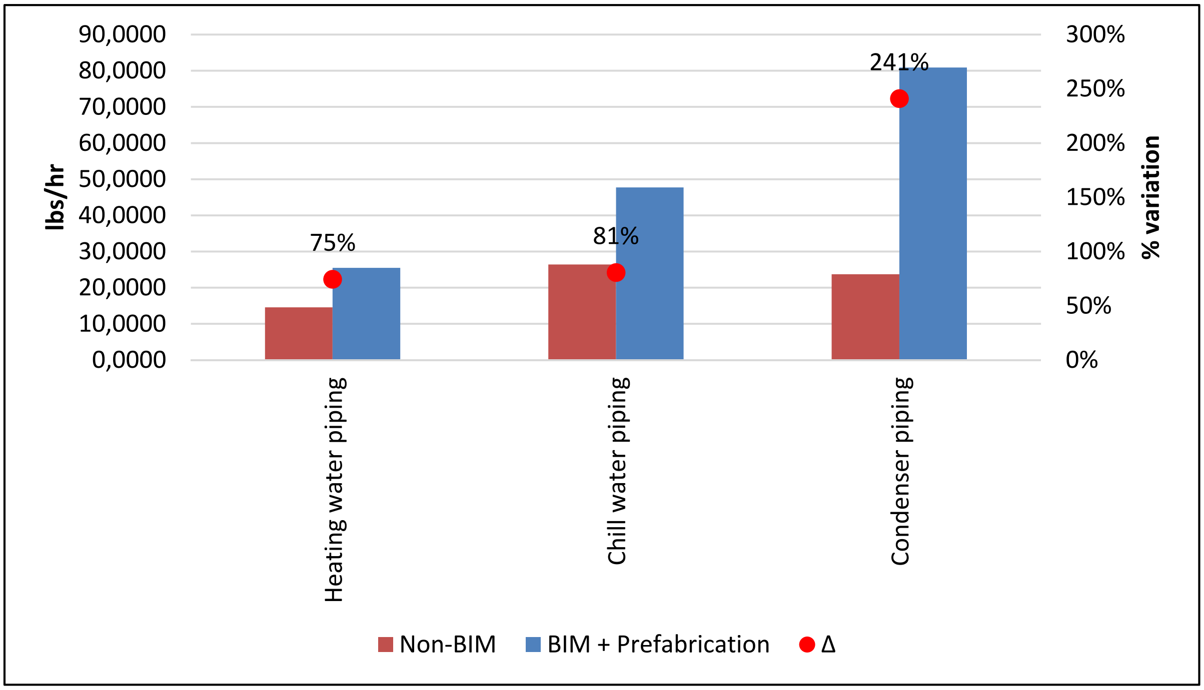

Figure 6.8 Productivity rate per system – BIM + Prefabrication vs. Non-BIM

increased the superintendent and the foremen's workload by approximately 2.5% (approximately 1 hour per week). The specificity of the cost codes also introduced complexity into the data tracking process due to the fact that the Organization's journeymen were asked to work on different systems in different locations concurrently. This points to a larger issue: how can a specialty contractor hope to improve his performance through BIM when important project items, such as scheduling, are outside his control? This issue is exacerbated when the trade is the only one implementing BIM.

The objective tracking of labor productivity data is an extremely time consuming and onerous task. The research team had a research assistant on site on a daily basis. For the organization to do this, they would have to dedicate man hours to this tracking or have the personnel self-report performance, which had been attempted in the past but was deemed inefficient and prone to errors. The research team was also tasked with analyzing the data. This step was also very time consuming and required the rigorous review of vast quantities of data, namely timesheets and project documentation.

The last stage of the AR cycle, specifying learning, is formalized in the following discussion. We first reviewed the factors affecting labor productivity cited in Table-A VIII-1 with the organization. Table 6.3 indicates the factors that were seen to be impacted by BIM on the project studied from the organization's perspective based on the survey (for clarity, only the factors which obtained 100% response as a factor that was indeed impacted by BIM are shown). 16 of the 84 factors identified in Table-A VIII-1 were seen to be impacted by BIM. Factors relating to the visualization capabilities as well as the constructability and prefabrication capabilities of BIM emerge strongly. One element that is intriguing is the positive impact of BIM on firm reputation, which is attributable to the fact that the Organization was able to make other trades benefit from their modeling effort through improved on-site coordination supported by the BIM.

Table 6.3 Impact of BIM on factors affecting labor productivity
for areas where BIM was used on the project studied

Environment	• N/A
Organization	• Firm reputation
Project	• Competencies of the project team • Constructability • Construction methods • Rework • Site layout
Individual	• Management - Activity interactions, sequence of work - Approvals and responses - Change management - Communication - Planning • Supervision - Quality control • Labor - Learning curve - Material and equipment availability - Understanding of project - Work assignments

Furthermore, we reviewed the key indicators of BIM's impact on productivity identified by Chelson (Fan, Skibniewski and Hung, 2014) which are: quantity of request for information (RFI), amount of rework, schedule compliance and change orders due to plan conflicts. We identified that BIM did have an impact on two of these indicators for the scope that was modeled and prefabricated. Indeed there were no RFIs nor any change orders due to plan conflicts for the mechanical penthouse. We were not able to measure the amount of rework, but according to the site superintendent there was very limited rework in the mechanical penthouse. This is mainly attributable to the fact that the organization took over the entire design, modeling, fabrication and installation of the mechanical penthouse, due to the design-assist delivery mode. BIM did not have, however, any impact on schedule compliance due to the limited scope and utilization of BIM on this project. Furthermore, the use of BIM on this project was perceived as beneficial in many ways:

- The site super-intendant was able to design the pipe layout in the mechanical penthouse in the model. It contained all the information pertaining to how the penthouse would be built, including spool drawings. The site super-intendant could thus focus on the installation process and sequencing of work instead of designing the penthouse in the field;
- Use of BIM as a tool to visualize, coordinate and negotiate work between the specialty trades. BIM was used by the site superintendent to discuss and negotiate equipment location and work sequencing with the other trades, notably the electrical contractor and the sheet metal contractor. This was also highlighted by Alin, Iorio and Taylor (2013);
- BIM benefitted other trades who didn't participate in the modeling process, namely the electrical contractor. For instance, the cable tray and equipment layout was all pre-determined through the model in the mechanical penthouse. The electrician knew exactly where to perform his scope of work without hindering the mechanical scope.

Finally, the recommendations that we can formulate from the action-research project regarding performance measurement are:

- Like any change management effort, there must be support from the top management and buy-in from the users to ensure the success of the benchmarking and performance assessment implementation process;
- Issues like cost codes, which encompass too many activities or elements, time sheets with too little information, skewed budgets, etc. must be addressed in order to obtain the right level of detail in the data collection stages;
- Finding the right balance in establishing the cost codes is an important consideration: too many cost codes will hinder the field supervisor's work, while too little cost codes will provide insufficient data for analysis;
- Greater use of BIM upstream by the organization, in particular to support the estimating process, would streamline the data analysis process during the performance assessment exercise.

6.8 Conclusion

Many studies have reported the benefits of BIM based on surveys and qualitative data. Empirical evidence of BIM's impact on project performance is increasingly being sought by organizations so that they can not only justify the costs of transitioning to BIM but also so that they can begin quantifying the direct impact of BIM. Improved labor productivity is one of the reported benefits that can directly influence an organization's bid for work. However, measuring and quantifying the impact of BIM on labor productivity is an extremely challenging endeavour. Furthermore, it has received sparse attention in the literature. This article has presented the findings of an action-research project aimed at assisting a specialty contracting organization in reconfiguring its performance assessment practices to allow it to effectively evaluate the impact of BIM on labour productivity. Over the course of this action-research, new cost codes and data analysis methods were developed to allow the research team to calculate an effective measure of labor productivity that would account for varying degrees of project complexity. In this case, the measure was units of weight installed per hour. Despite harsh project realities which heavily impacted the organization's performance on the project studied, considerable gains were noted for the areas where BIM and prefabrication was used.

This action-research was the first step in allowing the organization to measure and assess their project performance in terms of labor productivity. A lot of work, however, is still required to establish consistency in the measurement and reporting process. This consistency will subsequently allow the organization to review their bids accordingly. For the time being, due to the limited scope of BIM and the uncertainty associated with its implementation on any given project, it is still too early to start quantifying the positive impact of BIM in the Organization's bids (i.e. lower their labor costs). However, tracking these measures over time will afford the organization the consistency that is required so they can start quantifying the savings due to improved labor productivity with confidence.

Future action-research cycles could be performed to refine the overarching benchmarking and performance assessment strategy presented in Figure 6.5. Indeed, these future cycles would serve two purposes: first it would allow the Organization to reassess and refine the benchmarking and performance assessment strategy to ensure that it is being carried out properly and that behaviors regarding project tracking have changed. Second, as new capabilities are developed and emerge, the scope of the performance assessment could be widened to include these new capabilities. In the context of this particular cycle, we specifically targeted productivity to evaluate the impact of BIM in this research project. As stated initially, performance assessment is a much wider field; assessment strategies targeting capability and maturity were not addressed in this portion of the research project. Further limitations lie in the highly contextual and specialized nature of the mechanical contracting field and its labor force. Of course, the research was carried out on one project only, which as mentioned, limits the generalizability of the findings of actual productivity improvements. It is expected, however, that by carrying out the strategy that was developed in the course of the action-research, the organization will be able to replicate the performance assessment process to build their data base pertaining to labor productivity gains through BIM implementation.

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CHAPTER 7

DISCUSSION

7.1 Introduction

This chapter presents a discussion on the research design and the findings of the research project, their implications and their contributions to the research field and to practice. The originality and contributions of the works are also discussed, as are the opportunities for future work. This chapter does not summarize the discussions provided in each article, rather is provides an overarching discussion on the research project as a whole.

7.2 Discussion of the research design

The research design for the project presented in this thesis was rooted in the design-sciences due to its exploratory and prescriptive nature. The objective was to answer specific research question which would in turn help to solve a problem in practice. The problem in practice was identified by industry practitioners, a critical element related to DSR. It was further motivated by an apparent gap in the theory. This goal-oriented perspective is central to DSR. To further orient the research design, we adopted a critical realist perspective to frame the epistemic and ontological foundations of the research project. This served to inform the choice of a retroductive systematic combining methodology and the overarching mixed method approach to data collection and analysis. While these different methodological layers constitute a sound research design, they are not without their limitations.

From a DSR perspective, Hevner and Chatterjee (2010) have developed a checklist to help evaluate DSR projects. The checklist is based on eight specific questions (Hevner and Chatterjee, 2010, p.20):

1) What is the research question (design requirements)?
2) What is the artifact? How is the artifact represented?
3) What design processes (search heuristics) were used to build the artifact?

4) How are the artifact and the design processes grounded by the knowledge base? What, if any, theories support the artifact design and the design process?
5) What evaluations are performed during the internal design cycles? What design improvements are identified during each design cycle?
6) How is the artifact introduced into the application environment and how is it field tested? What metrics are used to demonstrate artifact utility and improvement over previous artifacts?
7) What new knowledge is added to the knowledge base and in what form (e.g., peer-reviewed literature, meta-artifacts, new theory, new method)?
8) Has the research question been satisfactorily addressed?

The first question has been answered in section 1.5. Clear research questions are seen to impact the reliability, dependability, auditability of a research project (Miles, Huberman and Saldaña, 2013). In this case, the structuring of the thesis is built around answering these research questions as outlined in Table 1.8. These research questions were informed in part by the uncovering of a problem in practice by both industry partners in sites 01 and 02.

The second question is addressed at length in CHAPTER 2 and in section 7.3.

The third question, the design process used to build the artifact, speaks to the methodology that was employed throughout the research project and was presented in section 1.7. Systematic combining was the principal research and discovery process used in this project. Originally, Dubois and Gadde (2002b) developed this approach for use on single case studies. They were attempting to overcome the prevalent notion in the research domain that single case studies lacked any form of generalizability and transferability. They highlighted the fact that replication across multiple case studies was founded on the positivistic belief in statistical significance and that this was somewhat misguided for case study research. In this research project, data was collected on multiple sites and across multiple case studies. For Van Aken (2005), descriptive relevance or external validity is the most fundamental aim of DSR. We were thus struggling between the appropriateness of a single case study as outlined by Dubois and Gadde (2002b) and the need to develop an artifact that could serve beyond the boundaries of the case study. Therefore, data from multiple sites were used and a form of methodological replication, in the collection and analysis of the data, was used. This is seen as a form of methodological triangulation and supports internal validity, credibility, authenticity of the research (section 1.7.3.3). On the other hand, external validity, transferability, fittingness of the research is ensured through transparency of research approach as discussed in section 1.7.3.4.

One particular limitation that isn't addressed by Dubois and Gadde (2002b) in their description of systematic combining is the use of the same data source to build and evaluate theory (or artifacts in this case). There is the danger of creating a self-fulfilling prophecy as discussed by Merton (1948) when using the same data to develop and test theories or artifacts or having the same person do the developing and the testing, which also speaks to issues of objectivity and confirmability (section 1.7.3.1). In the context of the research project, this was handled in various ways. One approach was through constant reporting and interaction with the project participants. Another way in which this was achieved was through purposeful reflexivity (Mruck and Mey, 2007). Reflexivity is defined as:

> the researcher's scrutiny of his or her research experience, decisions, and interpretations in ways that bring the researcher into the process and allow the reader to assess how and to what extent the researcher's interests, positions, and assumptions influenced inquiry. A reflexive stance informs how the researcher conducts his or her research, relates to the research participants, and represents them in written reports. (Charmaz, 2006, p.188)

Having performed most of data collection and analysis, I had to ensure that my training and experience as an architect didn't introduce bias into the research process. For one, I am convinced that BIM is part of the solution to foster collaboration and thus improve the outcomes produced by the industry, hence I have a bias towards BIM over traditional project delivery methods. However, this particular view could not be imparted during interviews, which could potentially introduce bias into the interviewee's response. I also had to take care to not introduce that particular bias into the coding exercise, namely by assigning a negative or positive value to an outcome based on personal belief. To overcome this, the use of the questions outlined in Figure 1.11 and linguistic cues developed as the codes emerged. Each action and outcome that were being coded were constantly being viewed from the interviewee's perspective. Other known biases include cultural biases (race, gender, class) positionality, i.e. being sympathetic to one particular view over another, architect over general contractors for instance or disregarding interview context and situation in the analysis. To further facilitate this 'reflexive action', I kept a research journal and annotated directly in the text to keep track of any assumptions that I made.

The fourth and fifth questions are an inherent part of the systematic combining process. In this regard, the grounding of the artifact in existing theory and consideration of rival conclusions for results is addressed in CHAPTER 3 whereas the development and iterative, local evaluation process and evolution of the artifact are discussed in CHAPTER 2.

The sixth question is addressed in section 7.5, namely the opportunity for future work to fully field test the artifact and a description of the methodology and metrics to do so. The seventh question is inherently addressed in this thesis, via the presentation of five scientific articles either published, accepted for publication or submitted for publication in peer reviewed journals. Three conference papers are also presented. Further to this, a number of reports have been produced and presentations given as part of this research project for dissemination to industry and academic stakeholders (refer to Appendix VII for a detailed list). Lastly, the eight question is relatively straightforward. Upon reviewing the outcomes of the research presented in this thesis, I let the reader answer the question of whether or not the research question have been satisfactorily addressed.

7.3 Discussion of the findings

The findings of the research project are five-fold: the constructs (finding 01), their relationships (the model – finding 02), the method of operationalization (finding 03), a substantive theory of collaboration evoked through the artifact (finding 04) and the measure of the impact of BIM on collaboration (finding 05). Being a DSR project, we look towards its guidelines as outlined by Van Aken (2005) (in Järvinen (2004p. 111-112)), Hevner and Chatterjee (2010); Hevner et al. (2004) to assess whether they are met by these findings (Table 7.1).

Table 7.1 Fit of research findings to DSR guidelines

Guideline	Fit
Guideline H01: Design as an artifact	The research project produced a viable artifact in the form of a series of constructs and their relationships, which were developed to characterize collaboration. The model was subsequently operationalized through the development of a method of instantiation.
Guideline H02: Problem relevance **Guideline VA02:** Goal relevance or the extent to which results refer to matters the practitioner wishes to influence	The business problem was highlighted by both industrial partners in their struggle with the assessment of the impact of BIM on collaboration and on project outcomes at the project or at the organizational level.
Guideline H03: Design evaluation **Guideline VA01:** Descriptive relevance or external validity	The artifact was locally evaluated in both research sites. Further work is required to fully evaluate the artifact, as described in section 7.5.
Guideline H04: Research contributions	The contributions of the research are outlined in section 7.4.
Guideline H05: Research rigor	The approaches used to validate the research process and its outcomes is presented in section 1.7.3 and further discussed in section 7.2.
Guideline H06: Design as a search process	The research project was iterative, as intimated by the evolution of the artifact presented in Figure 1.7.
Guideline H07: Communication of research	As discussed in section 7.2, this guideline is inherently addressed in this thesis via the presentation of scientific articles, conference papers and reports.

Guideline	Fit
Guideline VA03: Operational validity or the extent to which the practitioner is able to control the independent variables in the model	This particular guideline will have to be tested as part of the future work described in 7.5. However, as indicated by Van Aken (2005) the operational validity of the artifact, is assured due to the way in which it has been developed.
Guideline VA04: Non-obviousness	For Van Aken (2005), the technological rule or the artifact tends to not be a reductionist account of reality, this assures its non-obviousness. In the case of this research, it could be argued that the initial constructs are somewhat obvious and that they have been investigated in the past. As discussed in section 7.4, the originality of the artifact lies not in the constructs themselves but rather in the relationships developed in the model and their operationalization through the proposed method.
Guideline VA05: Timeliness	Timeliness, as described by Van Aken (2005), is a challenge. In this case, the research sites spanned several years and so the expectations of the industry partners were not for immediate feedback. However, as a way to divulge preliminary findings in a relatively short time span, a series of reports were produced and distributed.

7.4 Originality of the works and contributions

The principle contributions of the research work presented in this thesis are in the development and operationalization of an artifact that serves to frame an investigation into collaboration in the AECO industry and subsequently can act to inform, manage and assess collaboration and its outcomes in light of the transition to innovative project delivery approaches. This contribution includes a characterization of the concept of collaboration and its theoretical underpinnings, a better understanding of the impact of BIM on certain variables which are seen to affect collaboration, a way to conceptualize collaborative environments and a distinguishing of areas of focus to optimize collaborative environments. Secondary contributions lie in the development of a substantive theory of collaboration in the AECO industry, evoked through the framework, as well as the in-depth evaluation of the impact of BIM at the organizational and project level. Another contribution of this research work lies in the research design, the application of DSR, systematic combining and the use of qualitative data analysis technique to the AECO research domain, while increasingly popular, still remain sparse.

The originality of the works lie in the systematic and systemic investigation into collaboration in the AECO industry and the subsequent evaluation of the impact that innovative approaches to project delivery are having on this collaboration. From a practical perspective, this research supports the current trend in the industry whereby collaboration is receiving considerable attention due to the increasingly publicised shortcoming of the industry and the transition to innovative approaches to project delivery. From a theoretical perspective, this work aimed to address a gap in the current literature whereby the concept of collaboration was found to be amorphous and ill-defined. This was seen to lead to some confusion as to how to go about fostering it and assessing its performance. While the concepts developed in the framework are not novel in and of themselves, their articulation and the study of their genesis and influence in the collaborative environment are.

7.5 Opportunities for future work

The principal opportunity for future work is to instantiate the artifact and fully evaluate its usefulness for the management of BIM-based collaboration in a real world setting. While the artifact was evaluated locally in the context of this research project as an integral part of the development and build cycle, there was not the opportunity to fully implement it and test its usefulness in a real project or organizational setting for management. As outlined in Table 1.3 (refer to section 1.6.1), there are many different methods to evaluate an artifact that has been developed through DSR. A real world testing of the artifact should be carried out to demonstrate its utility in practice. A hypothetico-deductive experimental research design would allow the development and testing of a hypothesis, informed by the artifact, and its subsequent testing in a real-world setting (Figure 7.1).

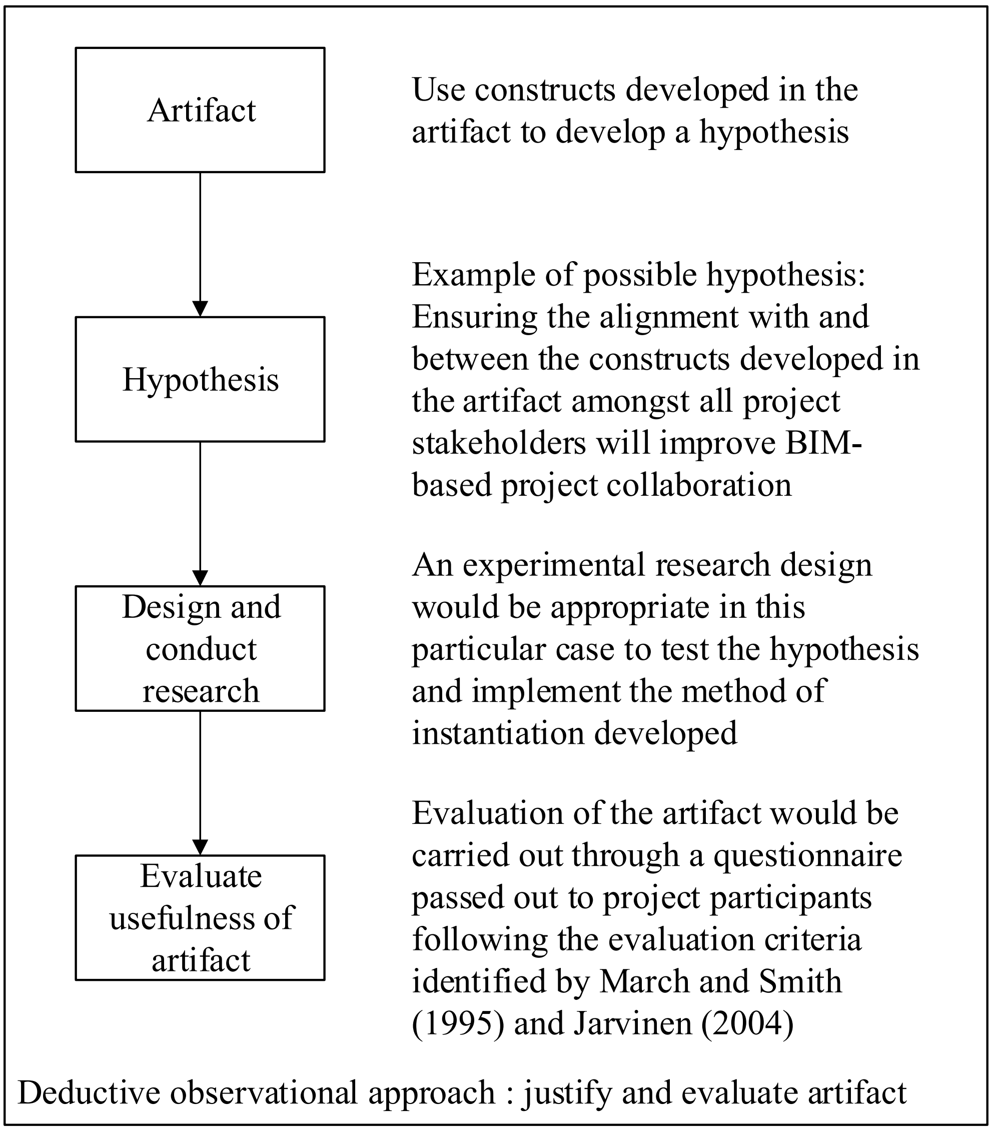

Figure 7.1 Proposed strategy to justify and evaluate the artifact for management and assessment purposes

Other opportunities for future work would be to develop tools to support the artifact's instantiation by providing means to evaluate the degree of alignment, track and assess the measures developed in the method of operationalization (uses, decision, performance indicators, information lifecycle indicators (value, evolution, quality, content) etc.) and provide a dashboard for the measured and perceived outcomes.

The scope of investigation could be widened to include other innovative project delivery approaches through the lens offered by the artifact. Indeed, the scope of the investigation presented in this thesis was limited to BIM-based collaboration and integration through organizational design (vertically integrated design firm) and design-build. A similar methodology to the one presented here could be used and the artifact could be leveraged to support the analysis. Without falling prey to “theoretical fitting” or “forcing” (Glaser, 1992), the artifact could inform this investigation, which could in turn help extend its theoretical and practical coverage.

Further work could also look into extending the scope of the artifact with regards to personal habits, emotions, moods, etc. Beyond the level of agency discussed, we didn’t extend our analysis into the realm of psychology which have been covered by the likes of Bandura (2000; 2001), Bourdieu (1977), Wood, Quinn and Kashy (2002)etc. although the line of inquiry could be opened up in the future. In building the artifact in its current form, we consciously kept to a highly rationalized model of specific behavior within a specific context. However, we did not purposefully ignore elements of behaviour, attitudes and so forth, the data analysis was undertaken with a sensibility to the influence of individual emotions (stress, fatigue, etc.) and their influence in the collaboration process, even if they are not explicitly developed. As mentioned, this could take part as future work.

CONCLUSION

The AECO industry faces a continual double-bind: collaboration is required to overcome the industry's inherent complexity, however, collaboration introduces additional complexity into the industry. How do we, as an industry, get out of this double-bind? We first need to better understand collaboration. The work presented in this thesis has taken a small step in this sense. This work encompasses a four year journey investigating collaboration in the AECO industry. The aim of this work was to systematically investigate the impact that innovative project delivery approaches, namely BIM, are having on collaboration in the AECO industry.

This aim was achieved by developing an artifact that aimed to answer the question: *What is the impact of innovative approaches to project delivery, namely BIM, on collaboration in the AECO industry?* This question was posed both from a theoretical and practical point of view. From a practical point of view, my experience is that organizations are struggling to get a sense for what the transition to innovative approaches to project delivery really entails and what it means for their practice. This was reflected in the concordant problems uncovered by the industry partners on site 01, 02, 05, and 06 as well as the workshop participants on sites 03 and 04. On the other hand, the theory on collaboration in the AECO industry was still ambiguous as to what it was investigating, was it behaviours? relationships? structures? processes? Indicators such as culture, trust, identity, etc, have been widely discussed, trust in particular, however I felt the need to develop new indicators for collaboration which could be used to develop a causal model of collaboration, thus allowing to uncover areas that were being impacted through BIM and other innovative approaches to project delivery.

To do so, I posed two research sub-questions, the first being *How can collaboration be characterized in the AECO industry?* and *How can we assess this impact on collaboration and on project outcomes?* The answers to these two questions, elaborated through the analysis of the data and the development and building of the artifact, formed the basis for answering the first question. It also allowed to develop a substantive theory of collaboration in the AECO industry, defined as the concerted or negotiated alignment of two frames of references (or more), i.e. the constructs and their relationships (Figure 1.1) as articulated in the model (Figure 1.2), that are juxtaposed to achieve a common motive. In looking forward, I also posed a prospective research question: *In light of this characterization and this assessment, how can we inform and manage innovative approaches to project delivery to enable collaboration?* This question serves to orient future work in this particular area and help further validate the usefulness of the artifact.

Throughout the thesis, I have attempted to steer clear from adopting too much of a dogmatic stance (collaboration as a mantra), a teleological stance (collaboration as an end in itself), a reductionist stance (collaboration as a set of measures) or a transitory stance (collaboration as a stepping stone in an evolution towards an uncertain end). Rather, I have adopted a systemic and process based stance on collaboration, innately tying it to the building project. Adopting this particular stance is not without its share of challenges, especially when dealing with a subject as complex and multifarious as collaboration. The artifact that was developed can appear overly simplistic or complex depending on how it is approached. It is can appear overly simplistic or reductionist in the limited number of constructs developed or overly complex in the exponential number of relationships it uncovers. I argue here that the artifact developed is a step towards building a systematic view of collaboration in the AECO industry, an endeavour that has been initiated long before my time. The artifact supports both simplicity and complexity, it is scalable. It supports detailed investigation or overarching evaluation. It can inform collaboration through innovation by identifying areas of alignment/misalignment. It can serve as a management tool for collaboration and implementation of innovation. That being said, the intent wasn't to develop "a grand theory of everything" (Briggs, 2006, p.579). The scope is quite clear: collaboration in the AECO industry and how it's being influenced through innovation. The artifact that is proposed, while overarching, can only be said to be applicable to the sites from which it was developed. Its extension to other scopes and contexts must pass through further testing. However, by having adopted strategies to ensure the relevance and the rigor of the artifact, there is little doubt that this extension can happen and be successful.

APPENDIX I

INFORMING ACTION IN BUILDING INFORMATION MODELING (BIM) BASED MULTI-DISCIPLINARY COLLABORATION

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Abstract

The emergence of Building Information Modeling (BIM) in the Architecture, Engineering, Construction and Operations (AECO) industry marks a significant shift in how temporary project networks collaborate to deliver construction projects. While technological solutions to enable this collaborative approach abound, agency and other social aspects of collaborative BIM remain sparsely researched. This paper explores how actions are informed in the deployment of BIM based multi-disciplinary collaboration. Employing a constructivist grounded theoretical approach and based on findings from two in-depth case studies of BIM implementation and deployment, the paper presents five categories that have emerged as being determinant in informing action in BIM-based multi-disciplinary collaboration. It is suggested that seeking alignment within and between these categories will positively inform action in the BIM-based collaboration process.

Introduction

Recent developments in the Architecture, Engineering, Construction and Operations (AECO) industry have identified the co-development of a shared digital model, containing a building's relevant lifecycle information, by a multi-disciplinary project network as a way to improve how projects are delivered and what is being delivered by the industry. Under the moniker Building Information Modeling (BIM), these developments mark a significant shift in how temporary project teams collaborate. While past research has focused on technological aspects that enable this cross-disciplinary collaboration, recent work has also inquired into the social aspects of this shift, notably the organizational and procedural facets supporting model-based project delivery. However, while collaboration remains a central tenant to work in this field, there lacks a systematic approach to the study of agency and action in collaborative BIM project delivery.

This paper explores how collaborative actions are informed in the deployment of BIM based multi-disciplinary collaboration. Employing a constructivist grounded theoretical approach and based on findings from two in depth case studies, the paper presents these emerging categories and discusses their implications on agency in the development and co-creation of a building information model. Initial findings suggest that a mis-alignment between and within these categories may result in the failure to successfully implement a collaborative, multi-disciplinary BIM environment. Indeed, an agentic approach to collaborative model-based project delivery, as presented in this paper, intimates consensus and alignment within and between these categories as being a key factor in the deployment of collaborative BIM-based project delivery. A simple, high-level, causal loop diagram illustrates the relationships between the categories.

Background

BIM has been characterized as both a tool and a process; it enables the digital construction of a building, or prototyping, prior to its physical construction, capturing all relevant information concerning a building's design, construction and operation (Eastman, 1992; van Nederveen et Tolman, 1992). As stated by the National Institute of Building Science (NIBS) in the US "A basic premise of BIM is collaboration by different stakeholders at different phases of the lifecycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder." (NIBS, 2007, p.21) Evidence suggests that better collaboration through BIM will increase project performance (Grilo et Jardim-Goncalves, 2010). It has been reported that properly implementing BIM on a project basis leads to significant benefits, such as better cost and schedule performance (Bryde, Broquetas et Volm, 2013), better communication and information flow (Barlish et Sullivan, 2012; Khanzode, Fischer et Reed, 2008), improved quality (Bryde, Broquetas et Volm, 2013; Suermann P, 2009) and increased productivity (Khanzode, Fischer et Reed, 2008; Kuprenas et Mock, 2009). These benefits point towards a better, more efficient, project delivery process where project performance is improved over traditional project delivery methods (Bryde, Broquetas et Volm, 2013).

While the benefits being reported make a compelling case for BIM, the transition to collaborative BIM is proving to be a considerable challenge. Many studies have been carried out attempting to identify and define specific barriers to BIM adoption (Azhar, Hein et Sketo, 2008; Bernstein et Pittman, 2004) as well as determinant factors in the successful implementation of BIM (Arayici et al., 2011; Liu, Issa et Olbina, 2010; Won et al., 2013). Technological barriers are often seen as the major culprit in the challenges facing multi-disciplinary project teams (Nour, 2009). The social aspects of collaborative project delivery, however, are increasingly seen as playing a determinant role in the implementation process. In fact, when looking at the most significant barriers to collaborative BIM, issues pertaining to interactions between project team members, for instance willingness to share information, consistently rank amongst the most important issues hindering full collaboration (Won et al., 2013). These issues lie in the development of an adequate collaborative environment in which BIM is deployed: issues such as procurement, delivery mode and contractual requirements (Ashcraft, 2008), individual scope, roles and responsibilities (Dossick et Neff, 2010; Linderoth, 2010) as well as varying levels of competence and maturity within the project team (Taylor et Bernstein, 2009) will influence the extent and effectiveness of collaborative BIM. These barriers lead to collaborative BIM failing to deliver on the promise of eliminating what has been coined as *information chaos* (Dubler, Messner et Anumba, 2010), amongst other shortcomings.

Different strategies have addressed these challenges by attempting to formalize BIM-based collaboration, most notable being BIM Project Execution Planning (PxP) (AEC (UK), 2012; Computer Integrated Construction Research Group, 2011). While the guides resulting from the BIM planning exercise lay a foundation for the collaborative BIM effort, by setting goals and objectives and offering technological and procedural guidelines, they don't address the inherent shift in behavior and agency that is required for BIM to be fully effective. Behavior, motivation, as well as other individual-level constructs (such as trust, culture, identity, etc.) have been tied to project performance and project outcome in the past (Liu et Walker, 1998; Phua, 2012; Rose et Manley, 2010). BIM, being a disruptive technology, exacerbates socio-cognitive barriers within multi-disciplinary project teams and requires a reconfiguration of practice (Forgues et Iordanova, 2010). This will impact behavior, motivation and other individual-level constructs. While setting goals and objectives is seen as a way to mediate this behavior, there is a need to go beyond this approach and understand how to foster conducive behavior as well as reach consensus and alignment between individuals in a project team, in order to appropriately and adequately inform action in multi-disciplinary BIM-based collaboration.

Research Methodology

The objective of this study is to investigate agency in multi-disciplinary BIM-based collaboration. As this study iterated between exploratory and explanatory, we employed a constructivist grounded theoretical approach (Figure-A I-1) (Charmaz, 2006; Green, Kao et Larsen, 2010). Rooted in the interpretivist paradigm, constructive grounded theory "serves as a way to learn about the worlds we study and a method for developing theories to understand them." (Charmaz 2006, p.10) Through this process we identified categories informing individual action in the BIM-based collaborative project delivery process.

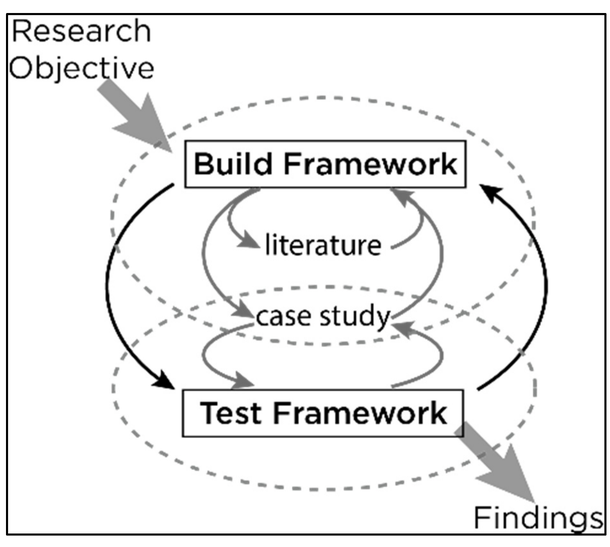

Figure-A I-1 Research approach

Data was collected through two case studies (Table-A I-1**)**. The cases were chosen due to their complementarity; they allowed the research team to cover a large spectrum of the construction supply chain as well as the project lifecycle. We performed a total of 83 interviews over the course of both case studies with a total of 43 interviewees. We also performed surveys (2), observed over 25 project meetings and analyzed meeting minutes. We collected project data such as RFIs, schedules, timesheets, etc. Lastly, we analyzed the various models and studied their development in their respective project settings. All interviews were transcribed and coded in Nvivo (QSR International, 2013). During the coding process, we were looking for keywords, linguistic cues and specific conversation turns, which would inform the higher-level categories. We then developed the categories affecting action through collaborative BIM (Miles, Huberman et Saldaña, 2013). Figure-A I-2 illustrates the coding schema developed, which allowed the elaboration of the various categories informing action in the collaborative BIM environment.

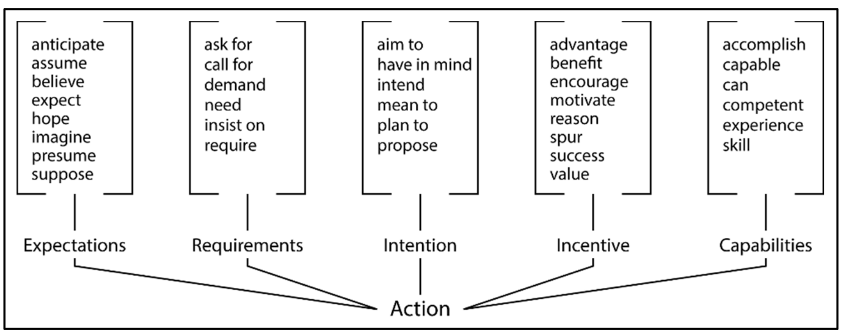

Figure-A I-2 Categories and linguistic cues

Table-A I-1 Description of Case Studies

	Case Study 1	**Case Study 2**
Case	Specialty mechanical contracting firm adopting and implementing BIM since 2010	Major new institutional construction project where BIM has been fully implemented
Location	Vancouver (BC), Canada	Edmonton (AB), Canada
Duration	25 months (on-going)	15 months (on-going)
Perspective	Organization	Project
Unit of analysis	Individual	Individual
Description	Studied the changes brought on by the adoption of BIM within the organization throughout 6 different projects where BIM was implemented	Studied the project team members directly involved in the delivery of the project. Studied all disciplines, major specialty contractors and owner
Data source	Interviews, meeting observation, field reviews, models and project documents.	Interviews, meeting observation, models and project documents.
Characteristic	Depth of data collection	Breadth of data collection

Category Development

The analysis of the data collected from the two cases allowed us to identify categories, which emerged as being determinant in informing actions guiding the multi-disciplinary collaborative modeling process. These categories are: expectations, requirements, capabilities, incentives, and intentions. The depth of collaboration within the multi-disciplinary team is greatly influenced by how these categories are addressed and managed within the project team. The categories also interact at varying levels of granularity, namely the individual level, the project level and the organizational level, as discussed by Dossick et Neff (2010) and further developed in Table 1. The following develops the five categories:

Expectations - The articulation and fulfillment of expectations emerged as one of the foremost categories informing how collaborative actions are carried out. An expectation is “the strong belief that something will happen or be the case in the future” (Oxford English Dictionary, 2013). Each individual project team member has their expectations entrenched in their discipline, in their organization and in their project respectively. In this case, expectations represent what project team member hope to gain from the use of BIM, how they expect to develop and use the model and what they expect to receive from other project team members. For example, the expectation on the mechanical contractors part in case study 01 was that he would receive mechanical models completed to a certain level of development, upon which he could build his pre-fabrication models (spool drawings).

Requirements - A requirement is “a thing that is needed or wanted” (Oxford English Dictionary, 2013). The formalization of expectations leads to requirements. The lack of clear requirements is often cited as one of the top barriers to BIM. Requirements are hierarchical, i.e. different requirements will not carry the same weight. Various project team members formulate them in response to their own needs and wants. For example, contractual requirements set out by the owner will dictate how the model is to be developed and handed-off at the end of the project for his future use. Beyond modeling requirements, stakeholders will have to deal with internal and external project requirements such as building codes and program.

Capabilities - A capability is an individual’s, organization’s or team’s “power or ability to do something” (Oxford English Dictionary, 2013). The notion of capability, otherwise known as competency or maturity, has been explored in past research on information technologies, information systems and BIM (Succar, Sher et Williams, 2013). Capabilities act as a moderating factor in the collaborative BIM effort by limiting the extent to which the model can be developed and used within the project team or within a specific organization. For example, in case study 02, a large “capability gap” was observed between the mechanical consultant and the mechanical contractor. This lead to the mechanical model not being fully developed for construction purposes and thus capped the total intrinsic value of the mechanical model.

Incentives - Incentives “motivate or encourage someone to do something” (Oxford English Dictionary, 2013). Incentives come under various forms, namely financial compensation, direct benefits related to the use of a tool or process and other types of gains. They can also have a negative impact, acting as barriers to the full deployment of BIM. For example, the measured reduction in change orders on a project or the measured increase in productivity in the field.

Intentions - An intention is an individual's "determination to act in a certain way" (Merriam-Webster Dictionary, 2013). Intentions emerge at the individual level and are heavily influenced by the other aforementioned categories. Intentions directly involve agency: behind intention lies motivation. For example, the architect's intention towards the modeling process in case study 02 were to simply produce 2D contractual drawings from the model, thus limiting the full development of the model for life cycle use.

Action – Action is seen as the execution of continuous thought, the implementation of practice. In Giddens's *Structuration theory* (Giddens, 1984, p.3) "human action occurs as a *durée*, a continuous flow of conduct, as does cognition." For Giddens, individual action occurs within three embedded sets of processes, his stratification model: reflexive monitoring, rationalization and motivation. The five aforementioned categories resonate within this model as they operate within one or a multitude of these processes. Action is the fulfillment of these categories and will be informed through their development and aggregation.

Relationships between categories

The five categories act and interact to inform individual action in the deployment of BIM-based collaboration; they were found to influence the creation, analysis, exchange and overall use of the model by individuals. The categories are articulated in different ways to inform action: the degree, scale, scope and duration of articulation will vary (Table-A I-2). Furthermore, high-level causal relationships emerge when studying how these categories interact. Figure-A I-2 illustrates this high-level causal loop diagram. In this case it represents an ideal situation where the categories inform constructive action in the collaborative deployment of BIM. For example, the causal link between expectations and requirements positively influence each other thus creating a reinforcing loop: as requirements structure the collaborative BIM effort, expectations towards the collaborative BIM process and the outputs from the model are mediated to suit these requirements, which intimates a process of learning. Similarly, capabilities are developed as actions unfold: a reinforcing loop occurs. On the other hand, when actions fulfill requirement or expectations, a balancing loop occurs. Causal links also follow a single direction. For instance, as capabilities are developed through experience and knowledge capture, understanding of the BIM, the tool and the process, will also be developed which will lead to an evolution of expectations. When requirements are put forth, intentions will be set to meet these requirements. The various articulations of the categories will also play a role in the causal relationship. For example, expectations on the owner's part will dictate project requirements. On the other hand, an owner's project requirements will serve to temper project team expectations. Incentives will influence intentions, both individual and at the organizational level. Lastly, the system is neither perfectly isolated (it cannot achieve minimum entropy) nor is it balanced. The dynamic nature of collaborative action will result in a transfer of impetus into one or more of the categories, namely the capabilities or incentives categories.

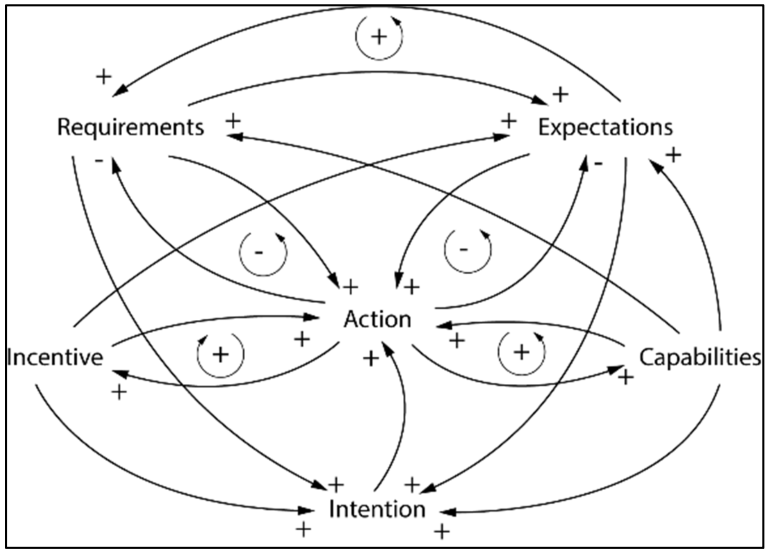

Figure-A I-2 High Level Causal Loop Diagram
Representing an Ideal Deployment of Collaborative BIM

Table-A I-2 Articulation of interactions between categories

Degree	Scale	Scope	Duration
Within Category	Individual	Intra-Disciplinary	Temporary
Between Category	Project Team	Inter-Disciplinary	Project Phase
	Organization	Single-System	Project Lifecycle
	Industry	Multi-System	Permanent

Conclusion

This paper set out to investigate agency in multi-disciplinary BIM-based collaborative project delivery in the AECO industry. Through a constructivist grounded theoretical approach, five distinct categories emerged as being core to informing project team members' action in the collaborative BIM process. Preliminary findings suggest that alignment within these categories, for instance between different project team members expectations towards BIM, will greatly impact the collaborative BIM process. In addition, alignment between categories, for instance between requirements and incentives, will also greatly impact individual action in the collaborative BIM process. This suggests that temporary project networks should seek to reach consensus and align themselves across these categories. A simple, high-level, causal loop diagram further illustrated the relationships between the various categories. Limitations of this study lie in the preliminary nature of the findings and the use of two case studies. Further research is required to further refine the various levels of granularity affecting each category and refine the causal loop diagram. Lastly, further work is needed to validate the impact of each category and further define strategies to encourage alignment.

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APPENDIX II

DIMENSIONS OF INTEROPERABILITY IN THE AEC INDUSTRY

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Abstract

Often cited as a major barrier to the seamless exchange of data and information among project team members evolving in the Architecture and Engineering, Construction (AEC) industry, technological interoperability has been the focus of many ongoing research efforts within the AEC field. In other knowledge fields, such as information systems (IS) and military research, the interoperability construct has evolved beyond the purely technological domain to encompass multiple dimensions. Within the AEC industry, these dimensions of interoperability have yet to take root. This paper introduces a conceptual framework that develops the interoperability construct across multiple dimensions. The framework defines emerging collaborative project delivery systems within the AEC industry by relating the technological, organization and procedural dimensions and situating them within the contextual dimension. The framework is underpinned by an information processing systems approach to project delivery in the AEC industry. Based on a two-part systematic literature review, a rigorous and structured process aimed at answering a very specific and targeted question within a given field, the paper presents the conceptual framework and discusses the various dimensions of interoperability. The paper concludes by presenting opportunities for future research through gaps identified in the literature. It is believed that by adopting this broader view of the interoperability construct in the AEC industry, the deployment of seamless collaborative project delivery systems and emerging technologies and processes, such as Building Information Modeling (BIM) will be better informed and structured and thus more effective and efficient.

Introduction

The past three decades have seen the emergence of interoperability as a field of study in response to the increasing heterogeneity and incompatibility of information systems introduced by technological innovation within networked organizations. Interoperability is defined as: “the ability of two or more systems or components to exchange information and to use the information that has been exchanged.” (IEEE, 1990) Originally, the issues surrounding interoperability were strictly concerned with data and information exchanges across platforms and systems from a technological perspective. Over the years, the original IEEE definition of interoperability has evolved within other knowledge fields, namely those of software engineering, military and healthcare research to encompass a broader scope of meaning relating to compatibility and cohesion across collaborative networked organizations (e.g. Chituc, Azevedo and Toscano, 2009). Naudet et al. (2010) reframe the concept of interoperability as a problem to solve rather than a particular definition: "An interoperability problem appears when two or more incompatible systems are put in relation." (Naudet et al., 2010, p.177) Interoperability has thus become synonymous with the capability for multiple information systems to coexist, interact and gain understanding from one another while exchanging functionalities (Chen and Daclin, 2006). This expands the interoperability construct from the technological domain into the organizational domain and beyond. Hence, the interoperability construct has evolved to encompass the fields of business and enterprise, data, information and knowledge, semantics, conceptual and cognitive factors, etc. (Chen and Daclin, 2006; Chituc, Azevedo and Toscano, 2009; Grilo and Jardim-Goncalves, 2010)

The motivation for this paper is three-fold. First is the need to address interoperability within the AEC industry. The report prepared for the National Institute of Standards and Technology (NIST) by Gallaher et al. (2004) has become synonymous with the need for the AEC industry to re-assess how information is exchanged and how organizations interact in a project setting. In their study on the cost of inadequate interoperability in the U.S. capital facilities industry, it is reported that interoperability issues represent costs of $15.8 billion to the capital facilities industry. The report hints to issues of interoperability beyond their technical roots. Second is the need to address interoperability from multiple perspectives. The multiple dimensions of interoperability have been developed in other fields such as IS research (Chen and Daclin, 2006) and military research (Tolk, 2003). In the AEC domain, the body of work by Antonio Grilo and Ricardo Jardim-Goncalves from the University of Lisbon, looks into both the fields of organizational (business) interoperability and technological interoperability. (e.g. Grilo and Jardim-Goncalves, 2010) They recognize "[…] the need to address a context wider than just the technological issues of interoperability on BIM." They go on to state that "to achieve interoperability successfully, organizations must address technological issues of connecting systems and applications, as well as how the connection between the business processes of each organization enables or hinders the establishment of the technical bonds, along with compatibility of the employees' values and culture of trust, mutual expectations, and collaboration […]" (Grilo and Jardim-Goncalves, 2010, p.526) Lastly, the information processing nature of collaborative project delivery systems, which characterize the AEC industry, tend towards this broader conceptualization of interoperability. In essence, construction project teams can be considered information processing systems (Winch, 2010), a notion which is being exacerbated by the emergence of BIM. This view points to interoperability as an approach to address issues of compatibility of information across these heterogeneous information-processing environments.

The objective of this paper is to present a conceptual framework which develops the interoperability construct along multiple dimensions, which characterize emerging collaborative environments within the AEC industry. The proposed framework is informed by a review of the literature from other knowledge fields and aggregates parallel developments in the field of interoperability. A systemic literature review, a rigorous and structured process aimed at answering a very specific and targeted question within a given field, was performed to enquire into the extent of diffusion of the interoperability construct within the AEC domain. It also aided in identifying gaps within the literature, which could inform future research. The paper is structured as follows: first the research methodology is described and the conceptual framework is presented. The paper goes on to present the multiple dimensions of interoperability and discusses their implication on the deployment of enhanced collaborative environments across project networks. Finally, this paper points to opportunities for future research offered by the conceptual framework.

Systematic literature review process

The review process was done in two stages. First, an initial extensive literature review on interoperability was performed to explore the knowledge domain across multiple research fields, namely computer sciences, information systems research as well as military research. The alignment of the interoperability construct within the conceptual framework and its applicability to the AEC domain took form during this initial review. Subsequently, a systematic literature review was performed to enquire into the extent of diffusion of the interoperability construct within the AEC research field. The objectives of this review were to (a) systematically review the evidence base regarding interoperability in the AEC industry, (b) validate the conceptual framework built from the initial literature review within the AEC knowledge domain and (c) identify gaps in the literature relating to interoperability in the AEC domain within the conceptual framework. The review structure was based on the staged systematic review process reported in Tranfield, Denyer and Smart (2003) and subsequently adapted by, amongst others, Thorpe et al. (2005). Figure-A II-1 illustrates the review process adapted from Thorpe et al. (2005). The systematic review process is a rigorous and structured process aimed at answering a very specific and targeted question within a given field (Pittaway et al., 2004). The advantages of a systematic literature review over a traditional narrative review are the transparency, clarity and focus of the review process (Thorpe et al., 2005).

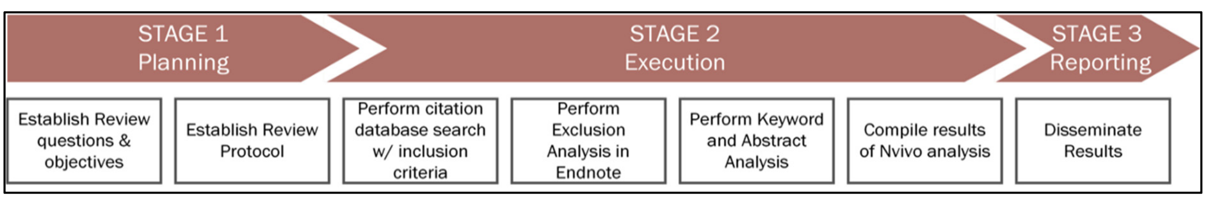

Figure-A II-1 Stages of the Systematic Literature Review
Adapted from Thorpe et al. (2005)

A total of 799 articles mentioning interoperability in the AEC domain were found through the database search utilizing the search strings “INTEROP* AND "Construction Industry" OR "Architecture, Engineering and Construction" OR "AEC". The databases searched were Science Direct, Web of Knowledge and Engineering Village. The citations and abstracts of these articles were brought into endnote for triage and analysis. After the first round of triage, which eliminated duplicates and articles that were not peer reviewed, a total of 525 articles remained. A keyword search and abstract analysis, which eliminated irrelevant articles following a list of inclusion and exclusion factors, brought that total down to 161 articles. The abstracts of these articles were further analyzed to identify those relevant to this paper’s scope and the articles subsequently reviewed. The review process identified several gaps in the literature, notably the heavy trend to discuss interoperability from a purely technological perspective, the discussion surrounding the development of the Industry Foundation Class (IFC), and the creation of standards and ontologies as solutions to the interoperability issue. Furthermore, the review revealed that interoperability was mostly mentioned as a barrier or inhibitor to BIM. Another gap identified was that the bulk of the research on interoperability was coming from Europe. This can be explained by the multiple initiatives looking into interoperability and its development in the enterprise software domain, which have been launched by the European Commission since 2000 (namely the ATHENA Integrated Project and the INTEROP Network of Excellence) (Chen and Doumeingts, 2003). The North American sector has not seen such initiatives. However, certain bodies, such as the National Institute for Building Science, who have recently published version 2.0 of the National BIM standard (NIBS, 2012), are developing tools for increased interoperability within the North-American AEC industry. Lastly, the literature review identified a scarcity of research into the contextual dimension.

Dimensions of interoperability in the AEC industry

The conceptual framework presented in Figure-A II-2 illustrates the multiple dimensions of interoperability, which define collaborative project delivery systems within the AEC industry. Three main dimensions are developed in this framework: the technological dimension, the organizational dimension and the procedural dimension (adapted from Staub-French and Khanzode (2007)). The contextual dimension encompasses these three dimensions and acts as a mediating force in the overall deployment of the project delivery environment. This conceptual framework distinguishes itself from others, such as the People-Process-Technology framework or the Technology-Organization-Environment framework (Tornatzky, 1990 p.157) based in IS research, the Model-Team-Process approach (Staub-French, Forgues and Iordanova, 2011) developed by DPR construction, the Product-Organization-Process (P-O-P) model (Garcia et al., 2004) developed at Stanford University's Center for Integrated Facility Engineering's (CIFE) or the Technology-Process-Policy (T-P-P) fields developed by Succar (2009), by representing the relationships between the dimensions, introducing context as a modulating factor and relating the interoperability construct along these multiple-dimensions. It also is unique in that it acts as a meta-framework for the characterization of collaborative project delivery systems in the AEC industry.

The Technology Dimension

The technology dimension is related to the deployment of information and communication technologies by encompassing the tools and technologies implemented within the collaborative project delivery system. Within this dimension, technological interoperability is related to the exchange of data and information within digital environments and "exists because of the lack of a set of compatible standards to allow using heterogeneous computing techniques for sharing and exchanging information between two or more systems." (Chen and Daclin, 2006, p.2) Within the AEC industry the issues of technological interoperability have been exacerbated due the heavy reliance on IT, in particular with the emergence of BIM. In fact it is seen as one of the most important challenges that hinder the adoption of BIM (McGraw-Hill, 2012). Either due to a lack of standards (e.g. Eastman et al., 2011) or the proprietary nature of CAD software

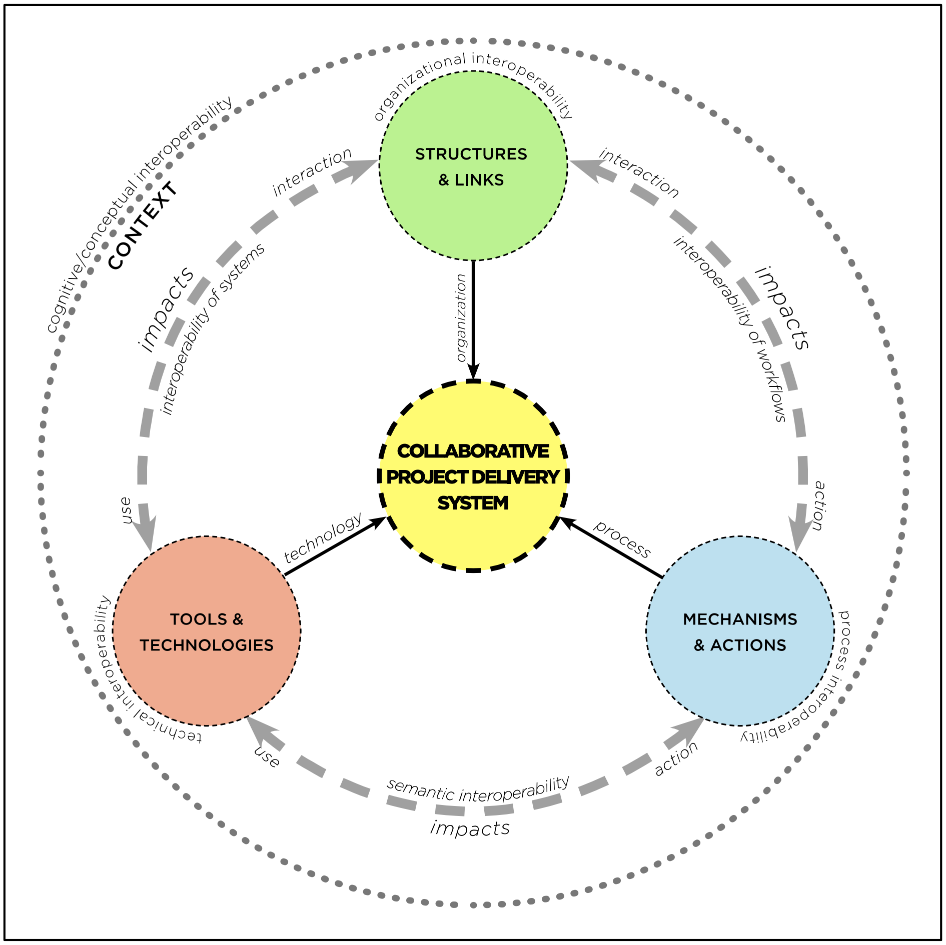

Figure-A II-2 Collaborative Project Delivery Systems – A Conceptual Framework

(Nour, 2009), low technological interoperability will translate to wasteful activities for the re-entry of data which has already been codified, as well as hinder value creation due to loss of data and incompatibility, as discussed by Gallaher et al (2004) who define interoperability as: "the ability to manage and communicate electronic product and project data between collaborating firms' and within individual companies' design, construction, maintenance, and business process systems." (Gallaher et al., 2004, p.ES-1).

Multiple efforts for standardization of data in the AEC industry have been put forth by initiatives such as the buildingSMART alliance (bSa; formerly the Industry Alliance for Interoperability (IAI)). They spearhead the openBIM effort in partnership with various institutions and software vendors and are developing the Industry Foundation Class (IFC). In recent years, IFC has been adopted as the principal schema for building related data exchange and has been heavily documented and researched in other works (e.g. Eastman et al., 2011; Laakso and Kiviniemi, 2012). As the facilities Operation and Maintenance (O&M) phase of the building life-cycle gets included into the model, the interoperability between the data created for design and construction and the subsequent transfer of that data for O&M purposes introduces its own barriers. The Construction Operations Building information exchange (COBie & COBie2) schema "addresses the handover of information between construction teams and the owner. It deals with operations and maintenance (O&M), as well as more general facilities management information." (Eastman et al. 2011, p.131) The development of these standards signifies a push towards a life-cycle view of building information. However, these standards don't address how this information is generated and exchanged throughout this lifecycle, which falls into the process dimension of project delivery.

The Process Dimension

The process dimension enables the collaborative project delivery system through mechanisms and actions. It is related to the generation of information and knowledge, its management as well as its exchange across the project network and throughout the project life cycle. For Winch (2010), "[…] the construction project is an information process through time - an information flow that stimulates and controls material flow." (Winch, 2010, p.211) Process interoperability is concerned with developing avenues to allow mapping, connecting, merging and translating of incompatible or heterogeneous processes (Chen and Daclin, 2006). Instances such as the BIM Project Execution Planning Guide (CIC, 2009) attempt to map out and streamline the inter-disciplinary modeling process through process interoperability. The opportunities for improvement within the process dimension can be further developed along the interoperability-integration spectrum. While process interoperability aims at connecting processes, process integration aims for alignment and unification. Both are fundamentally concerned with process improvement. Approaches to integrating processes, such as lean construction (Ballard et Howell, 1994), product lifecycle management (PLM) (Stark, 2011), and supply chain management (SCM) (Vrijhoef and Koskela, 2000) are aimed at value creation through reduction of waste and elimination of redundancy. That being said, the opportunity to align or integrate processes will be highly dependent on the structure that is put in place and the barriers, or absence-of, which are introduced by the organizational dimension.

The Organization Dimension

The organization dimension structures the collaborative project delivery system. It relates to contractual set-ups, hierarchical links created, roles and responsibilities. Organizational interoperability is "concerned with the incompatibilities of organizations structure and management techniques implemented in two [or more] enterprises." (Chen and Daclin, 2006) It "addresses interoperability issues between two or more systems from a business/economic perspective, as opposed to technical aspects." (Chituc, Azevedo and Toscano, 2009) It relates to the ability of organizations to collaborate across boundaries, setting collective goals and objectives and assessing performance. Moving towards organizational interoperability requires that interactions between organizations be structured in a way that removes these barriers and incompatibilities. The domain of organizational interoperability is mainly characterized by the interoperability of business practices and enterprise. The growing interest of AEC researchers within the social and organizational domain (e.g. Whyte, 2011) has produced much work that could be noted as delving into the field of organizational interoperability. Organizational interoperability exists at two levels: the organizational level (intra-) and the project network level (inter-). Dossick and Neff (2010) and Dubois and Gadde (2002) look into the discrepancies in the types of couplings within project networks, stating that organizations forming these networks are often tightly coupled through technology whereas they are loosely coupled organizationally. This concept of loose vs. tight couplings within project networks is analogous to the notion of interoperability in that it seeks alignment through structure. This varying degree of coupling often stems from the misalignment of scope, project and organizational goals within the project delivery environment.

The Contextual Dimension

The contextual dimension defines the environment in which evolves the collaborative project delivery system. It represents anything that is outside the system (Naudet et al., 2010). It is concerned with issues such as norms, regulations, policies, markets and cultures, which are unique to each project setting. Other work has touched on the contextual dimension, such as Succar (2009) who presents his policy field as "[…] a group of players focused on preparing practitioners, delivering research, distributing benefits, allocating risks and minimizing conflicts within the AEC industry." (Succar, 2009, p. 359) The presence of this multitude of actors outside the project team boundary brings to light the multiple perspectives and knowledge domains which exist in the AEC industry. Through a socio-constructivist lens, knowledge can be seen as being molded by an individual's language, history and culture (Vygotsky, 1978). This will in turn shape his interactions within this social setting and structure his 'world view'. Therefore, context can be influenced through cognitive and conceptual interoperability, which are related to understanding, meaning and knowledge development across boundaries. As such, interoperability will exist at the interface between individuals and their cognitive functions (i.e. individual knowledge) while conceptual interoperability will reside at the interface between groups of individuals where meaning is consensus based (i.e. between disciplines). Within the AEC domain, Mutis and Issa (2012) discuss cognitive and conceptual interoperability (named semantic reconciliation) in the AEC industry by stating that:

> two important aspects are emphasized in [cognitive] interoperability: (1) the "understanding" of information from different actors, and (2) information used which is symbolized by representations such as visual and textual re-presentations. (Mutis and Issa, 2012, p.8).

Induced by the industry's heterogeneity and fragmentation as well as a heavy reliance on inter-disciplinary understanding, barriers to cognitive interoperability hinder the ability to reach consensus on meaning of concepts within the construction domain.

Relationships between dimensions

The conceptual framework presented in Figure-A II-2 illustrates the relationships between dimensions of collaborative project delivery systems. The tools and technologies deployed along the technology dimension will impact the types of actions performed, while the mechanisms deployed within the process dimension will impact how the technology is used. As such, Semantic interoperability is situated at this interface between the procedural and the technological dimension. It is related to understanding through 'language' used by information systems to understand and interpret information and data. According to Chituc, Azevedo and

Toscano (2009), semantic interoperability refers to aspects such as information/knowledge representation and management, as well as the ability for interacting systems to learn by adapting, recombining and sharing knowledge. Chen and Daclin (2006) discuss syntactic and semantic incompatibilities of information to be exchanged. Syntactic incompatibility refers to different people or systems using different structures to represent information and knowledge. Semantic incompatibility refers to the lack of clearly defined semantics, which allows "unambiguous understanding of the meaning of information." Thus, it relates to both the mutual understanding of meaning between human agents the interpretation and processing between computers. The tools and technologies deployed along the technology dimension will also impact how teams interact within the collaborative project network; conversely, its structure will impact how technology is used. In this case, the interface between the organizational and technological dimension has been refined within the military research domain. Tolk (2003) presents a scale relating technological interoperability to organizational interoperability and states that: "To deal with organizational interoperability above technical interoperability, the domain of data and information has to be lifted up into the domain of knowledge and awareness." With regards to BIM, Taylor and Bernstein (2009) discuss the alignment of business practices with technological innovation to capture its full benefits. The authors establish that project teams should strive to align their practice paradigms (i.e. how they use the technology) within the project team to create the optimal collaborative environment and fully benefit from the technology. This speaks to the interface between the organizational and procedural dimensions, or the interoperability of workflows. As such, the structure of the collaborative project network will impact the actions carried out within its structure. On the other hand, the mechanisms put forth by the collaborative network will determine its interactions.

Conclusion

This paper introduced a conceptual framework that develops the interoperability construct across multiple dimensions and at their connections. The framework defines emerging collaborative project delivery systems within the AEC industry by relating technological, organization and procedural dimensions and situating them within a given context, which acts as a mediating force. The framework is underpinned by an information processing systems approach to project delivery. The initial conceptual framework was built through an extensive review of the literature. A systematic literature review was then performed to enquire into the extent of diffusion of the interoperability construct within the AEC research field. Interoperability was presented across these three interrelated dimensions. Sub-dimensions of interoperability were also presented, such as semantic, workflow and systems interoperability. Future avenues of research present themselves at the interfaces between dimensions. For example, while technological interoperability has been researched, the extent of the influence of process interoperability or integration on this dimension is unclear. Current limitations of this framework are the lack of thorough validation. The authors are currently carrying out further research to validate the conceptual framework as well as develop the various dimension of interoperability. Limitations of the literature review process were the necessity for the appropriate search strings and analysis factors to be developed and the possibility of missing relevant articles due to inadequate labeling in the database. To increase the reliability of this review, a third party should replicate the process. This systematic review process is also being developed further in the authors work.

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APPENDIX III

INVESTIGATING MODEL EVOLUTION IN A COLLABORATIVE BIM ENVIRONMENT

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Abstract
As the adoption and implementation of building information modeling (BIM) continues to gain momentum, the benefits and challenges of its implementation and use are becoming better defined. However, there still lacks an understanding into the reconfiguration of practice that is being induced by BIM within multi-disciplinary project teams. Part of this reconfiguration of practice involves the development of the model through the generation, authoring and exchange of project information. This paper presents the finding of a research project that investigated the evolution of a BIM developed by a vertically integrated project team on a large institutional project for design and construction purposes. The objective of the research project was to develop measures to investigate the evolution of a BIM in a collaborative and multi-disciplinary project setting. The research team analyzed the bi-weekly iterations of the models produced by the design team following a rigorous protocol. Timesheets were obtained for all project team members involved in the modeling process. The measures developed adopt both the product and the process perspective of BIM. These measures were tested to verify how they correlated to one another and to the overall time spent in the project and in BIM. Four categories of measure are developed: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. These measures can serve as a benchmark to evaluate the efficiency of the modeling and ultimately the project delivery process.

Introduction
The transition to building information modeling (BIM) based practice in the Architecture, Engineering and Construction (AEC) industry promises considerable benefits over traditional practice mainly due to the possibility for project teams to co-develop, coordinate and optimize the digital prototype of a product (building, infrastructure, etc.) prior to its execution. This prototype is developed as a parametric model, acting as a database containing a product's information available for reuse during its entire lifecycle (Eastman et al., 2011). These benefits are accrued through better information authoring, exchange, management and retrieval (Crotty, 2011); in theory BIM is allowing project teams to mitigate information chaos in the project

lifecycle (Dubler, Messner and Anumba, 2010). Considering that project teams can be considered information processing systems (Winch, 2010), this push to eliminate information chaos within the project team is central to one of the core tenants of BIM which is to improve the efficiency and performance of the AEC industry (Eastman et al., 2011). On the other hand, the transition to BIM constitutes a departure from traditional practice (Dossick and Neff, 2011). As such, organizations are currently caught in a period of disruption in the AEC industry: the promise of BIM is alluring to many and in this regard, they are moving forward with its implementation. However, they are being confronted to deeply entrenched practices, hence the notion of paradigm shift and the need to reconfigure these practices to leverage the benefits of BIM (Taylor and Bernstein, 2009). While theoretical developments in the area of BIM implementation are taking root, there is still a need to define and assess how this shift is affecting practice and more precisely how it is impacting the generation, authoring, exchange and management of project information across a project's lifecycle.

From this perspective, this paper aims to increase our understanding of how a BIM evolves throughout a project and the factors that mediate its progression by developing measures to investigate its evolution in a collaborative and multi-disciplinary project setting. This paper specifically aims to answer the following questions: (1) what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? (2) How do these measures correlate between themselves, across time and across disciplines? And (3) what do these measures tell us of how a BIM is evolving throughout the project? The case study of a new institutional building procured under a design-build delivery mode is used to develop these measures and answer these questions. Four categories of measure were developed: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. Other measures that have been developed are discussed in the paper, however they were not operationalized. These measures are: measures of project complexity, measures of information quality and measures of information flow. The paper concludes with a discussion about the implications of these measures as well as opportunities for future work.

Background

The transition to BIM is not without its set of challenges (e.g. Eastman et al. 2011), chiefly amongst them, interoperability, or the ability of heterogeneous information systems to communicate (IEEE, 1990) is consistently ranked as a top barrier to BIM. Amongst the many dimensions of interoperability identified (Poirier, Forgues and Staub-French, 2014), technological interoperability remains one of the most important issues which hinders the flow of information in current BIM-based project environments. While strategies to overcome these issues have been developed, namely the OpenBIM standards developed by buildingSMART International, they are still in development. Furthermore, organizational, procedural and contextual barriers, that have been documented in the past, prior to the emergence of BIM, (e.g. Egan, 1998) are still having as important, if not a bigger, impact on the flow of information within the project team than the newly introduced technological barriers.

In light of these challenges, different approaches to formalize information handoffs in a BIM-based collaborative environment have been developed, namely the information delivery manual (IDM) part of the OpenBIM standard from buildingSMART International (ISO 29481-1, 2010) , the model elements table developed by the American Institute of Architects (AIA) in 2008 (AIA, 2008) , the Level of Development (LOD) Specifications developed by the BIMForum released in 2013 (BIM Forum, 2013), as well as the COBie data exchange format developed by the USACE in 2007 and in particular the Data Drops developed in conjunction with the BIM task group in the UK (East, 2007). While these approaches allow to either map out or align model based information authoring and exchanges expectations, they represent set points in time and are often aligned to the tradition project phases, further contradicting the required change in practice to move towards seamless information flow through BIM. Furthermore, these approaches do not allow to assess the dynamic nature of information throughout a project.

Sparse work has looked into the assessment of model evolution in the AEC industry. As such there are little metrics to perform a comprehensive evaluation. However, some work has been performed to investigate specific elements which touch on model-based information evolution. Leite et al. (2011) investigate the effort that it takes to develop a model from a LOD 400 to LOD 500. The main objective is to evaluate the modeling effort in relation to the level of detail. They then evaluate the impact of LoD in supporting MEP design coordination. The study shows that additional modeling effort can lead to more comprehensive analyses and better decision support during design and construction. Sacks et al. (2005) provide a set of benchmarks to evaluate the BIM implementation process in terms of productivity gains between a traditional 2D CAD workflow and a 3D modeling workflow. They go on to find that the transition to BIM has improved productivity between 15% and 41% for design and detailing in structural engineering practice (Sacks and Barak, 2008). East and Bogen (2012) propose an experimental platform and a methodology to consistently evaluate building models. The tools proposed are experimental and mainly for research purposes. Du, Liu and Issa (2014) propose a cloud-based BIM performance benchmarking application, called BIM Cloud Score, to allow an overall view of BIM utilization in the AEC industry and facilitate performance improvement for individual companies. The authors developed a series of 6 indicators and 21 measures for the assessment of both the process and the product (the model). The BIM Cloud Score is still a hypothetical tool and has yet to be commercialized. Furthermore, some of the metrics, information quality as an indicator of performance for instance, are summarily discussed and lack robustness. To that effect, Berard (2012) develops 8 specific metrics and describes a scale of observable phenomenon (akin to a maturity model) to evaluate information quality from the contractor's perspectives. He operationalizes these metrics to validate their applicability and usefulness in the AEC industry. While useful, the contractor perspective is narrow and the author doesn't differentiate between quality of information processes and quality of the product information itself. Dubler, Messner and Anumba (2010) look into the question of process information and study information exchanges through BIM from a lean perspective. They develop the 7 types of waste identified in the Lean approach and map that to types of waste related to information exchanges through BIM. Manzione et al. (2011) develop a BIM Integrated Management Model (BIMM) comprised of four stages, called loops, and a total of 11 steps. In the control loop they operationalize the 6 indices (or measures) of information flow developed in Tribelsky and Sacks (2010) and based on lean concepts. These indices allow measurement of information flow in the process of detailed design where construction documents are prepared. The indices develop in Tribelsky and Sacks (2010) identify information flow bottlenecks, large batch sizes and accumulation of work with the objective of finding faults or bottlenecks in the project development process. They also developed an index for measuring rework which was later validated in Tribelsky and Sacks (2011). In this subsequent paper, the authors find that an unpredictable information flow results in unpredictable project outcomes. This body of work pertaining to evaluating information flow is highly relevant and speaks to the shift in practice from this perspective. In parallel, the BIMM offers a framework to structure how this information should be managed in a project delivery setting. However, certain areas of evaluation are lacking such as information quality, design evolution and productivity.

Other domains have looked into assessing the evolution of design and production. Namely, the field of software engineering has developed many measures to evaluate the development (e.g. Ampatzoglou and Chatzigeorgiou, 2007) and quality of software design (e.g. Yacoub, Ammar and Robinson, 1999). In order to close the gap identified in terms of comprehensive evaluation of design development and evolution in the AECO industry in light of the reconfiguration of practice prompted by BIM, the developments in these fields could be leveraged and applied to the AEC industry. The table below presents various metrics to evaluate different aspects of design and product evolution (Table-A III-1)

Table-A III-1 Measures to evaluate design and product evolution from various domains

Author	**Du et al. 2014**	**Berard 2012**	**Dubler et al. 2010**	**Tribelsky and Sacks 2010**	**Ampatzoglou Chatzigeorgiou 2006**	**Yacoub et al. 1999**
Domain	AEC	AEC	AEC	AEC	Software	Software
Purpose	Product and process performance	Information quality	Information exchange waste	Information flow	Software size & complexity	Software quality
Metrics	Productivity – speed of development Effectiveness Quality Accuracy Usefulness Economy	Relevance Consistency Correctness Precision Availability Distribution Flexibility Amount of information	Overproduc-tion Inventory Extra Processing Motion Defects Waiting Transporta-tion	Action rate package size work in progress rework batch size development velocity bottleneck	Size (Lines of code, number of classes) Complexity Coupling Cohesion	Complexity Coupling Dynamic coupling

Research methodology

This research project is part of a larger more comprehensive research project aimed at studying the impact of BIM on project delivery in the AEC industry. The aim of this particular scope of the research project was to investigate the evolution of a BIM in a collaborative, multi-disciplinary project environment by answering the following questions: (1) what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? (2) how do these measures correlate between themselves, across time and across disciplines? And (3) what do these measures tell us of how a BIM is evolving throughout a project? In light of this, the objective of this scope of the research project was to develop and test measures to evaluate the development of information through a BIM. To fulfill these objects, a mixed-method case study methodology was employed. The case studied is that of the new construction of a major institutional building in Edmonton, Alberta, Canada. The $260 million, 39,000 m2, project was procured under a design-build contract with the government of Alberta. The project team was made up of 29 different stakeholder organizations. For the scope of research described in this paper, the research team performed data collection over an 18 month period, which corresponded to the construction documentation phase of the project. More precisely, the research team collected the bi-weekly iterations of the models produced by the design team over this 18 month period and analyzed them following a rigorous protocol. 41 iterations of the model were analyzed for the four main disciplines: architecture, structural, mechanical and electrical, for a total of 164 models. The models were analyzed in their native format (Autodesk Revit 2012 & 2013) and in a model checking and coordination software (Autodesk Navisworks Manage 2014). The models were all purged to remove all unused elements prior to analysis to ensure consistency. Furthermore, Industry Foundation Class (IFC) files were produced for every model and analyzed using the text file, the NIST IFC Analyser (Lipman, 2011) and Solibri Model Checker v.9.5. This was done to expand the scope of analysis to include measures such as Lines of Code in the IFC schema, number of entities, model components and model revisions. Table-A III-2 presents these measures. Timesheets were obtained for all project team members involved in the design and model development process. The total hours spent on the project and the number of hours spent by BIM personnel (individuals who were working directly in the model) were compiled. The measures were analyzed in three ways: the correlation between the measures, the correlation of the measures between the disciplines and the evolution of the measure across time were calculated for all disciplines and between disciplines. The 'R' language and environment for statistical computing was used (R, 2008). Spearman's rank correlation coefficient (ρ) was used to evaluate the correlation between variables due to its sensitivity to monotonic relationships over linear relationships. A cluster analysis was also performed in R to evaluate the appropriateness of the measures developed. The analysis were run for both absolute values (cumulative, ρ_{abs}) and relative values (variance per time period, ρ_{var}) for each measure.

Table-A III-2 Data collection points for model analysis across all disciplines

Native model	IFC file	Timesheets
File size (purged)	File size	Total hours per discipline
Scheduled Objects	LOC in the schema	BIM hours per discipline
Quantities – all	Entities	
Clashes	Components	
Sheets created	Model revisions	
Views created		
Annotations (Legends, etc.)		

Project setting

The context of the case studied was characterized by the following elements: it was a publicly funded project procured under a design-build agreement with the provincial government. The design team was from a vertically integrated firm offering architectural and engineering services. As such, the core design team was working on the same network in real-time. Bi-weekly updates of the models were published to a cloud-based project management software to be distributed to the general contractor and sub-trades. Key sub trades were contracted in a design assist role and provided a gross maximum price upon completion of design development. The contracts with the sub-trades and with the client were based on 2D drawings and specifications. As such, the model represented the core database containing project information, however a lot of effort was put into preparing and distributing 2D documents, which themselves contained annotations and specifications that were not found in the model. Therefore, it cannot be said that the model contained all relevant project information. A BIM project execution plan (PxP) was prepared to outline the scope and uses of the model in the project. On key element that was introduced in the PXP was the "Statement of Collaboration Intent" which outlined the intentions of each project stakeholder with regards to BIM use in the project. This is where the level of development was detailed for all disciplines and for all model elements. For example, the statement of collaboration intent for the architectural discipline was the following: "Most elements will only have as much data as we need to produce a 2D set of drawings". This particular statement was made because the contractual documents and all deliverables for the project were to be 2D documents. Any further modeling that was required for coordination and fabrication purposes would have to be performed by the trades. The active participants in the modeling process on the project were the following: architecture, interior design, structural engineer, mechanical engineer, electrical engineer, general contractor, structural steel contractor, mechanical contractor, electrical contractor. Furthermore, the project context was particular in that, even if this was a design-build project, the client still had considerable involvement during the design phase. The project team had to release progress documents at set milestones, both internally for costing updates and externally for project review by the client. Therefore, two parallel work streams were developed whereby part of the design and documentation effort was put on developing the model and part of that effort was put on producing the 2D documents. Despite this particular context, it is still possible to say that this project was a collaborative BIM-enabled, multi-disciplinary project, with early involvement of key trades and general contractor. In this regard, the evolution of the BIM was intimately tied to the evolution of the project. In the evaluation of the various models, it is assumed that the modeling process is consistent throughout the project and across the project team.

Findings

Measures developed

All disciplinary models were thoroughly analyzed to answer the first question: what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? The thorough investigation of the models allowed us to extract the 12 variables presented in the first two columns of Table-A III-2 and view their evolution across time for all four disciplines. Addressing the second question (how do these measures correlate between themselves, across time and across disciplines?) facilitated a categorization of the measures as follows: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. Lastly, the third question (what do these measures tell us of how a BIM is evolving throughout a project?) was addressed for each category to evaluate how the measures identified vary in relation to time spent on BIM by the various disciplines in the project team. Figure-A III-1 illustrates the relationships between the measures of model evolution. Figure-A III-2 illustrates the percentage variance of the four measures at a given period for all disciplines. This percentage variance could be compared to the project average for each measure, compared against a given target, or in the case of a retrospective study such as this one, against the final model which serves as a benchmark.

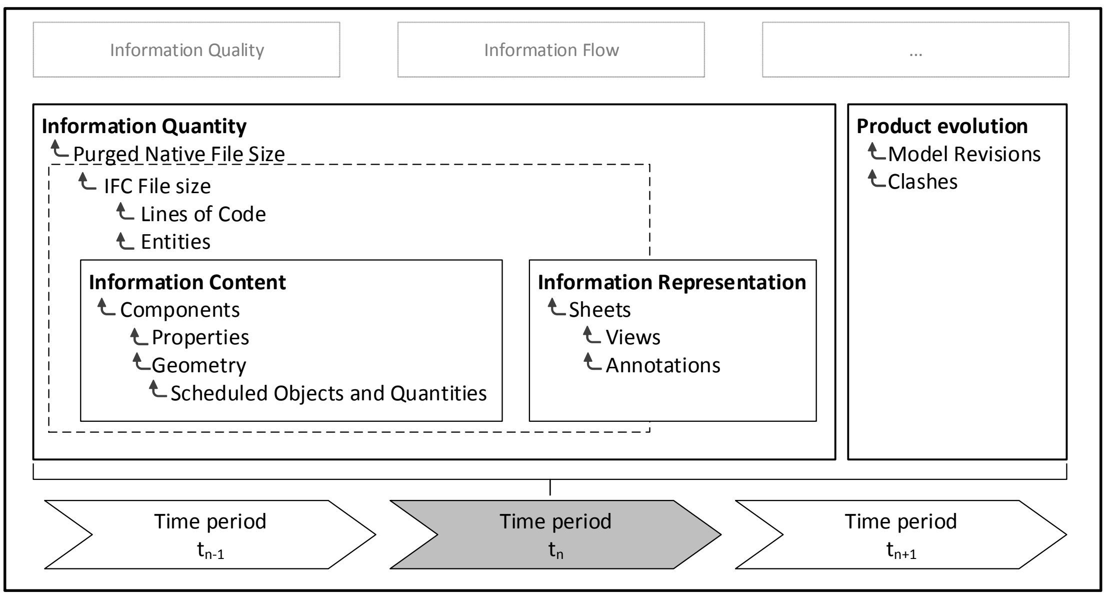

Figure-A III-1 Relationship between measures of model evolution

Measures of information quantity: File size and lines of code in the schema
The measure of information size is a reflection of the overall information contained within the model in terms of bytes of encoded data or information. This measure is represented by file size (both from the purged native file and the IFC file) and the number of lines of code in the IFC schema (LOC) (from the IFC file). The main issue with file size as a measure is in the way the information is encoded by the software platform or how the model is created, with issues associated to the modeling process and elements included in the model. Native file size includes all geometry in the model, properties, relations, annotations, views, sheets, images or renders and other representations that would support the project development process, whereas the IFC files only contain the information that was processed at export, which in itself introduces variability due to the potential loss of information during export (Koch and Firmenich, 2011). It must be noted that a version upgrade was performed (from 2012 to 2013 version) for the native software used in the project, which could impact how the IFC files were exported. Regardless, IFC file sizes and LOC are very strongly positively correlated across all disciplines (min ρ_{var} = 0.898 for architectural). There is a mid-positive correlation between

purged native file size and IFC file size for mechanical ($\rho_{var} = 0.506$), while it is considerably lower for electrical ($\rho_{var} = 0.265$) and architectural ($\rho_{var} = 0.163$), which could be caused by information that is not directly included in the model, such as renders, or level of detail of model elements. A quasi-null, although negative, correlation was found for structural ($\rho_{var} = -0.042$), perhaps due to how individual structural members are encoded in the native file as opposed to the IFC file. In the analysis of the correlation of measures of information quantity between disciplines, there is a low positive correlation between all disciplines for purged native model size meaning that file sizes are not particularly coupled across disciplines ($0.179 < \rho_{var} < 0.386$). There is a weaker correlation and more variability between IFC model sizes across disciplines ($-0.270 < \rho_{var} < 0.482$). A low to mid positive correlation was found between the time spent in BIM and the file size variation for all disciplines ($\rho_{var\ arch} = 0.309$, $\rho_{var\ struc} = 0.405$, $\rho_{var\ mech} = 0.702$, $\rho_{var\ elec} = 0.670$), which indicates a direct relationship between time spent in BIM and the purged native file size. The weaker correlations in architecture and structure could be in part due to the negative variations in size, for instance when certain elements in the model were rationalized. In investigating the evolution of measures of information quantity in relation to time spent in BIM over the course of the project, it was observed that the native file sizes for all disciplines progressed in a linear fashion whereas IFC files sizes jumped drastically at set points in time for both mechanical and structural.

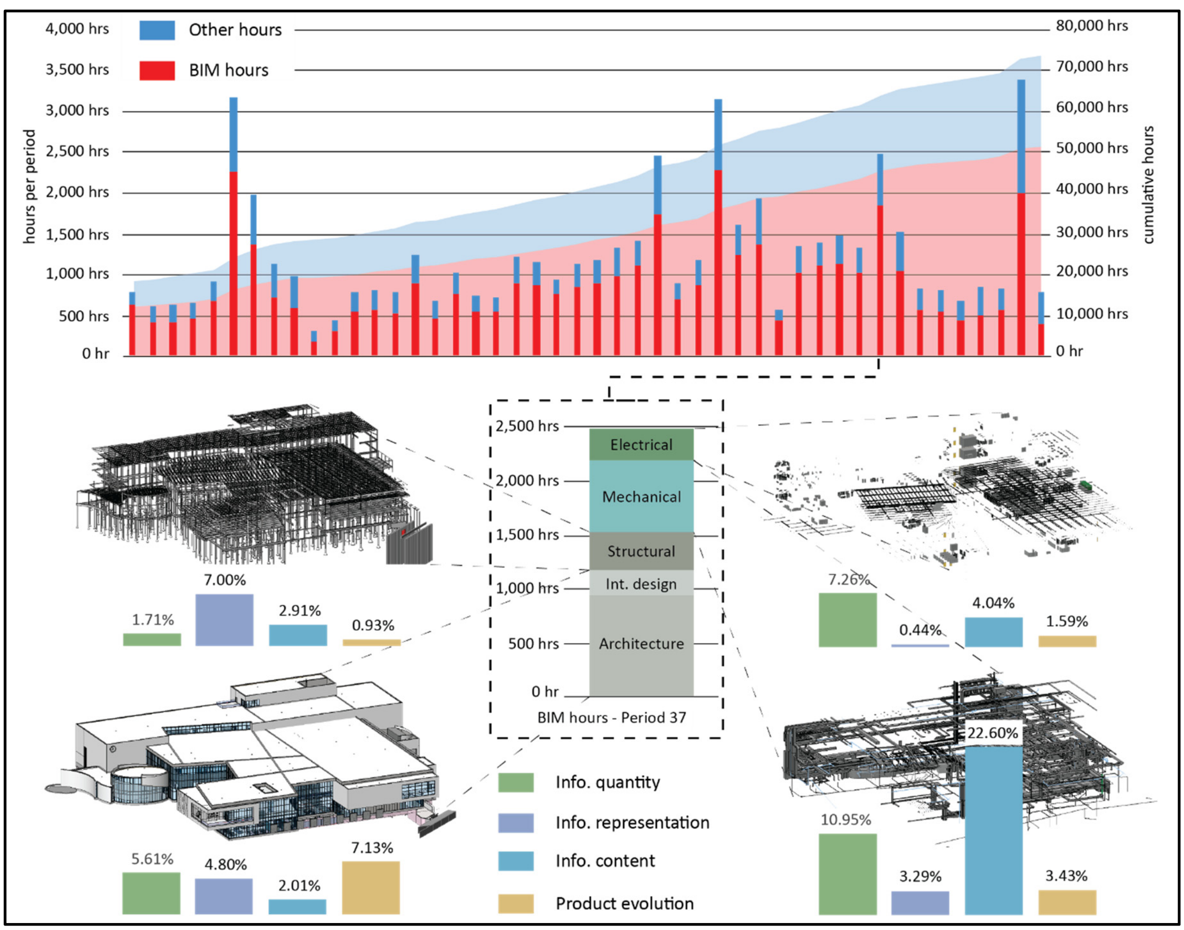

Figure-A III-2 Percentage variation of all measures for given period

Measures of information content: Entities, components, scheduled objects and quantities
The measure of information content relates to the geometry and properties of the elements in the model. While the number of entities in a model can be interpreted as a direct measure of the raw yet structured information contained in the IFC schema - there is a perfect correlation between LOC (consequently, IFC files size) and number of entities (ρ_{var} = 1.000) across all disciplines - the export to IFC process can introduce variability as mentioned. Therefore the measures of components and scheduled objects, which are attributable to model authoring and the project development process, would seem better suited for this measure. Indeed, individuals interact directly with these components in developing the model. The main difference between scheduled objects (extracted from the native file) and model components (extracted from the IFC file) are their practical use: scheduled objects are related to model uses whereas model components are related to model authoring. A mid to strong positive correlation was found between the number of entities and the number of components for all disciplines ($0.655 < \rho_{var} < 0.810$). There was also a mid to strong positive correlation between the number of scheduled objects and the number of components for all disciplines ($0.415 < \rho_{var} < 0.688$) In the evaluation of the correlation of measures of information content between disciplines, specifically components, a low to mid positive correlation was found between all disciplines ($0.103 < \rho_{var} < 0.696$). A low to mid positive correlation was found between the time spent in BIM and the variation of number of components for all disciplines ($\rho_{var\ arch} = 0.105$, $\rho_{var\ struc} = 0.189$, $\rho_{var\ mech} = 0.301$, $\rho_{var\ elec} = 0.418$). In investigating the evolution of measures of information content over the course of the project, it was observed that architectural (3.3% avg. increase) and structural (0.8% avg. increase) disciplines tended towards a slow progression of model components and scheduled objects whereas mechanical and electrical had 'tipping points', directly related to project milestones (in this case work packages) where a lot of content was created rapidly.

Measures of information representation: Views, sheets and annotations
The creation of views, sheets and annotation supports the design process and become the deliverables for the project. Views are embedded into sheets and annotated to create project documents. The presence of these elements are a characteristic of the parallel 2D – 3D modeling and documentation process. Whereas measures of information content tends to stabilize during the construction documentation workflows; the number of views and sheets continues to grow as the need for additional representations are required to translate and communicate project information to the various project team members. While the definition of what is represented on sheets is an industry standard (i.e. plans, elevations, sections, details and schedules), views are highly contextual and not only discipline specific but subject to individual workflows, meaning that there is limited correlation between the number of views and sheets; each sheet will contain at least one view or schedule, but not all views and schedules will be included in a sheet. A low positive correlation was found between number of views and sheets across each disciplines ($0.181 < \rho_{var} < 0.277$); this measure is unrelated between disciplines. A low to mid positive correlation was found between the time spent in BIM and the variation of number of views for all disciplines ($\rho_{var\ arch} = 0.112$, $\rho_{var\ struc} = 0.101$, $\rho_{var\ mech} = 0.284$, $\rho_{var\ elec} = 0.446$). In the investigation the evolution of measures of information representation over the course of the project, the architectural discipline has the highest total number and the most rapid progression of views, however structural discipline has the highest

views to sheet ratio at 12.82 views per sheet on average. Understanding the rate of information representation progression can allow to evaluate the time spent on the production of 2D drawings, a relatively redundant procedure given the emerging uses of BIM directly on site and in facilities maintenance.

Measures of product evolution: Clashes and Revisions

The overall variation of the above measures (quantity, content and representation) over time will be measures of information evolution. Product evolution and information evolution are differentiated in this case. As such, the number of clashes and revisions in the model can be interpreted as a measure of the refinement of the model as design progresses. The measure of clashes is extracted through clash detection software and is a standard process in current BIM based practice. Three classes of clashes have been developed: true-positives (identified as a clash and is a clash), false-positives (not identified as a clash but is a clash) and false-negatives (identified as a clash but is not a clash) (Leite et al. 2011). In addition, clashes were totaled for each discipline. The number of revisions is extracted by directly comparing model iterations in a model checking software. Three classes of revisions were extracted: elements added, elements removed and elements modified (elements that have one or more characteristic modified). Evaluating the correlation of measures of product evolution between disciplines, the number of revisions showed mid positive correlation ($0.393 < \rho_{var} < 0.641$), whereas the number of clashes show higher positive correlation ($0.608 < \rho_{var} < 0.915$). One element of note is that the design team did not start purposefully addressing clashes before the very end of construction documentation, therefore the measure of the evolution of clashes throughout the project is more or less a valid measure in this case. Furthermore, the models were released on a bi-weekly thus allowing the project team to complete any coordination cycle and thus the clashes that were found would be resolved in the upcoming cycle. Moreover, evaluating the correlation between the number of clashes and the number of revisions would seem a valid point of investigation, indeed this could indicated that clashes reduce as revisions increase, which would be a valid statement. The contrary however wouldn't make sense. In evaluating this measure, the research team found a null to low correlation ($-0.214 < \rho_{var} < 0.227$), which confirms that the two measures are weakly related, if not unrelated. A null to mid correlation was found between the time spent in BIM and the variation of number of clashes ($\rho_{var\ arch} = 0.146$, $\rho_{var\ struc} = -0.073$, $\rho_{var\ mech} = 0.420$, $\rho_{var\ elec} = 0.494$) and the variation of the number of revisions ($\rho_{var\ arch} = -0.024$, $\rho_{var\ struc} = 0.230$, $\rho_{var\ mech} = 0.573$, $\rho_{var\ elec} = 0.370$). In the investigation the measures of product evolution over the course of the project, no clear trend was discernible for both number of revisions and number of clashes. It would be expected that both would tend towards 0 over time.

Additional measures: Measures of project complexity, information quality and flow

The measure of model complexity and of level of development are difficult to quantify. While specifications exist for level of development (e.g. AIA, 2008), the exercise is carried out manually and remains somewhat subjective. In terms of complexity, some measures could be used such as use of generic model elements and place holders or number of objects per area (Du et al. 2014). Clevenger and Haymaker (2011) have developed some measures of complexity in the design process which could be further investigated in the context of model evolution. However, further work is required to develop measures of complexity that are relevant and directly computable as both measures of product and process in a BIM environment, namely in the investigation of complexity, coupling and cohesion in the IFC schema. Lastly, as discussed, measures of information quality and flow are core to the AEC industry. While the question of information flow has been tackled from various perspectives, the question of information quality is seemingly underrepresented in the AEC research domain. One could say that information flow is a subset of information quality as a measure of process efficiency and quality. The work performed by Dubler (2010) and Berard (2012) speak to these measures, however, they remain difficult to operationalize. For instances, measures of information accuracy and precision have to be validated in the field and compared to a suitable referent. Measures of information relevance are highly subjective and dependent on a stakeholder's perspective. Trieblesky and Sack's (2010, 2011) as well as Demian and Walters' (2014) work tackled some of these issues with information flow, however, the authors acknowledge that the work performed was extremely onerous. Furthermore, while information exchanges can be more readily mapped and measure, information quality is highly subjective and dependant on the stakeholder's point of view. Information, its value and its quality in the model is a field of research that requires much more investigation.

Discussion and Conclusion

This paper presented the findings of a research project with the aim of investigating model evolution in a collaborative multi-disciplinary BIM-based project setting. Measures were developed to assess this evolution and allow a consistent empirical approach to information evolution in the project delivery process. The measures were tested for correlation between each other, across disciplines and their variation was evaluated across time. While most measures identified were correlated within their categories, further investigation is required to understand this implication across other project settings. Work is also necessary to understand proportionality in the evolution, for instance spending a lot of time on a particular 2D detail will not increase the weight of the model as adding or duplicating a specific component, say a piece of furniture, which takes a lot less time and contributes. Furthermore, in developing these measures and gaining access to data, the research team was faced with multiple challenges. A clear advantage was gained through BIM in this research project due to the possibility of querying project information in a structured manner. However, it would have been advantageous to have access to weekly iterations instead of bi-weekly iterations of the model. The exercise would have gained in precision. In addition, a main challenge was faced in developing a coherent measure of time spent in BIM versus time spent on the model. The research team did not have access to the file logs, nor did the time sheets completed by the employees contain relevant cost codes for various BIM activities. Time spent in BIM had to be extrapolated from the personnel that were identified as BIM users in the project. An additional challenge lay in exporting the IFC files in a consistent manner across different versions of the native software platform. IFC 2x3 was the standard format for export, and a special IFC export plug-in was used, however the mechanics behind the export were unknown to the research team and was seen to introduce a lot of variability between versions of the software platform. There is also some inherent loss in information in the transfer process (Koch and Firmenich, 2011) Moreover, while it was assumed the modeling process be consistent across the project team, each individual has their own way of working and interacting with the model, for instance creating 2D views to modify the model rather than working directly in 3D.

This differences introduce variability in the investigation. In analysing the data, the research team was confronted with the choice between absolute values (i.e. the compiled value or sum of values since the start of the project) and relative values (the variation between model iterations). Absolute values were used for correlation analysis in this paper whereas, the relative values were used in the time analysis. In the data extraction process, a rigorous protocol was required to replicate every step across the entire project. The research team is looking into automating this process for future work. It is also seeking to expand the scope of data extraction through the use of tools such as COBie data drops and the spreadsheets produced as a formal way to validate project progress. Further work is also required to replicate this evaluation across various project settings. However, in expanding this investigation to include different models, a considerable effort to normalize the data across the different project contexts will have to be carried out. For instance, the uses of BIM which impact the development of the model will have to be factored. The analysis of additional models would allow the regression analysis of multiple data sets to validate the evolution of the measures developed in this paper.

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APPENDIX IV

SITE 01: DATA COLLECTION

Table-A IV-1 List of interviewees on site 01

	Name	Organization	Role	Interview 01	Interview 02	Interview 03	Interview 04	Interview 05
Owner/Client	Brian Soutar	Alberta Infrastructure	Project Director	28-02-2013				
	David Murphy	Alberta Infrastructure	Project Coordinator	12-03-2013		12-04-2013		
	Neil McFarlane	Alberta Infrastructure	Project Director	17-01-2013	07-12-2013	12-04-2013	25-07-2014	30-04-2015
	Rachel Sommer	Alberta Infrastructure	Project Coordinator	12-03-2013		12-04-2013		
	Robert Axten	Alberta Infrastructure	Project Manager	22-04-2013		12-04-2013		30-04-2015
	Ron Muir	Alberta Infrastructure	Operations Manager				25-07-2014	
	Jim Tessier	Alberta Infrastructure	Operations Manager				25-07-2014	
General Contractor	Amjad Shorrab	Ledcor	MEP Project Manage		07-10-2013		24-07-2014	
	Anthony Nguyen	Ledcor	Project Coordinator			12-06-2013		
	Don Neufeld	Ledcor	Senior Superintendent		07-10-2013		24-07-2014	01-05-2015
	Fallon Ladouceur	Ledcor	BIM Coordinator	01-03-2013	07-10-2013	12-06-2013	24-07-2014	01-05-2015
	Fil Abella	Ledcor	Project Coordinator		07-10-2013			
	Jamey Singh	Ledcor	Project Director	01-03-2013	07-10-2013			
	Kyle Dolen	Ledcor	Superintendent	15-03-2013				
	Mike Roeper	Ledcor	Project Director		07-10-2013	12-06-2013	24-07-2014	
	Trevor Messal	Ledcor	Senior Project Manager	01-03-2013	07-10-2013	12-06-2013	24-07-2014	01-05-2015
	Maclean Kampula	Ledcor	MEP Superintendent					30-04-2015
Designer	Allan Wilson	DIALOG	Architecture	27-02-2013	07-12-2013	12-05-2013	23-07-2014	30-04-2015
	Amisha Pope	DIALOG	Mechanical	27-02-2013			23-07-2014	
	Carol Hoveland	DIALOG	Interior Design				23-07-2014	
	Crystal Mentes	DIALOG	Architecture	27-02-2013	07-12-2013	12-05-2013	23-07-2014	
	Diana Williamson	DIALOG	Mechanical		07-12-2013	12-05-2013	23-07-2014	
	Donna Clare	DIALOG	Architecture	27-02-2013	07-12-2013	12-05-2013	23-07-2014	30-04-2015
	Doug McConnell	DIALOG	Architecture	27-02-2013				
	Elizabeth Wollbaum	DIALOG	Structural	27-02-2013	07-11-2013		23-07-2014	
	Gerald Murnane	DIALOG	Architecture	22-03-2013			23-07-2014	30-04-2015
	Jim Montgomery	DIALOG	Structural	22-03-2013				
	John Crate	DIALOG	Project Manager	19-04-2013		12-05-2013		
	Justin James	DIALOG	BIM Manager	27-03-2013				
	Manigo Ho	DIALOG	Electrical	28-03-2013				
	Mark Merron	DIALOG	Mechanical				23-07-2014	
	Micheal Corpuz	DIALOG	Architecture	27-02-2013	07-12-2013			
	Michelle Sigersson	DIALOG	Interior Design				23-07-2014	
	Ryan Renihan	DIALOG	Structural	27-02-2013	07-11-2013	12-05-2013	23-07-2014	
	Tim Mcginn	DIALOG	Mechanical	19-04-2013			23-07-2014	
	Trina Larsen	DIALOG	Electrical	27-02-2013	07-12-2013	12-05-2013	23-07-2014	

	Name	Organization	Role	Interview 01	Interview 02	Interview 03	Interview 04	Interview 05
Sub-contractors	Jesse Kornelsen	Collins	Structural Steel	25-03-2013	07-10-2013		25-07-2014	
	Greg Penney	Collins	Structural Steel					29-04-2015
	Ed Wanke	MCL Power	Electrical	13-03-2013				
	Remy Posch	MCL Power	Electrical		07-11-2013			01-05-2015
	Derek Matter	Priority Mechanical	Mechanical	13-03-2013		12-04-2013		
	Jody McNeill	Priority Mechanical	Mechanical	13-03-2013		12-04-2013		29-04-2015
	Brittany Mendiuk	Priority Mechanical	Mechanical				25-07-2014	29-04-2015

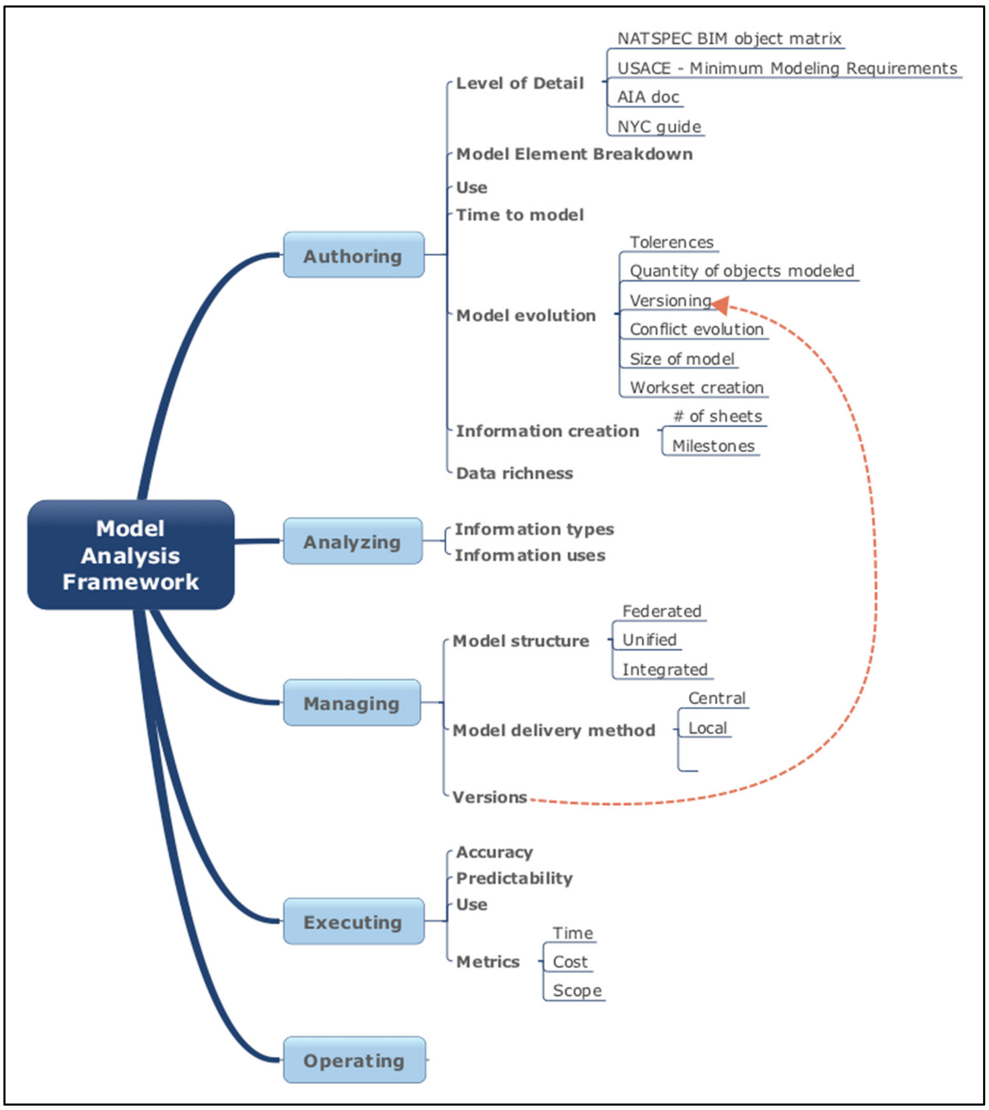

Figure-A IV-1 Model analysis framework

APPENDIX V

SITE 02: DATA COLLECTION

Table-A V-1 List of interviewees on site 02

Name	Organization	Role	Interview 01	Interview 02
Bob Cooke	Division 15 Mechanical Ltd.	President & CEO	26-06-2012	23-10-2013
Dale Miller	Division 15 Mechanical Ltd.	Construction Manager	26-06-2012	
Dinos Hadjiloizou	Division 15 Mechanical Ltd.	Project Manager / BIM Manager	26-06-2012	23-10-2013
Robert Campagnaro	Division 15 Mechanical Ltd.	Project Manager	26-06-2012	
James Dixon	Division 15 Mechanical Ltd.	Project manager	23-10-2013	
Dan Cooke	Division 15 Mechanical Ltd.	Project coordinator	23-10-2013	
Le Hien Huyen	Division 15 Mechanical Ltd.	BIM Coordinator	26-06-2012	22-10-2013
Mike Champion	UBC Operations	Project Manager	2013-03-11	

APPENDIX VI

OTHER DATA SAMPLES: DATA COLLECTION

Table-A VI-1 List of interviewees on other sites

Name	**Organization**	**Role**	**Interview 01**
Dan Conwell	Sutter Health Facility Planning and Development	Director, Planning Architecture and Design	15-09-2014
Samir Emdanat	Ghafari Management Services	Director	17-09-2014
John Hale	Department of National Defence (Can)	BIM Director	02-07-2014
Ole Kristian Kvarsvik	Nosyko AS (formerly at Statsbygg) (Nor)	Head of business and technology	30-10-2014
Will Lichtig	Boldt	Construction Executive	17-09-2014
Chris Mallett	Cabinet Office (UK)	Head of Digital Construction Technologies, Major Projects Authority	13-11-2014
Evan Matthews	Uk BIM Task Group	International liaison	01-12-2014
Brian Oakley	Alberta Infrastructure (Can)	Director, Planning	16-07-2014
David Philp	Uk BIM Task Group	Head of BIM	01-12-2014
Don Ward	Cabinet Office (UK)	Chief Executive of Constructing Excellence	13-11-2014

APPENDIX VII

LIST OF REPORTS AND PRESENTATIONS

Site 01: Royal Alberta Museum Project
Poirier, E and Staub-French, S. 2013 "Royal Alberta Museum Research Project: Benchmarking Report" Submitted June 30, 2013, Revised October 5, 2013

Poirier, E and Staub-French, S. 2013 "Phase III – Interim Presentation" Presented to Alberta Infrastructure, December 04, 2013

Poirier, E and Staub-French, S. 2014 "Royal Alberta Museum Research Project: Interim Report – 50% Working Documents" Submitted April 17, 2014, Revised June 12, 2014

Poirier, E and Staub-French, S. 2015 "BIM and Integration at Alberta Infrastructure" Presentation to the Assistant Deputy Minister, Alberta Infrastructure, April 30, 2015

Site 02: Division 15 Mechanical Ltd.
Forgues, D., S. Staub-French, S. Tahrani and E. Poirier. 2014. "The Inevitable Shift Towards Building Information Modelling (BIM) In Canada's Construction Sector: A Three-Project Summary." Montreal, Quebec, Canada, CEFRIO: French Center for Automation of Organizations.http://www.cefrio.qc.ca/media/uploader/Construction_ICT_final_summary_report_March_20_2014.pdf

Poirier, E. 2014 "Division 15 Mechanical Ltd.: Performance Assessment & Benchmarking" Presentation to the BIM steering committee, Division 15 Mechanical Ltd, June 25, 2014

Poirier, E, Staub-French, S. and Cooke, B. 2015 "The Impact of BIM – A Summary of Findings from a 3 year case study at Division 15 Mechanical Ltd." Submitted May 04, 2015, Revised May 15, 2015

Site 03: Collaborative BIM workshop, Montreal, Quebec
Poirier, E. 2013 "Introduction au BIM Collaboratif" Presentation given February 12, 2013

Poirier, E. 2013 "Synopsis – Atelier BIM Collaboratif" Submitted February 15, 2013

Site 04: BIM-PLM workshop, Montreal, Quebec
Poirier, E., Aksenova, G., Collot, P., Rivest, L., Forgues, D., and Doré, S. "Transitioning to Building Information Modeling and Product life-cycle Management in the Quebec Construction Industry: Challenges, Possible Solutions and Proposed Action Items" Submitted June 17, 2014, Revised September 03, 2014

Site 05: Pomerleau General Contractors

Poirier, E. 2014 “Performance Measurement and Organizational Benchmarking – Phase 1” Submitted November, 2014

Poirier, E. 2014 “Performance Measurement and Organizational Benchmarking – Phase 2a” Submitted March 03, 2014

Site 06: Société Québécoise des Infrastructures

Poirier, E., Forgues, D., Tahrani, S. Tremblay, S and Tousignant, M. 2014 “California Pacific Medical Center – Rapport de visite” Submitted September 30, 2014. Revised December 04, 2014

Forgues, D., Tahrani, S., Poirier, E. and Aksenova, G. “Analyse du contexte sur le déploiement du BIM et des pratiques intégrées dans les projets gouvernementaux – Rapport d’appui au dossier d’opportunité” Submitted December 12, 2014. Revised January 15, 2015

APPENDIX VIII

SUMMARY OF FACTORS AFFECTING CONSTRUCTION LABOR PRODUCTIVITY FROM SELECTED LITERATURE

Table-A VIII-1 Summary of factors affecting construction labor productivity from selected literature

Factor	Source
Environment	[02][04][05][07][11][14]
Surrounding events (revolutions)	[06]
Unforeseen events/Natural disasters	[05]
Weather	[01][02][03][04][05][06][07][08][09][11][12]
Industry	[01][06][11]
Adversarial relations	[05]
Availability of skilled labor	[02][06][09]
Economy	[01][05][11],
Governmental regulations (building codes, etc.)	[01][05][07]
Market conditions	[01][05]
Population base	[02]
Organization	[08][14]
Firm reputation	[08]
Information technologies	[06][11]
Organizational culture	[05]
Research and Development	[01][11]
Size of firm	[01]
Project	[02][03][05][07][12][13]
Competencies of the project team	[05][10]
Constructability	[04][05][06]
Construction methods	[02][05][07][12][14]
Cost predictability	[05]
Payment	[05][07][08]
Procurement type and delivery mode	[02][05][06]
Project size and complexity	[02][03][05][06][08][12][13][14]
Project finances (insurance, interest, etc.)	[05]

Factor	Source
Quality of design work	[02][03][04][09][10]
Rework	[04][05][07][09][10][12]
Scope or design changes	[02][05][06][07][09][10][11][13]
Site conditions and location	[01][02][04][05][06][08][09][13]
Site layout	[02][03][09]
Subcontractor integration	[11]
Uniqueness	[01][11]
Use of IT	[05][06][11]
Individual	
Management	[01][02][04][06][09][11][13][14]
Activity interactions, sequence of work	[09][11][12]
Approvals and responses	[03][09]
Change management	[04]
Client interference	[02][04][05]
Communication	[03][04][06][08]
Crowding	[03][04][07][08][10]
Flow, coordination of work	[02][03][04][06][08][09][10]
Management skills, quality	[01]2[03][05][06][08][11][13]
Material and equipment management	[02][03][04][06][07][08][09][10][12]
Overstaffing / Crew size	[02][03][04][08][09][10][11][12]
Planning	[01][04][05][06][10][11]
Subcontractor management	[06]
Scheduling (acceleration, compressions)	[02][08][09][11][13]
Stacking of trades	[02][04][09][10]
Supervision	[03][07][10]
Authority of supervisors	[03]
Consistency of supervision	[03]
Coordination supervision, performance monitoring and control	[01][03][05]
Error tolerance	[08]
Inspections (waiting, lack of planning)	[10]
Quality control	[02][07][11]
Quality of supervision	[02][03][04][06][07][09][10][12]
Safety officer	[03][07]
Seniority	[11]
Labor	[01][02][03][04][05][06][07][10][11][13][14]

Factor	Source
Absenteeism	[02][03][04][05][07][09][10]
Age	[06]
Benefits	[06][07]
Cooperation	[04]
Empowerment	[03][05][08]
Experience	[05][06][07][11]
Fatigue	[02][06][09][10]
Incentives	[03][06][07][08][10]
learning curve	[01]2[04][08][09]
Material and equipment availability	[02][03][04][06][07][08][09][10][12]
Motivation	[01]2[03][04][07][09][10][11][13]
Multiple shifts	[04][08]
Overtime	[02][04][06][07][08][09][11]
Personal problems	[07][10]
Physical limitations	[04]
Recognition	[03][04]
Relations between workers	[04][08][09]
Safety	[01][03][07][08][12]
Satisfaction	[07]
Suitability of tools and equipment	[03][04][05][07][10][12]
Training / education	[03][06][08][11]
Travel distance to worksite	[02][04][08][10]
Treatment	[04][10]
Trust in supervisors	[03]
Turnover	[02][04][05][09][10]
Type of work (discipline)	[02][07][08]
Understanding of project	[03][07]
Union membership	[01][08]
Wages	[02][03][06][10]
Work assignments	[02][04]
Working conditions (lighting, noise, etc.)	[02][03][04][05][06][07][10][11]

[01] (Adrian, 2004)

[02] (Borcherding and Alarcon, 1991)

[03] (Dai, Goodrum and Maloney, 2009)(CII 2006)
[04] (Dozzi and AbouRisk, 1993)
[05] (Durdyev and Mbachu, 2011)
[06] (El-Gohary and Aziz, 2014)
[07] (Enshassi et al., 2007)
[08] (Kazaz, Manisali and Ulubeyli, 2008)
[09] (McDonald and Zack, 2004)
[10] (Rivas et al., 2011)
[11] (Rojas and Aramvareekul, 2003b)
[12] (Sanders and Thomas, 1991)
[13] (Schwartzkopf, 1995)
[14] (Thomas et al., 1990)

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