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An Actor–Network Approach to Developing a Life Cycle BIM Maturity Model (LCBMM)

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Abstract: Building information modelling (BIM) has considerable potential for addressing sustainability issues in construction, but its benefits can be constrained by the failure to adopt BIM across the full project life cycle. Systematic whole-of-life BIM adoption can be supported by maturity models, but most models are limited by a lack of theoretical grounding, socio-technical dichotomies and the failure to adequately consider the full asset life cycle, often by overlooking the operations phase. This study aims to (1) develop a BIM maturity model that addresses these limitations by (2) using an in-depth analysis of an early adopter case study, thus addressing the lack of empirical research in BIM adoption experiences. A single interpretive research study was conducted to qualitatively analyse a US-based university. The data were gathered through interviews, field visits and document analysis. Actor–network theory (ANT) concepts scaffolded the analytical approach. The findings show that a complex BIM socio-technical network emerged, developed and converged during the project management stage but struggled to achieve durability as an ongoing solution to facilities management. By analysing the elements of success and failure across each stage, the researchers distilled five key lessons to achieve whole-of-life BIM maturity and proposed a life cycle BIM maturity model (LCBMM) supported by a practice guide.

Keywords: building information modelling; BIM maturity; actor–network theory; facilities management; BIM leader; life cycle BIM maturity; whole-of-life cycle; early adopter; innovator

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1. Introduction

Studies show that the building and construction sector accounts for 18.1% of the carbon emissions in Australia [1] and 39% of the carbon emissions globally [2]. One solution that has been proposed to support better environmental performance is building information modelling (BIM) [1,2]. BIM is a process by which digital geometric and non-geometric information about the physical and functional properties of a structure is captured and managed to support decision-making across all the stages of an asset's life cycle [3]. A 3D model of an asset, for example, can provide users with the potential for visualization, facilitating important processes, such as clash detection. Such 3D models can also be enriched to incorporate dimensions of time (4D) and costs (5D). In addition, a dimension of sustainability (6D) can be incorporated into BIM to allow decision-makers to simulate the energy behaviour of a building. Interestingly, facility management emerges as a seventh BIM dimension (7D). There is an increasing consensus among researchers about their understandings of 4D and 5D but little consensus on what 6D and 7D are; hence, these "two areas are still in their infancy, illustrated by some ambiguities to which these BIM dimensions refer" [4] (p. 3).

Underdeveloped conceptual understandings of BIM 6D and 7D are problematic, one reason being that significant environmental challenges (6D) are linked to the operational and facilities management phase of the project life cycle (7D). Studies indicate that most of the carbon emissions from buildings (29% of the 39%) are operational emissions [2]. If BIM is to be mobilized to address this challenge of operational emissions, then robust, systematic understandings of BIM 6D and BIM 7D must be developed.

The presentation of BIM (2D to 7D) as some form of hierarchy indicates that BIM adoption progresses in a processual, though not necessarily strictly linear, manner, with much of the BIM community congregating around 4D and 5D. This observation would suggest that BIM adoption is underpinned, and can be managed, through models of maturity. This study focuses on BIM maturity models, exploring the strengths and limitations of the existing ones, then providing ways for enriching them. A specific concern is to enable users to better manage the operations and maintenance phase of projects.

Owner organisations that repeatedly adopt building information modelling (BIM) across multiple projects have a clear need to understand BIM "process maturity" [5] not only at the project level but also at the organisational level. According to AS/NZS ISO/IEC [6], "an organisation reflects process maturity when "it consistently implements processes within a defined scope that contributes to the achievement of its business needs (current or projected)". An owner organisation's BIM maturity is determined by the ability to consistently implement BIM in sub-organisational units, including facility management.

The significance of facility management in BIM research is a growing field of study, but interest in the area is nevertheless a relatively recent development. Over the past decade, the focus of building information modelling (BIM) research and practice has gradually shifted towards the operational phase from the early phases of the building life cycle. A noticeable growth in studies was reported not only on explorations of social, technical, cultural, procedural and economic benefits and challenges in adopting BIM in facility management (FM) [7–11] but also on specific applications. Repeated 'calls for research' in gap areas were presented in seven review articles between 2014 and 2018 [12]. Research on specific BIM applications in FM [13] has emerged. Real-world BIM in FM applications has been reported in the last three years [14–18].

1.1. Relevance and Novelty of the Research

While contemporary research studies now argue for the need of whole-of-life cycle BIM [19,20] covering the planning, design, construction and facility management phases, a clear research gap in terms of understanding BIM maturity across the whole-of-building life cycle has been reported [11,20].

Little research has also explored the initiation stage experiences of case study organisations [9,10]. Sharing implementation-level stories either as exemplars [11], or disseminating lessons learned throughout the adoption process, are rare [11,13] and are necessary in supporting the industry's maturity at the macro level [21,22]. Particularly, studies that share early adopters' implementation experiences of the innovation adoption process [11] to motivate BIM followers [23], and to serve as the foundation for developing more powerful generally applicable BIM solutions [12] are limited. Dixit et al. [23] also argue that there is a significant misalignment between the body of knowledge (BOK) and the body of practice (BOP) in the understanding of BIM–FM integration leading towards whole-of-life BIM maturity.

This paper explores these two gaps simultaneously. Specifically, the study focuses on the development of a whole-of-life BIM maturity model that addresses the key limitations identified through a comparison of the existing models (Aim 1). The development of the model is based on an in-depth qualitative case study of a US-based university that is recognised as a leader in BIM adoption, a methodology that addresses the need for more real, organisationally grounded studies (Aim 2). A holistic, empirically grounded maturity model, we argue, can then lay the groundwork for other goals, including the use of BIM for environmental sustainability goals during the operations and maintenance phase.

1.2. Structure of the Work

The paper is structured as follows. In Section 2, key BIM maturity models are compared and potential directions for BIM model development are identified based on the research gaps. In Section 3, actor–network theory (ANT) is proposed as a robust analytical approach for creating a model that addresses the existing limitations. In Section 4, the case description, data gathering and data analysis techniques are presented. Section 5 presents the results in three stages: the key lessons learned, the proposed life cycle BIM maturity model and a practice guide. Theoretical, practical and societal implications are presented in Section 6. The paper concludes with limitations and directions for future work.

2. Existing Conceptualisations of BIM Maturity

2.1. Definition of BIM Maturity

The idea of BIM maturity is linked to the concept of process maturity. Process maturity can be defined as the extent to which "a specific process is explicitly defined, managed, measured, controlled, and effective" [5]. An organisational unit reflects process maturity when "it consistently implements processes within a defined scope that contributes to the achievement of its business needs (current or projected)" [6]. Process maturity is important as it is understood to be linked to growth in capability as well as processes' richness [5]. Drawing from this definition of process maturity, "BIM maturity" has been defined as the level of "quality, repeatability and degree of excellence" in relation to performing a BIM-related task or delivering a BIM service or output [24]. The existing definitions of BIM maturity appear to converge around the idea that adopters utilise BIM at different levels of effectiveness. However, definitions are just the start of theory building [25], and the task that follows, model development, is usually more complex. Still, a growing body of work has emerged around the objective of modelling maturity in BIM.

The existing conceptualisations of BIM maturity appear to converge around the idea that adopters utilise BIM at different levels of effectiveness. A growing body of work has emerged around the objective of modelling maturity in BIM, such as NBIMS-CMM [26], BIM MM [3], QuickScan [27], the UK BIM maturity model [28], BPM [29], VDC Scorecard [30], MBMM [31] and BIM CAREM [32]. A literature review was conducted to identify the existing "mainstream" BIM maturity models, which were classified as such because they were either highly cited or widely adopted from an academic and/or practice standpoint, as discussed below. A comparative analysis of the models is presented in Table 1.

2.2. Overview of BIM Maturity Models

The aim of the national BIM standard capability maturity model (NBIMS-CMM) [26] was "to help users gauge their current maturity level, as well as plan for future maturity attainment goals through commonly accepted, standardised approach". The interactive capability maturity model (I-CMM) is a further enhancement of CMM, developed to meet the growing need for an accurate and up-to-date model [33]. The BIM maturity matrix (BIM MM) [3] is one of the early comprehensive BIM maturity models covering granularity at multiple levels. The model proposes five levels of maturity for BIM: initial, defined, managed, integrated and optimised.

QuickScan [27] is a benchmarking tool for project/organisational performance with a reasonably extensive scope covering 44 measures in four main areas, including: organization and management, mentality and culture, information structure and information flow and tools and applications.

The BIM capability assessment reference model (BIM CAREM) [32] was developed to assess the BIM capability of AEC/FM processes covering 166 components and is grounded on the meta-model of AS/NZS ISO/IEC [6]. VDC Scorecard [30] was designed to measure the performance of the projects of virtual design firms with a reasonably extensive scope covering 74 measures. The distinct feature of the tool is the establishment of confidence levels to measure the degree of objective compliance.

Table 1. Comparison of maturity models.

	Complexity of BIM Elements (Scope)	Hierarchy and Structure (Classification/Levels of Measures)	Flexibility	Conceptual/ Empirical Validity (Validated through Empirical Data)	Focus on Whole-of-Life BIM Maturity	Focal System: (Project, Organisational Industry Maturity)	Maturity Process
Capability maturity model CMM (NBIMS 2007) [26]	Limited to technical aspects	Simple	Limited flexibility	Single evaluation method	No	Project	Linear
BIM proficiency matrix BPM (IU 2009) [29]	Limited to technical aspects	Simple	Limited flexibility	Single evaluation method	No	Project	Linear
BIM maturity index: BMI (Succar 2010) [3]	Limited to policy, process and technology aspects	Simple	Relatively flexible	Conceptually grounded	No (some focus on BIM in FM)	Organisation	Linear
BIM Quickscan (Sebastian and van Berlo 2010) [27]	Relatively extensive (organisational and technology)	Simple	Limited flexibility	Empirically grounded	No	Organisation	Linear
BIM CAREM: BIM capability and maturity assessment models (Yilmaz et al., 2016) [32]	Relatively extensive (organisational and technology)	Relatively complex	Relatively flexible	Empirically grounded	Yes (some focus on FM)	Organisation	Linear
Multifunctional BIM maturity: MBMM (Liang et al., 2016) [31]	Relatively extensive (technology, process and protocol aspects)	Relatively complex	Relatively flexible	Empirically grounded (publicly available open and vendor specific data set)	No	Projects, organisations and industry	Linear
VDC Scorecard (Kam et al., 2016) [30]	Relatively extensive	Simple	Limited flexibility	Empirically grounded	No	Project	Linear

A recent model, called a multifunctional BIM MM [32], focuses on BIM maturity in projects, organizations and industry in general, covering measurements across three domains: technology, process and protocol, which are organised in a hierarchical pyramid with sub-domains. This model was later applied in a Hong Kong context in BIM implementation projects from a specific vendor [34]

It should be noted that the most widely used national professional organisation-driven assessment tools include NBIMS-CMM in the United States [35] and the UK BIM maturity model, both of which are simple and easily understood by stakeholders [28]. The UK BIM model was later applied in developing countries, such as Nigeria [36], despite the unknown validity of the results.

The BIM proficiency matrix (BPM) [29] was developed at an academic institution and has been criticised for a lack of compression due to its heavy focus on the technical aspects of BIM implementation rather than process and protocol [34]. The Arup's BIM maturity measure [35] was developed by a world-leading professional services firm to assess the BIM maturity of projects. Despite the limited academic rigour and validity of the BIM maturity measure, it has recently been applied to measure the BIM maturity of the firm's European projects.

2.2.1. Scope and Structure

Models exhibit varying degrees of complexity in terms of the scope of the BIM elements and hierarchy. For example, the scope in the majority of the models was limited to certain BIM aspects (simple) or a combination of them (relatively extensive) classified into simple or relatively complex levels according to the measures under each level. They categorise the "elements" of BIM by dichotomising the social and the technical. Sebastian and van Berlo [27] (p. 254) distinguish between the "hard" and "soft" aspects of BIM, clearly demarcating a line between elements such as tools vis-à-vis culture and mentality. Succar [3] distinguishes between technology, process and policy and, in so doing, separates hardware, software and networks from the micro, meso and macro contexts within which BIM is implemented. To the best of the authors' knowledge, none of the existing models capture the complexities of the BIM elements, including interaction between them and their development. There is scope to explore the development of a model that captures the relationality between the social and technical BIM elements.

2.2.2. Flexibility

Models exhibit varying degrees of flexibility to be applicable across situations. At least one study has suggested that greater flexibility is better as this study has made the call for standardisation across BIM maturity models [32]. However, as far as the existing models are concerned, development has taken place in such a detailed way that standardisation is no longer realistic or feasible. That said, we do believe it is necessary to find models that have robust explanatory power and generalisability. To achieve this, we believe that there is a need not just for models that are economical but that are also built on a few key principles instead of a myriad of detailed, narrowly defined elements.

2.2.3. Conceptual and Empirical Grounding

BIM maturity models are wide-ranging in terms of the degrees of conceptual and theoretical grounding. The work of Succar [3], for example, is strong in terms of being conceptually informed, while industry-driven models [27,30] have been validated through empirical data or multiple case studies. Few of the models, however, are both conceptually and empirically grounded. An exception is the work of Yilmaz et al. [32]. Their BIM-CAREM model was conceptually grounded, then empirically refined through interviews and case studies. There is a need to explore the possibility of developing a model that exhibits theoretical and empirical grounding simultaneously. Gaps exist in the simultaneous reflection on the theoretical and empirical rigor through longitudinal project data and the adoption experiences of organisations.

2.2.4. Whole-of-Life BIM Maturity

In examining these models, it is noted that many of them demonstrate robust consideration for early life cycle stages of assets, but the models are inconsistent when it comes to explicating an active role for facilities management as part of their criteria for maturity. The VDC Scorecard [30], which is more objective, is limited to measuring the performance of the projects of virtual design firms. The objective of QuickScan [27] is to provide a benchmarking tool for project/organisational performance without any particular emphasis on the facility operation and maintenance in the design and validation of the tool. There are some emerging exceptions. In the BIM MM (BIM maturity matrix), for example, integrated models are assumed to be generated and managed by "all key project stakeholders" [3], while Yilmaz et al. [32] define Level 3 maturity by specifying the "organisation-wide" adoption of BIM. These models at least carve out space for the implicit assumption that BIM must be embraced by disciplines such as FM. That said, Yilmaz et al. [32] including FM in a "later" stage of maturity instead of at the earliest stages is a point that should be interrogated, and we consider this in greater detail below.

2.2.5. Focal System—Project/Organisational/Industry

Some models [26,29,30] are specifically developed with project-specific measures and are not suitable for measuring the level of the BIM maturity of an organisation or the industry as a whole. Some organisation-level maturity models lack a focus on the BIM in FM, hence being limited [27,31]. MBMM is designed to measure project, organisational and industry-level maturity despite the validity of the model not yet being established through a rigorous dataset. There would be clear advantages to developing a model that is scalable, in the sense that it can be applied on micro-, meso- or macro-level entities.

2.2.6. Maturity Process

A final point of comparison involves the depiction of the maturity processes. Models generally present the attainment of maturity as a linear process of development. Succar's five-stage model starts from "defined" and peaks at "optimised" [3]. The models of Liang et al. [31] and Yilmaz et al. [32] also comprise four stages each, ranging from Stage 0 to Stage 3. The Kam et al. [30] VDC scorecard describes BIM-related practices as conventional, typical, advanced, best practice or innovative. This linearity is logical, but it can impose a restrictive level of order. There is a need for models that capture the possibility that the maturity may be complex and non-linear.

The discussion carves out space for the need for a new BIM maturity model with the following features: high structural complexity, high flexibility, theoretical and empirical grounding, a rich understanding of BIM elements, whole-of-life BIM maturity, scalability in terms of applicability to projects, organisations and industry and non-linearity. To develop such a model, the use of an analytical approach called actor–network theory (ANT) is proposed. This is discussed in the next section.

3. Analytical Approach: Actor–Network Theory

ANT is a collection of theoretical, conceptual and methodological approaches built on the premise that much of reality is the outcome of human and non-human actors interacting in networks [37–40]. Families, organisations, computers and technologies, such as those used in BIM, are all complex human and material assemblages. ANT is, thus, one example of a sociotechnical approach. It is, however, distinct in a few ways. For example, ANT broadly conceptualises actors and agency, assuming that both humans and non-humans are "ontologically equal" in that they can bring about change [41]. ANT assumes that it is relations between actors, not autonomous actors themselves, that should be at the centre of analysis in seeking to understand phenomena. It has been noted that "Being connected, being interconnected, being heterogeneous, is not enough . . . It's the work [. . .] that should be stressed" [42] (p. 64). Finally, ANT researchers argue that networks are formed through a process called translation, and, while they can appear durable, all networks are contingently stable and can fail at any given time [37,38]. There is a small but growing body of work that has used ANT to enrich understandings of BIM [43,44] as its conceptual and methodological toolkits endow it with distinct affordances.

In ANT, network creation is understood to be driven significantly, though not deterministically, by a focal actor called a prime mover. This actor begins network-building by framing a problem in a certain way, identifies the characteristics of the actors needed to solve that problem, then seeks to enrol these actors using strategies [38]. The roles and identities of the actors become interdefined relative to one another, and this is a process that is negotiated. It is from these juxtapositions that the actor world draws its coherence and its consistency. The strength of a BIM network depends on "its capacity to create adhesion between numerous allies" [45] (p. 208). If the prime mover is successful, the actors converge into a single network that becomes so coherent it begins to look like a single black box [40]. This leads ANT researchers to describe this network as converged [46]. Converged actor networks establish a form of order; thus, the goal of the ANT researcher is "to explore and describe local processes of patterning, social orchestration, ordering and resistance" [40] (p. 387).

Actor networks can persist through stabilisation and may expand to other locations [38]. Non-humans play a significant role in the stabilisation of networks, an example being policy manuals "ensuring" that the processes are carried out in the same way across dispersed locations. The most durable networks run according to programs of action inscribed into devices ("inscripts") that extend the reach of a network: texts, oral messages and technological artefacts, such as machines. An inscript that is both highly durable and highly mobile is called an "immutable mobile" [47]. The more immutable a mobile is, the more irreversible it becomes. Technologies are examples of immutable mobiles, and Latour [48] (p. 103) goes so far as to argue that "[t]echnology is society made durable." Still, durable or not, the ongoing work of sustaining a network is often a problematic process, mainly because the agency of the prime mover can be interrogated at any point by the agency of other actors. Actors can refuse to be enrolled, or they may destabilise a network that has been running smoothly. Even the most stable network, therefore, is always an assemblage of contingent order. ANT researchers thus study networks bearing in mind that they are simultaneously provisional and stable [40], and that contingency and persistence are two dimensions of the same network [49]. This recurring cycle of problematisation, enrolment, convergence, stabilisation and expansion is known in ANT as 'translation'.

An ANT-informed BIM study would be premised on a number of assumptions and would emphasise specific issues over others. For example, when studying a group of human actors working on a 3D model, ANT scholars might focus on how the model and the humans fulfil roles that are interdefined relative to one another [38], a process that involves strategy and negotiation. Researchers might focus on how BIM networks converge, possibly around a central actor, such as a 3D model, or how specific non-human actors in the BIM assemblage (for example, a piece of hardware or a contract) can constrain human actions to fit routinised patterns. Researchers have argued that an ANT-informed approach carves out space for exploring software as an active agent, while a non-ANT study may "underestimate its influence" by assuming it is passive [50]. This nuanced treatment of the social and technical actors sensitises the researchers to other actors that might be overlooked by traditional sampling methods. ANT also focuses on relationality rather than autonomous actors, and this has important implications for BIM studies. Most models treat the social and technical elements of BIM as separate "ingredients.", but BIM elements are linked in complex ways, in a dialectic with the social contexts within which they are created and used [51], and the social context can permeate innovations more deeply than diffusion theorists acknowledge. Other researchers would go so far as to say that BIM embodies entanglements where the social and the technical, the innovation and the social system, are "ontologically inseparable from the start" [52] (p. 1). There is merit, then, in exploring BIM using approaches underpinned by a relational ontology rather than an ontology of separateness when exploring digital technologies such as BIM.

ANT is thus presented here as a viable (though certainly not the only) approach that can be used for engaging with BIM phenomena. It is flexible in its definition of actors and broadens the analysis to include non-human agents. It is scalable in that it breaks down distinctions between micro and macro systems; thus, projects, organisations and even entire societies can be analysed in the same way. As we will further show in Section 6, ANT has conceptual latitude that can lead to insights obscured by other approaches as its elements resonate with most of the columns in Table 1.

A final point to note is that there is an ongoing debate as to whether ANT is a theory or a method. The authors take the position in one relevant paper [50] that it ought to be described as an analytical approach sitting between the two.

4. Research Design and Methodology

4.1. Methodology

The research made use of a single qualitative case study grounded in interpretivism. Research has established that a single case can be useful for conceptual and theoretical development [51,53,54]. In the field of built environment, studies built on a single case, or on a few strategically selected cases, have been published in influential, highly ranked publications [55–57]. This study, rooted in the interpretivist tradition, makes use of qualitative techniques.

Interpretivist, qualitative studies are rooted in a key assumption: that the social world is made up of interactions founded on complex shared meanings. Such meanings are intersubjective in the sense that they cannot be detached from the people that create them [58]. These meanings are also multiple: there is no "one true meaning" that emerges as a single objective truth [59]. This is in contrast with, for example, positivist studies using quantitative methods, which assume an objective world made up of entities with clearly defined, verifiable attributes. The differences in assumptions are profound and have far-reaching implications. First, they lead to different methodologies. Positivist studies seek knowledge in the form of law-like, quantifiable propositions and, thus, employ statistical and experimental methods. Different researchers using these methods should arrive at a single set of findings [60]. Interpretivists seek the richness of meaning by immersing themselves for prolonged periods in empirical settings, using methods such as semi-structured interviews and ethnography [54,58].

The diverging assumptions of interpretivist and positivist studies lead to different definitions of "good" research. Both traditions value reliability and validity but define these in different ways. Interpretivist researchers do not seek to "triangulate", aim for replicability or search for the one single truth. Researchers aim to develop an interpretation that is "reliable to the degree that they are understandable and plausible to others" and valid to the extent that the movement from data to analysis to results is rendered in ways that are rigorous and transparent [61].

4.2. Case Study Description

The case study organisation is referred to as Innovation University. Innovation University was selected because it was, at that time, one of three universities in the US known to be pioneers of BIM. This selection is consistent with theoretical sampling given that Innovation University can be understood as an "exceptional" case [62]. Innovation University is a large tertiary institution with a campus of over 900 buildings managed by a facilities management unit (referred to here as Operations Management Unit or OMU) that is semi-autonomous within the institutional structure, receiving partial funding from the government and capital funding from the institution, and independent as an auxiliary business enterprise.

Following their first BIM project in 2010, Innovation University was one of the first in the United States to develop a set of BIM implementation documents, comprising a guide, template and contract language. The organisation is, therefore, known as an 'innovator' in the construction industry in relation to BIM project implementation. Data suggest that the interest in BIM within Innovation University began with a full-time academic, Prof. X, at the School of Built Environments whose research interests included topics related to 3D modelling. Prof X, who has been involved in modelling for construction since the early 1990s, was instrumental in the University's first BIM imitative in 2006 at project level. He led a small team of researchers who were also working as interns at a unit referred to here as the Major Projects Unit (MPU). In the early years, the BIM effort in the MPU gained momentum, and a series of projects (educational, educational and research, athletic and medical buildings) were swiftly completed. The first was a straightforward one involving modelling a university building in 3D, then 'walking' stakeholders through the model. Later projects included attempts to embed BIM requirements into contracts, after which the university and partners began to venture into 3D and 4D modelling. Another project involved visualisation in the form of design reviews in the context of a fully immersive experience. In another project, OMU involvement increased, involving maintenance technicians and supervisors in the virtual reality design review.

4.3. Data Collection

Data were gathered through internal document reviews, model reviews, observations on practices and semi-structured interviews. Ethics clearance was obtained prior to conducting the study from the Human Research Ethics Committee of project's Chief Investigator's University.

Two researchers were involved in the field visits. Researchers were allowed to review BIM models and non-geometric information used in projects and to observe day-to-day work practices. They were also given access to the organisation's strategic documents and BIM suite of documents. The researchers analysed internal BIM documents, such as implementation guides, contract specifications, project databases, models, published papers and presentations (related to the case study), and other relevant internal materials, such as organisational policy documents, as well as related public documents and archival documents.

The main data gathering technique was in-depth interviews, which have been described as being at the "heart" of good qualitative research [54] (p. 19), allowing researchers access to the rich and detailed meaning-making processes of the participants. Interviews were conducted with seven stakeholders who took part in the initial BIM implementation process and agreed to participate in the study: two individuals from upper management, one from middle management, one technical person, one from an academic unit and two interns (one academic and one graduate). A maximum variation sampling method was, therefore, used to capture the diversity of the adoption experiences. The heterogeneity of the sample was further enhanced by including participants from design, construction and facility management. The participants were interviewed in October 2016 with open-ended questions that focused on topics such as participant motivation for the BIM implementation initiative, participants' adoption experience, the adoption process, any milestone projects, challenges, best practice guides or strengths and lessons learnt. The questions were customised depending on the interviewee's position. On average, the interviews lasted approximately 45 min. The interviews were audio-recorded with the participants' consent and later professionally transcribed.

4.4. Data Analysis

Analysis was conducted in four cycles, as shown in Figure 1 below. These cycles are explained below.

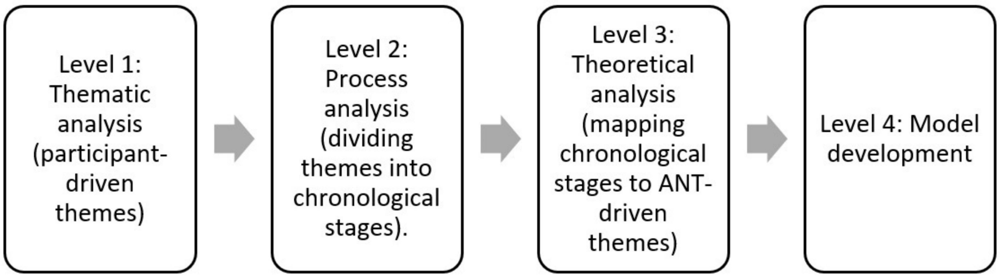


Figure 1. Four cycles of data analysis.

The model is closely aligned with the method prescribed by Gioia et al. [54], a widely accepted approach with more than 4800 citations on Google Scholar. Under the Gioia method [54], the analysis proceeds in key phases: first-order analysis to identify participant-driven themes, second-order analysis driven by theory-driven themes, then model development through the identification of dynamic relationships between the second order themes. We followed this process here, but, as Figure 1 indicates, we added an additional step between the first- and second-order analysis. The intervening step (Step 2 in Figure 1) involved the clustering of the participant-driven themes as they related to chronological periods. This intervening step allowed a time-based component to emerge from the analysis, slicing the data into the beginning, middle and end stages of the case study. This allowed the researchers to set the stage for Stage 3, where the network could be seen to unfold around the stages of creation, convergence and stabilization/destabilisation. Each stage of analysis is explained further.

In the first cycle (Level 1), the researchers conducted a thematic analysis where no a priori categories were imposed and themes were allowed to emerge from the data to closely capture participant language. A total of 31 themes were identified. Some examples included "lack of capability of trades in using BIM" [8], "trialability of BIM" [9], "importance of data over 3D models" [17] and "radical change" [23].

In the second round of analysis (Level 2), the themes were mapped into stages, a chain of events or stages that unfolded and led to a certain outcome [63]. The researchers created a chronological interpretation of the mix of themes, developing an early-stage process map and noting that specific themes could be mapped to various stages: a stage when BIM was an initiative of the research team (Stage 1), a coordinating mechanism for managing construction projects (Stage 2), then a (failed) system for asset operations and maintenance (Stage 3). For example, Themes [8] and [9] above could be traced to Stage 2, while Themes [17] and [23] could be traced to Stage 3. This does not mean that all the themes were precisely arranged into a detailed, day-to-day series of events, but grouping themes into broadly defined and sequenced stages was a sensemaking process that added a layer of organisation to the large dataset and laid the groundwork for the next stage of analysis.

In the third stage of analysis (Level 3), researcher categories based on ANT concepts were mobilised to further break down each stage. Specifically, the themes of prime mover, problematisation, actors, multiplicity, obligatory points of passage, interdefinition and immutable mobiles were used. The same concepts were used as analytical lenses across all three stages. A multi-researcher approach was used to verify the trustworthiness and rigour of the thematic analysis [64]. The themes, areas and sub-areas were agreed upon by two researchers in iterative brainstorming sessions.

An important point to make about the analysis is that the Level 1 participant-driven themes could be combined with the Level 3 research-driven categories of this stage, allowing for a "tandem" of voices to be heard [54]. As the authors show in the analysis, the network dynamics underpinning each stage were driven by the same elements (ANT concepts), suggesting they were the factors that influenced "success" in each stage.

In the final stage of analysis (Level 4), the authors moved from analysis that was tightly bound to data and categories to the development of a model and a practice guide.

5. Results and Findings

5.1. Results

The results are structured as follows: a high-level summary of the three stages of network development drawn from empirical data (Table 2); a more detailed analysis of each of these three stages using seven elements of actor–network theory (Table 3); and narratives providing a thick description of how each of these ANT elements contributed to network failure during the operations and maintenance stage (Section 5.1). The last sub-section then focuses on building a maturity model based on these findings (Section 5.2).

Table 2. A process-driven analysis of BIM adoption, consistent with Level 2 analysis.

Stages	**Key Events/Developments**
STAGE 1 Research Stage: Initial creation of BIM network	• At that time, Innovation University was supporting the "lean" philosophy • Industry networks, as well as states and national bodies, were encouraging BIM through conferences and the issuance of new standards and regulations • Began at an academic unit, School of Built Environment, with a researcher named Prof. X • Issue of BIM was framed as a research topic; graduate students were recruited • One graduate student was also working at the Major Projects Unit (MPU)
STAGE 2 Project Management Stage: Expansion of BIM into projects	• Graduate student at MPU linked the MPU Manager (Manager Y) to Prof. X • Manager Y gathered a group of interns into a BIM Execution Team and began embedding them in ongoing projects • Manager Y laid the groundwork for BIM in construction projects by asking "what is your biggest problem with the construction process" then looked for opportunities to use BIM • The BIM Execution Plan became a stable part of larger, but time-bound, project networks • Project actors began to use BIM heavily for clash detection and coordination • BIM models became focal to construction activity, imposing discipline on everyday work and even becoming part of contractual obligations and selection criteria • Some BIM adoption practices have been formalized into a BIM implementation guide • However, BIM efforts began to falter when Manager Y and many interns eventually left the team
STAGE 3 Operations and Maintenance Stage	• With the departure of key drivers for BIM, there was a lack of leadership in implementation of BIM in Operations and Maintenance Unit (OMU) • A lack of ownership of the model also emerged among OMU actors, traceable directly to a lack of meaningful involvement in the earliest stages of model-building • The lack of model ownership led to widespread resistance to accommodating the model in day-to-day work • Challenges arose in terms of adopting data, hardware, software, role descriptions and work practices to the requirements posed by BIM adoption • BIM adoption in operations and maintenance initially failed, but more recent data (beyond the scope of this study) suggest that efforts have now been renewed and are gaining traction

Table 3. An ANT-driven analysis of the three stages, consistent with Level 3 analysis.

	Definition (Callon 1999)	Stage 1: Initial Creation of BIM Network (Research Stage)	Stage 2: Repeated Convergence of BIM Network (Project Management Stage)	Stage 3: (Failed) Stabilisation of BIM Network (Operations and Maintenance Stage)
ELEMENT 1 Prime mover	Actor that initiates the work of network creation	Prof. X	Prof. X and Manager, shared	No clear OMU champion. Network programs of Prof X and Manager were being imposed on OMU.
ELEMENT 2 Problematisation	Process of identifying a problem and framing a solution, which grounds network goals and programs	BIM was a "research topic".	BIM was a solution that was enacted in a series of projects.	BIM was (supposed to be) a solution that was enacted as ongoing support for OMU. However, OMU actors were sporadically, not meaningfully, involved in problematization.
ELEMENT 3 Actors	Humans and non-humans capable of exercising agency	Human actors: Prof. X, researchers. Non-human actors: funding, small research lab, software, hardware.	Human actors: Dual role researchers who were also project interns Extended to human actors in projects: architects, engineers. Buildings and facilities being built/renovated. Combined hardware and software resources of both the lab and the projects.	Entrenched network of human and non-human actors following traditional OMU programs that were hard to replace.
ELEMENT 4 Multiplicity	Actors being embedded in multiple networks (see Singleton and Michael 1993)	In general: aligned with university and industry networks.	Significant, congruent, strong overlap with network in previous stage.	Almost independent of network in previous stage.
ELEMENT 5 Obligatory points of passage	Requirements that actors must fulfil in order to become enrolled into a network	Agreement (implicit or formal) to work with Prof. X.	3D model—strict obligation to conform Later, BIM implementation guide and addendum contracts with partners; strict obligation to conform	3D model—refusal to conform. Seen as a lack of representativeness
ELEMENT 6 Interdefinition	Juxtaposing and simplifying roles so that they dovetail with one another	Organic. Defined by research contracts and proposals.	Complex. Mandatory compliance with model requirements. Led to adhesions and convergence.	Multiple controversies. Failure to achieve adhesions.
ELEMENT 7 Immutable mobiles	Devices that capture network programs in ways that persist over time and place (see Lower 2005)	Not significant.	Reliant on humans to stabilize the network. Network was durable but not stable. When these humans left, network destabilized.	Network failed to converge; hence, did not stabilize.

Table 2 is offered first to provide a high-level view of network development. As mentioned earlier, the development of Table 2 flowed from a Level 2 analysis. Stage 1 shows how BIM initially emerged through departmental research interests. Stage 2 shows how this small early network evolved to include key actors that were strategically positioned to link to real-life research projects. Due to word limits, much of the narrative will focus on Stage 3, but references to Stages 1 and 2 will be done strategically to highlight contrasts. The Stage 3 narrative then shows the attempt to link this project-oriented network to the ongoing goals of facilities management.

Having presented a high-level description of the three levels of network development, each of the three stages is then analysed more deeply using seven elements of ANT. This analysis is shown in Table 3 below:

AN ANT-informed approach lays the groundwork for a particular "flavour" of BIM maturity. One can argue that, from an ANT perspective, a network is mature when disparate actors have converged and routinised to the point of punctualisation, with actors so coordinated that they begin to look like a single actor [40]. One may argue, then, that BIM maturity might be achieved at "the moment when social assemblages gain stability by aligning actors and observers" [48] (p. 103). This aligns with the work that suggests that BIM capability is achieved when a network shows it can "predictably and repeatedly [deliver] BIM services" [27] (p. 255). The table presented resonates with this ideal.

A key finding of this study is that the same set of concepts has explanatory power for Stage 1, Stage 2 and Stage 3. The seven concepts in the first column of Table 3 thus point to the elements that influence BIM success or failure regardless of whether an organisation is at the exploratory stage of BIM adoption, at a stage where it is using BIM on a project basis or whether an organisation is mobilising BIM on an ongoing basis as an asset owner. Mobilising these concepts shows, among other things, why Stage 2 was a largely successful sub-case of BIM adoption, while Stage 3 can be better characterised as a failure, at least at the time the study was conducted. The narrative that follows below provides details of Stage 3, but contrasts to previous stages are provided at strategic points to support the argument that these components have explanatory power.

5.1.1. Prime Mover (Element 1) Not from OMU; Problematisation (Element 2) Did Not Involve OMU

In Stage 1, BIM was clearly driven by Prof. X, who problematised BIM as a research topic. In Stage 2, the role of prime mover was taken up by Manager Y, who problematised in terms of "what is your biggest problem in the construction processes", then subsequently presented BIM as a solution. Manager Y's focus was primarily on the Major Projects Unit. However, prior to the emergence of university interest in BIM, the OMU and MPU were already linked, albeit through an association that was complex and rather difficult.

As the design and construct arm of Innovation University, the MPU was tasked with handling major infrastructure projects. MPU readily took up the use of BIM with various stakeholders. Findings suggest that, within MPU, the creation of adhesions leading to a solid compromise in Stage 2 was significantly driven by the disciplinary power of 3D models. The model was focal because it was central to many key interactions in the network as it was part of the work of architects, engineers and construction managers:

> *So, what I really saw was a bunch of architects and engineers who were all wrapped up in making the model look better, a bunch of construction managers that would then throw that model away or strip that model apart and just use the bones of it to build their stuff with it. And then I saw an opportunity for us [as owners] to take it.*

An initial analysis of data would point us towards activities; "making the model look better", "throwing it away" and "ripping it apart" are typical insofar as they portray humans actively "working on" an object. Notably, facilities managers were not mentioned.

Upon completion, these projects and their associated information (in the form of databases, spreadsheets, drawings, plans, etc.) were then turned over to the OMU and were deeply resisted. BIM models were envisioned to address "the biggest problem in construction", but little explicit reference was made to how BIM could address "the biggest problem in operations management." It is not surprising, then, that one OMU staff member claimed:

> *We haven't been involved as early as probably should have been. I mean it's a whole, it's a change of culture for us, because normally the phrase that my boss likes to use is, Innovation University, [. . .] we build a building, so construction services builds a building, and they throw it over the fence and say, "Here, take care of it." So we don't get a say in what, or how the building is constructed.*

5.1.2. Resistance of Humans to a Non-Human Actor (Element 3); Refusal to Pass through Obligatory Points of Passage (Element 5)

In Stage 2, human actors in the BIM project management network achieved strength by building adhesions resulting from actors conforming to the discipline of the 3D model. By creating a 3D model, the MPU actors were undertaking the process of displacement: representing a building through a digital geometric model, then using that representation instead of the actual building for decision-making. The physical structures themselves were not present in conference rooms; the models, therefore, had to act as "spokespersons" for the absentee assets [38], communicating their features, attributes, properties and characteristics.

As far as the MPU was concerned, the models were taken to be valid "spokespersons" of the buildings, as shown by multiple actors demonstrating their willingness to interdefine themselves and their activities relative to the model. When the MPU completed its projects and "threw them over the wall" to the OMU, it was because they assumed they would also be accepted as valid representations of the assets for the OMU. However, representativeness can always be contested, and the question "Is a spokesman or an intermediary representative?" [38] (p. 79) is a recurring one. The issue of representativeness can thus trigger dissent, and this was what began to emerge in the OMU. OMU actors were also concerned that this misguided representation was just the first in a chain of other misguided representations, to the point that industry standards would fail to act as spokespersons for asset owners:

> *I can't remember the organisation, but it was being led by the contractors and I thought, "Well there's a problem here," you know? "This is backwards," you know? They're telling us what we need as opposed to our telling them what we need . . . I came back and challenged [MPU Manager] to reverse that equation because otherwise we're going to have national standards that are developed by the service providers as opposed to the owners who should be defining what they need.*

5.1.3. Difficulties in Interdefinition (Element 6) and the Failure to Achieve Adhesions

In Stage 2, interviewees reported that strong adhesions and seamless interdefinitions were achieved between actors, mainly because the 3D models became a central organising device that different supply chain actors had to conform to. Different actors were forced to conform to the requirements that the model specified. The model prescribed the behaviours of other actors in the network in ways that compelled them to change:

> *I could see it in 3D, all my guys could see it in 3D, all my contractors could see it in 3D [. . .] as I found later, [they] didn't think about things like pipe slope, they didn't think about things like intersecting things. But by doing a 3D [model] it forced the designers to think about that.*

In the OMU, the model failed to impose its requirements. Apart from actors' unwillingness to form adhesions with the 3D model, there were a number of other "controversies", that is, failures to create adhesions, that could not be resolved [65]. First, there was a gap in information sharing, a failure to create adhesion in different data storage repositories:

My recollection, loosely, was file sharing was not overly convenient at that time, so they may have used an FTP site, I think, a lot of times they were bringing USB keys and plugging them in, and I also think even with the nice computer they bought, they had some challenges with it still if it gets low, because of the amount of content, it's not a small building, so learning how to cut up the scope of the project in a way that you can do smaller chunks and not max out your computer when you look through it.

Second, there was a lack of interoperability between the systems. For example, because converting the data from the formats used in BIM Tool A to formats used in the FM tool was not a seamless process:

[BIM Tool A data could be downloaded] into just a standard Excel spreadsheet, and what we have to do is change the format to a common separated value file, reformat the data [. . .] There's a lot of formatting behind that. And a lot of times when you try to push that kind of stuff into [FM tool], it doesn't like the formatting. So we'll take the text, put it into Notepad, which is, it's very primary and it strips off a lot of that formatting, and then we can import that and it's cleaner.

To bridge the gap and achieve the alliance, multiple actors (Notepad, actors doing the typing) would have to be enrolled.

Third, rapid changes in actors made it difficult to build adhesions. For example, a change in the OMU's FM tool-based system triggered the need for updates in the BIM Tool A model and vice versa. An update in one system would reopen a controversy (an inconsistency between inert-system data). Given the frequency of updates, controversy in the management became an ongoing process:

Yeah, you still have to have the human interface. And the other part of that that is important to anybody that owns a model is if you do something on the facilities side, where you modify a system or change a pump, you change it in FM tool, you want a notification sent to whoever's maintaining the model, "Hey, this has changed. This is not the pump that's in there now. This is the pump that is now in this location". Another manufacturer, another model, another change in size of the pump or design [. . .] It has to work both ways. It should work both ways.

Attempts to accomplish coherent alliances had to be aided by mediators, many of which were human actors. At one point, for example, external contractors were brought on board in a series of meetings to address the interoperability issues between BIM Tool A and FM tool, but, in the end, these meetings were not sustained. In many cases, however, the work of building agreements between the actors fell not on external human actors but on human actors within the OMU who found themselves doing frustrating and labour-intensive work:

If I was doing it every day, I'd feel comfortable and I'd just go ahead and do it for you right here, but I have to take the document and walk through the process because I'm just not that familiar with it or that comfortable with it right now.

Controversy management, therefore, created new tasks and necessitated the significant expansion of roles. This was difficult in the OMU. In the BIM MPU network, roles could shift to accommodate new tasks because BIM actors were able to interdefine their roles relative to the new systems:

[. . .] so that I could back off of my day job and take some time away from that and devote it to work with the BIM folks and do the things that we could do there.

In the BIM OMU network, however, the routines and responsibilities were more fixed and less accommodation could be made for extra work. Human actors could not readily redefine their roles to fit their new mediator roles.

5.1.4. Incongruent Multiplicity (Element 4); Layering New BIM Programs over Entrenched Facilities Management Programs

The rigidity in the roles could also be traced back to the fact that the OMU was already a stable network running according to old programs based on traditional ways of doing things:

> *You've got people who have been here for 20 years, 30 years; this is the way we do it, we're going to do it this way., you know how to work stupid . . . it's just so much effort that it's going to take time away from their job. And this goes back to the original statement that they're overworked, they're have too much work to do, not enough time or not enough money.*

Again, going back to the concept of multiplicity, the new BIM OMU network involved actors who were simultaneously enrolled in an entrenched network, this time one with incongruent goals, leading to unwillingness on the part of actors to take on new BIM-related roles.

5.1.5. Absence of Immutable Mobiles (Element 7)

The lack of immutable mobiles, critical to network stability, was a feature as early as Stage 2, which persisted well into Stage 3. In Stage 2, BIM network convergence successfully occurred across a series of projects, with the main immutable mobile being in the form of a stable set of BIM Execution Team members. After a series of projects, however, the durability faltered. By the time interviews were conducted in October 2016, critical human actors had left the network. The departure of key champions had a palpable effect. At a later time, another interviewee looked back on this pool of shared actors and commented:

> *[. . .] frankly when [MPU Manager] left there was a vacuum down there, right. And then [Person 1] left, then [Person 2] left, then [Person 3] left. Now we have one person. So there's a vacuum, right, I mean there's, I mean we're not able to implement as much [. . .] So we do rely on this group, and the group did disappear, to be honest with you it disappeared [. . .] we finally hired somebody; starts in October. And we're hoping that he re-energises everything.*

It seems the loss of these actors was felt mainly because the interviewees assumed that their internal knowledge had disappeared along with them, or at least had not been adequately captured in explicit form or inscribed into devices.

Each of the three stages of the case study was analysed using key ANT concepts, such as prime mover, multiplicity, obligatory points of passage, and immutable mobiles [38,66]. An in-depth ANT analysis is not just a description of phenomena but also an explanation. As Latour notes: "the explanation emerges once the description is saturated" [48] (p. 129).

Following the first three stages of analysis, a fourth stage of analysis involves moving from this detailed single case study to the beginnings of a more generalisable maturity model. The process of discerning a model from the data involves a process of interpretation described as "unbounded", "inductive" and "generative" [67] (p. 23). This is different from the earlier stages of analysis, which were marked by a methodological commitment to stay close to the data [68]. Instead, at this stage,

> *. . . there is room for a conceptual leap in this process as well . . . [this leap] often accompanies our close familiarity with the data in both a gestalt sense and in the sense of deep immersion in the data and the data structure.* [54] (p. 22)

5.2. *Life Cycle BIM Maturity Model*

Following the analysis involving themes, process stages, and ANT conceptual categories, the final stage of analysis now involves model-building. The model proposed here has five key features that reflect five important lessons learned from the case study:

5.2.1. Non-Linear, Stage-Based Model

First, the maturity model was anchored to key ANT stages. The terms used are "emerging", "developing", "converged" and "durable", with "durable" reflecting the stage of greatest maturity. Importantly, the model depicts these stages in a non-linear way, showing that a converged network could fail, or a stable and durable network could be recreated in a different way.

5.2.2. FM Involvement at Early Stages

Second, model development was guided by the need to highlight the involvement of FM at early stages, specifically at the stage where building information models are developed and iteratively defined. The model thus highlights that FM networks must be involved in the process of problematisation, at least at the operational stage where 3D models are developed as solutions to problems.

5.2.3. Iterative, Ongoing Renegotiations in Collaboration

Third, the proposed model had to highlight that the process of 3D model development was ongoing, not once-and-for-all; thus, the model should reflect this iterative process as well. The interviewees observed how architects and engineers were continuously modifying the 3D model, "making the model look better", "throwing it away" and "ripping it apart". The model thus highlights that any achieved convergence and stability are always contingent, a point that is key to ANT [40].

5.2.4. Stability Based on Formalised Knowledge Resources

The case study and the model show that durability is ultimately achieved through "immutable mobiles", that is, formal knowledge-based resources that capture BIM programs, processes and standards in written form. These resources cut across space and time [47]; thus, they enable BIM-enabled patterns of work to persist even when champions leave the organisation. Formalised knowledge management involving explicated knowledge thus replaces tacit knowledge that exists in the heads of people and that is inevitably lost when such people leave.

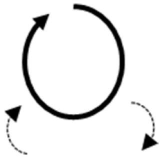
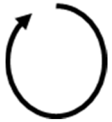
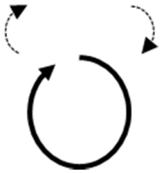
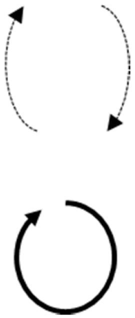
5.2.5. Accommodation of Similarities and Differences of Different Life Stages

Finally, the model shows shared problematisation, while it also depicts that development, convergence and durability can be enacted differently. The case study shows that maturity in a BIM PM network is demonstrated by the network's ability to repeatedly converge around a series of BIM solutions that drive integrated projects. Maturity in a BIM FM network, on the other hand, is demonstrated by the network's ability to continuously offer BIM services. The model is, thus, nuanced enough to capture these points of divergence.

Having noted these key lessons and drawing from the concepts and stages of the four-stage analysis, the proposed life cycle BIM maturity model was developed and is shown in Table 4 below.

The life cycle BIM maturity model (LCBMM) is endowed with both specificity and interpretive flexibility and can be translated into actionable knowledge for practice. An example provided here is a practice guide, which can serve as a self-assessment tool that allows strategic decision-makers to assess their current stage in, as well as identify possible next steps for, the BIM journey. An example practice guide is proposed below (see Table 5).

Table 4. Proposed BIM life cycle maturity model.

Maturity Stage		Change Driving BIM Network	
EMERGING BIM		FEATURES OF EMERGING BIM (1) Leader ("prime mover") champions BIM (could be top-down or bottom-up) (2) Congruence ("multiplicity") is achieved with other systems: industry, larger organization, supply chain, etc. (3) Strategic goal-setting ("problematization") is achieved through shared definition of problem and shared view of the idea of BIM as a strategic solution	
		PROJECT MANAGEMENT NETWORK	FACILITIES MANAGEMENT NETWORK
DEVELOPED BIM		FEATURES OF FULLY DEVELOPED BIM (1) Shared iterative development of dynamic models is carried out by PM and FM as solutions to problems across full asset life cycle	
CONVERGED BIM		FEATURES OF FULLY CONVERGED BIM IN PM (1) Standards for compliance ("obligatory points of passage") are established before entry into project: partners commit to BIM implementation through contracts and recruitment standards. FM passes through this as well. (2) Strong interfaces with FM are created (3) Strong interfaces are created through inter-definition of project team actors' tasks and outputs with model's requirements and standards	FEATURES OF FULLY CONVERGED BIM IN FM (1) Strong interfaces are created within FM around model through alignment between types of information, types of systems, task and job descriptions. An important assumption is that these adhesions are facilitated by FM's having been an actor in iterative co-development of model in previous stage.
DURABLE BIM		FEATURES OF DURABLE BIM IN PM (1) Congruence achieved by dismantling old routines in partner networks and industry networks that are contrary to BIM-driven network programs (2) Core group of stable human actors present as consultants across projects (3) "Immutable mobiles" are deployed in the form of documents (guides and contracts) that are present across the network	FEATURES OF DURABLE BIM IN FM (1) Congruence achieved by dismantling old routines in FM that are contrary to BIM-driven network programs (2) * Core group of stable human actors present as full-time BIM FM managers who champion BIM in operations or as trained technicians * (3) "Immutable mobiles" are deployed in the form of BIM tool user guides, templates and updated software installed in all computers; standardized meeting agenda includes section on BIM projects* * These two items did not emerge in Stage 3, the case study, given that the network failed to stabilise. However, they did emerge in follow-up interviews. We theorise on these items here, but readers may want to treat these with a different level of confidence

* means the sentences are linked to the sentence in the last row (next page).

Table 5. Practice guide.

	Emerging	**Developing**	**Converged**	**Durable**
Extent of BIM adoption	Experimental and sporadic	Repeated, but not yet coherent and seamless	Coherent, seamless but not yet sustained	Coherent, seamless and sustained
Leadership for BIM	Strong champion; formal or informal role; may or may not be in executive team	Strong champion, formal role	Strong champion, formal role supported by emerging formalised standards	BIM "business as usual" due to formalised standards; leadership upholds these; changes in leadership no longer disruptive
Goal-setting for BIM	BIM presented as nice-to-have, add on	BIM presented as a required solution for selected contexts (for example, highly complex projects)	BIM required as a solution for construction and pre-construction challenges	BIM required as a central solution for challenges across the life cycle
Specificity of BIM requirements	Informal and emerging	Some BIM requirements defined in core areas (e.g., in tendering and contracts for specific projects) imposed selectively, for example on specific contractors	BIM requirements defined; formalised requirements systematic (e.g., specified in contracts; standards go further back and cascade into selection criteria for partners or recruitment criteria for personnel)	BIM requirements defined; formalised requirements systematic and comprehensive, including training, education, and working on a BIM culture through formal and informal means
Resource integration	BIM-related roles inter-defined in a core BIM team	Core team embedded across multiple BIM projects; roles and tasks in projects begin to cohere around 3D model through mechanisms of mutual adjustment	Roles, tasks, hardware and software are designed for integration (for example, a strategic role is appointed to oversee BIM, universal data schemas are defined; systems are rendered interoperable)	*(Same as convergence)* Roles, tasks, hardware and software are designed for integration (for example, a strategic role is appointed to oversee BIM, universal data schemas are defined; systems are rendered interoperable)
Formalisation of processes	Low formalisation; internal BIM guidelines and standards are being developed or external guidelines are being assessed	Early drafts of role descriptions, manuals, specifications, guidelines are developed but are undergoing iterative modification	Comprehensive set of role descriptions, manuals, specifications, guidelines available	Formalisation drives BIM as business-as-usual. Comprehensive set of role descriptions, manuals, specifications, guidelines available, key resources are shared externally as best practice

The guide has four stages of maturity based on the proposed model, and each stage reflects different degrees of achievement linked to five different criteria. Each criterion, in turn, is linked to an ANT concept. Consistent with the ideals of interpretivism, the movement from concept to practice guide criterion is plausible, though not inevitable (others may propose different ones). "Leadership", for example, can be linked to the notion of prime mover; goal setting to problematisation. "Specificity of requirements" refers to the chain of obligatory points of passage that actors might go through to become part of the BIM network. These might include formal tendering criteria or contractual requirements, or informal mechanisms such as "socialising" long-term supply chain partners so that they come to a space where they accept the value of embracing BIM. "Resource integration" refers to the degree to which human and non-human actors achieve seamless interdefinition: interoperability between systems, universality in data schemas, roles that dovetail and support BIM. An important point about this practice guide is that it refrains from foregrounding individual actors through standards such as "quality of people" or "quality of hardware". While these are important, it is the adhesions between the BIM elements that are foregrounded here. Finally, formalisation of processes" is linked to immutable mobiles: devices such as documents, contracts, systems and standards that make BIM an ongoing, "business as usual" undertaking. The "durable" column is the height of maturity and is consistent with the notion of "predictably and repeatedly delivering BIM services" [27].

6. Discussion

To uphold the ideals of interpretive research, it is emphasised that (1) the LCBMM and the practice guide are presented as one set of plausible interpretations of the data; (2) that interpretive research supports that other plausible interpretations can exist; and (3) that interpretive research seeks a balance of "telling" readers about one interpretation while simultaneously inviting them to develop their own; hence, detailed quotes are provided in part to give them opportunities to develop their own interpretations [59]. Moreover, "validity" and "reliability" are defined differently in interpretative studies relative to their positivist/quantitative counterparts. The findings "are reliable to the degree that they are understandable and plausible to others [...] i.e., does the researcher explain how s/he came up with the analysis in a way that the reader can make sense of?" [61] (pp. 21–22), while validity is achieved through enabling "[t]he reader . . . [to] be able to see the data-to-theory connections in the form of linkages among the quotes in text, the 1st-order codes in the data structure, and their connection to the emergent 2nd-order concepts/themes" [54] (p. 22). Reliability and validity were thus achieved in this study by rendering a four-stage analysis of the data and by making the movement from transcripts to model transparent by providing a coherent and evidence-based narrative with evidence in the form of quotes.

6.1. Research Implications/Theoretical Contribution

The key contribution is the proposed life cycle BIM maturity model (BIM LCBMM). The model is not offered as a replacement for existing ones but as a viable alternative model linked to a distinct set of assumptions and features that address some of the limitations we have seen in the existing models. The model developed fills a niche that was clearly defined in Table 1. The model was grounded on concepts and in-depth methodological guidelines for examining real-world phenomena, addressing the aim of achieving validity for a BIM maturity model. Its flexible notions of networks, which could be a person or a country, support the development of models that have potential applicability across projects, organisations and industries. Its emphasis on humans and non-humans, as well as on relations rather than autonomous elements, adds a layer of complexity in an analysis of the elements of BIM. The model reflects a relational ontology [69]. Its key features foreground interactions between actors and networks: adhesions between actors, congruence between networks, problematisation negotiated between PM and FM. This is in contrast with other models that focus on individual elements and dichotomise the social and the technical.

Perhaps most importantly, the ANT notion of translation also provides a way of capturing "whole-of-life" considerations from BIM. The maturity model unpacks the concept of BIM maturity in ways that appropriately foreground the role and considerations of facilities management. Apart from some notable exceptions [3,32], very few authors have carved out space for the considerations of FM in BIM maturity. Maturity models that support BIM adoption in operations and maintenance pave the way for better decision-making during this stage. Whole-of-life maturity models set the stage for managing challenges linked to facility management, including the persistent challenge of operational emissions.

To be clear, the case study made no mention of environmental challenges because most of the motivations for BIM use by participants were related to constructability. Still, 3D models were available, and using these models for other diverse purposes is not a stretch. The emerging empirical work has shown how 3D and 4D models, mainly used initially for work sequencing and constructability concerns, could be readily adapted to address other goals, such as work health and safety [70,71]. A similar argument can be made here: that models for routine facility management can be reoriented to support environmental performance (energy analysis, envelope variations and interactions, evaluation of environmentally sustainable proposals, etc.) [4]. The important, and perhaps foundational, task is to carve out space for BIM use in operations and maintenance in the first place. This was the aim we set out to address with our maturity model here.

Second, our model tempers the common tendency to present maturity as a linear process. Our model is processual, but it is grounded in ANT and captures complexities, among them the non-linearity of development and the dynamism of each stage, to the point that even durable models are understood as being only contingently stable. This assumption of non-linearity also explains why we do not see BIM 6D adoption for sustainability goals as a prerequisite for BIM 7D adoption for facility management. Instead, these two BIM dimensions can be linked in complex, non-sequential ways.

6.2. Practical Implications

The BIM LCBMM is also useful for practice. A key strength is its parsimony. It breaks down maturity into four stages, with each stage linked to a few conditions. These few stages are nevertheless robust enough to explain how maturity unfolds differently in PM networks as opposed to FM networks. It avoids presenting a litany of elements or settings. This is not to say that there is no value in more comprehensive networks. Again, our goal is to provide a more practical alternative and tractable model, and one way to do this is to offer an economical one given the broader trend for increasingly complex conceptualisations. The practice guide discussed above is one example of a practical resource that can be developed from the model. The detailed analysis, an ideal in qualitative case study research, is in the form of a narrative that is also a rich description providing portable principles [54] with considerable potential resonance with other settings.

6.3. Implications for Society

More work is needed beyond this empirical study to make strong claims about the implications of this research for society; nevertheless, some impacts can be theorised here. Because the BIM LCBMM and practice guide are ANT-driven, they are scalable and can be applied to teams, organisations, supply chains and larger societies. The practice guide can be adopted by an influential stakeholder in society to support a drive for large-scale transformation. In the UK, for example, the BIM for the Work Health and Safety Working Group, a government unit, has developed a BIM maturity model specifically for work-health and safety and has made it available for clients for self-assessment and for encouraging more robust BIM uptake [72]. In a similar manner, the model and/or the practice guide proposed here can be used by a government client with a large volume of capital projects to support efforts to mandate the use of BIM by supply chain partners in its projects. In the state of NSW, Australia, government units for transport and health have begun the process of requiring BIM during the tendering phase of their capital works projects [70,71]. The BIM LCBMM and practice guide provide a roadmap that could inform the government client in its attempt to bring its partners along on its BIM journey.

7. Conclusions

In the absence of an empirically and theoretically grounded whole-of-life BIM maturity model that adequately covers facility management, this study investigated the adoption experience of a real-life case study organisation to propose a holistic maturity model. An innovative case study organisation's BIM adoption experience was explored using the ANT analytical approach, and theoretically grounded in-depth analyses of the organisational experiences at each stage were conducted to develop a life cycle BIM maturity model (LCBMM).

The study has shown that the existing BIM maturity models have specific affordances, but, taken collectively as tools for analysis, they reveal gaps. The existing models overlook that the social and technical elements can be tightly linked, that there are possibilities for entities of varied scales (micro, meso, macro) to be examined using the same tools and assumptions and that there is a need to consider the entire asset life cycle without obscuring the operations stage. The study has demonstrated that ANT is a robust analytical approach that can drive the development of a model with these attributes. The developed model clearly highlights important principles: that the early FM involvement during the problematisation process strongly influences the stabilisation, and that successful life cycle maturity models should also include iterative collaboration and formalised knowledge resources to achieve the highest level of maturity through network convergence and stability. The practice guide was also provided to highlight the practical use of the model.

Since the findings are based on a single case study, further work can involve validating the model further and refining the model through case studies involving other conditions. For example, different model stages may arise in studies involving smaller universities or in late adaptors who may skip through the emerging and developing phases by leapfrogging on the findings of early adopters.

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