Building information modelling framework: A research and delivery foundation for industry stakeholders

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1. Building Information Modelling

Building Information Modelling (BIM) is a set of interacting policies, processes and technologies generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" [67]. The following sections expand on the BIM term, list related industry and academic efforts and identify the need for an investigative framework (Fig. 1).

1.1. BIM: the term

Building Information Modelling (BIM) is an emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry. Researchers have been investigating the components and repercussions of building product models [21] for many years before the emergence of BIM as a new term. While the mere presence of a label or an acronym is viewed by some researchers as a sign of poor lexical literacy [70], others refer to names as "vital for communication and useful for understanding a situation" [11]. Many industry writers and analysts have contested the many terms available while others have argued for the acceptance of BIM as is because of its adoption by industry's major CAD developers [54]. Whether the term itself is useful, agreed upon or contested, BIM is continuing its proliferation in both industrial and academic circles as the 'new CAD paradigm' [40].
subdivision of the BIM domain. Structured subdivisions promote understanding, dissemination and gradual implementation by presenting data and arguments in manageable sections. There is also a need for a framework that positions BIM as an ‘integration of product and process modelling’ [47] and not just as a disparate set of technologies and processes. Lastly, there is a lack of and a necessity for a framework that attempts to bridge the chasm separating ‘academic’ from ‘industrial’ understandings of BIM by providing a research and delivery structure adaptable to their complementary yet unique requirements.

1.4. Availability of other frameworks

BIM implementations and discussions continue to increase in intensity as more organisations and national bodies recognise its value-adding potential. This is evidenced by the accelerating emergence of guidelines and major reports dedicated to exploring and defining the requirements and deliverables of BIM (Table 2). These guidelines and reports — although valuable in their own right — do not provide a foundational framework suitable for the systematic investigation of the BIM domain. The availability of a

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**Fig. 1.** Visual abstract of this paper.
framework will assist in organising domain knowledge, elicit tacit expertise and facilitate the creation of new knowledge. The utility of such frameworks is ably articulated by Minsky (1975) who states: “Here is the essence of the theory: When one encounters a new situation (or makes a substantial change in one’s view of the present problem) one selects from memory a structure called a Frame. This is a remembered framework to be adapted to fit reality by changing details as necessary. A frame is a data-structure for representing a stereotyped situation…Attached to each frame are several kinds of information. Some of this information is about how to use the frame. Some is about what one can expect to happen next. Some is about what to do if these expectations are not confirmed. We can think of a frame as a network of nodes and relations.” [60]

2. BIM Framework: an introduction

This section introduces the BIM Framework, a research and delivery foundation that maps domain dynamics and allows AECO stakeholders to understand underlying knowledge structures and negotiate BIM implementation requirements.

The framework is multi-dimensional and can be represented by a tri-axial knowledge model (Fig. 3) comprising of:

• BIM Fields of activity identifying domain ‘players’ and their ‘deliverables’. These fields are represented on the x-axis.
• BIM Stages delineating implementation maturity levels (y-axis)
• BIM Lenses providing the depth and breadth of enquiry necessary to identify, assess and qualify BIM Fields and BIM Stages (z-axis)

2.1. BIM Fields

This section identifies three interlocking BIM Fields of activity (Fig. 4): Technology, Process and Policy (TPP) with two sub-fields each: players and deliverables. An introduction to the three BIM Fields is provided below followed by Field Interactions and Field Overlaps.

2.1.1. The BIM Technology Field

Technology is “the application of scientific knowledge for practical purposes” [65]. The Technology Field clusters a group of players who specialises in developing software, hardware, equipment and networking systems necessary to increase efficiency, productivity and profitability of AECO sectors. These include organisations which generate software solutions and equipment of direct and indirect applicability to the design, construction and operation of facilities.

2.1.2. The BIM Process Field

Process is “a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs: a structure for action” [18]. The Process Field clusters a group of players who procure, design, construct, manufacture, use, manage and maintain structures. These include facility owners, architects, engineers, contractors, facility managers and all other AECO industry players involved in the ownership, delivery and operations of buildings or structures.

2.1.3. The BIM Policy Field

Policies are “written principles or rules to guide decision-making” [13]. The Policy Field clusters a group of players focused on preparing practitioners, delivering research, distributing benefits, allocating risks and minimising conflicts within the AECO industry. These players do not generate any construction products but are specialised organisations — like insurance companies, research centres, educational institutions and regulatory bodies — which play a pivotal preparatory, regulatory and contractual roles in the design, construction and operation process.

<table>
<thead>
<tr>
<th>Sample terms</th>
<th>Organisation or Researcher</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Asset Lifecycle Information System</td>
<td>Fully Integrated &amp; Automated Technology</td>
<td>[24]</td>
</tr>
<tr>
<td>Building Information Modelling</td>
<td>Autodesk, Bentley Systems and others</td>
<td>[4,5]</td>
</tr>
<tr>
<td>Building Product Models</td>
<td>Charles Eastman</td>
<td>[21]</td>
</tr>
<tr>
<td>BuildingsSMART™</td>
<td>International Alliance for Interoperability</td>
<td>[38]</td>
</tr>
<tr>
<td>Integrated Design Systems</td>
<td>International Council for Research and Innovation in Building and Construction (CIB)</td>
<td>[42]</td>
</tr>
<tr>
<td>Integrated Project Delivery</td>
<td>American Institute of Architects</td>
<td>[2]</td>
</tr>
<tr>
<td>nD Modelling</td>
<td>University of Salford — School of the Built Environment</td>
<td>[52]</td>
</tr>
<tr>
<td>Virtual Building™</td>
<td>Graphisoft</td>
<td>[29]</td>
</tr>
<tr>
<td>Virtual Design and Construction &amp; 4D Product Models</td>
<td>Stanford University— Centre for Integrated Facility Engineering</td>
<td>[26,25]</td>
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</table>

Other terms: Integrated Model, Object Oriented Building Model, Single Building Model etc.
2.1.4. BIM Interactions

BIM interactions are push–pull knowledge transactions occurring within or between fields and sub-fields (Fig. 5). Push mechanisms [37] transfer knowledge to another field or sub-field while pull mechanisms transfer knowledge to satisfy a request by another field or sub-field. Sample transactions include data transfers, team dynamics and contractual relationships between fields and sub-fields. The identification and representation of these interactions are an important component of the Framework’s deliverables.

Table 3 below summarises the three BIM Fields, lists their players and deliverables and identifies some of their interactions.

2.1.5. BIM field overlaps

The three fields overlap as they share players and deliverables (see Fig. 6). This overlap between fields occurs when:

1. A deliverable requires players from two or more fields. The development and application of non-proprietary interoperable schemas (IFCs for example) require the joint efforts of Policy players (researchers and policy makers) as well as Technology players (software developers).

2. Players pertaining to one field generate deliverables classified in another. For example, the Australian Institute of Architects is an ‘industry body’ whose members are Process players

![BIM Framework: Fields, Stages and Lenses — tri-axial model.](image)
(architects) generating Policy deliverables (guidelines and best practices) rather than Process deliverables (building designs and construction details).

2.2. BIM maturity stages

There are voluminous possibilities attributed to BIM representing an array of challenges which need to be addressed by Architecture, Engineering, Construction and Operations (AECO) stakeholders. Having identified the BIM Fields, this section identifies the multiple stages which delineate implementation maturity levels.

BIM Stages — the second ‘dimension’ of the proposed framework — identifies a fixed starting point (the status before BIM implementation), three fixed BIM maturity stages and a variable ending point which allows for unforeseen future advancements in technology. This paper uses the term Pre-BIM to represent industry status prior to BIM
implementation and Integrated Project Delivery (IPD) to denote an approach to or an ultimate goal of implementing BIM [2].

The BIM Framework identifies BIM maturity within organisations, projects and industry as a series of stages which stakeholders need to implement gradually and consecutively. Each of these stages is further subdivided into steps. What separates stages from steps is that stages are transformational or radical changes while steps are incremental [35,75]. BIM maturity includes TPP (technology, process

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### Table 3

<table>
<thead>
<tr>
<th>BIM Fields — players, deliverables and interactions</th>
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<tr>
<td><strong>Policy Field</strong></td>
</tr>
<tr>
<td>Policies are “written principles or rules to guide decision-making” [13]</td>
</tr>
<tr>
<td>The field of interaction generating research, talents, standards and best practices for the purpose of safeguarding benefits and minimizing contestation between AECO stakeholders</td>
</tr>
<tr>
<td>Governments, researchers, educational institutions, insurance companies and regulatory bodies, ...</td>
</tr>
<tr>
<td>Regulations, guidelines, standards, best practices, bench marks, contractual agreements, educational programmes</td>
</tr>
<tr>
<td>Skilled graduates, standards, guidance into Process</td>
</tr>
<tr>
<td>− Skilled graduates, standards, guidance into Process − Concepts, mathematical solutions into Technology</td>
</tr>
<tr>
<td>− Subject matter experts from Process − Interoperability from Technology</td>
</tr>
<tr>
<td>Sample interactions between fields and sub-fields</td>
</tr>
<tr>
<td>− Sample interactions between fields and sub-fields</td>
</tr>
<tr>
<td>Push into other fields</td>
</tr>
<tr>
<td>Pull from other fields</td>
</tr>
<tr>
<td>Push-pull within the same field</td>
</tr>
<tr>
<td>− Interoperability from Technology</td>
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**Fig. 6.** BIM Fields’ overlapping players and deliverables — fan model.
and policy) components and is subdivided into three stages (Fig. 7) which are:

- BIM Stage 1: object-based modelling
- BIM Stage 2: model-based collaboration
- BIM Stage 3: network-based integration

Without overwhelming this paper with all variables the Framework measures BIM Stages against, it is important to introduce at least two of them: BIM Data Flows and Project Lifecycle Phases.

2.2.1. BIM Data Flows

Building Information Models are made of ‘smart’ objects [39] which represent physical elements like doors and columns [26] and encapsulate ‘intelligence’ [33] (refer to Fig. 8). An AECO smart object is different to a CAD entity that holds little or no meta-data [39]. Object intelligence, also referred to as ‘semantic richness’ [33] and data flows between BIM stakeholders are both critical and detectable variables of BIM maturity.

BIM data flows are varied and include the transfer of structured/computable (ex: databases), semi-structured (ex: spreadsheets) or non-structured/non-computable data (ex: images) between computer systems [49,33]. This transfer may be file-based or through data push–pull between servers and client machines [28]. As such, BIM data flows do not only include sending and receiving ‘semantically rich’ objects — the main components of BIM models — but also the sending and receiving of document-based information [27].

This variety in data and its methods of transfer between BIM players may be classified and later measured against BIM maturity stages in a multitude of ways. The author will however identify only one ‘umbrella’ classification suited for the purposes of this paper. BIM data flows can either be BIM data ‘exchanges’ or BIM data ‘interchanges’:

- A BIM data exchange is when a BIM player exports or imports data that is neither structured nor computable. A typical example of data exchange is the export of 2D CAD drawings out of 3D object-based models resulting in significant loss of geometric and semantic data.
- A BIM data interchange is when a BIM player exports and imports data that is structured and computable by another application. Interchanges assume ‘adequate interoperability’ between the sender and the receiver systems — 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” [41]. BIM interchange — an interoperable exchange of BIM data — may occur in many technical ways including the exchange of proprietary (ex: RVT and DGN), open-proprietary1 (like DWF and many eXtensible Markup Languages) or non-proprietary file formats (ex: IFC and CIS/2). A typical example of ‘adequate interoperability’ is the export of a CIS/2 file from one BIM application and its subsequent import by another without major loss of object data richness.

2.2.2. Project Lifecycle Phases

Construction projects pass through three major lifecycle phases: Design [D], Construction [C] and Operations [O]. The Framework subdivides these phases into sub-phases (Table 4) which are in turn further subdivided into multiple activities, sub-activities and tasks (Fig. 9). Example: [D] Design Phase, [D1] Architectural, Structural and Systems Design, [D1.1] Architectural Design, [D1.1a] Conceptualisation, [D1.1a.01] 3D Modelling.

BIM implementation will arguably change the components of and relations between lifecycle phases, activities and tasks; changes caused by varying BIM interactions (refer back to Section 2.1.2) and BIM Maturity. The next few sections will include a hypothetical

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1 For more information on proprietary/open-proprietary, please refer to http://www.openformats.org/en1.
representation of the effects of BIM Maturity on lifecycle phase duration, phase overlap and model semantic richness. First, a synopsis of pre-BIM — industry status prior to BIM implementation:

### 2.2.3. Pre-BIM Status synopsis

The construction industry is characterised by adversarial relationships where contractual arrangements encourage risk avoidance and risk shedding. Much dependence is placed on 2D documentation to describe a 3D reality. Even when some 3D visualisations are generated, these are often disjointed and reliant on two-dimensional documentation and detailing. Quantities, cost estimates and specifications are generally neither derived from the visualisation model nor linked to documentation.

Similarly, collaborative practices between stakeholders are not prioritised and workflow is linear and asynchronous. Under pre-BIM conditions, industry suffers from low investment in technology and lack of interoperability [17,62].

### 2.2.4. BIM Stage 1: object-based modelling synopsis

BIM implementation is initiated through the deployment of an ‘object-based 3D parametric software tool’ similar to ArchiCAD®, Revit®, Digital Project® and Tekla®. At Stage 1, users generate single-disciplinary models within either design [D], construction [C] or operation [O] — the three Project Lifecycle Phases. BIModeling deliverables include architectural design models [D] and duct fabrication models [C] used primarily to automate generation and coordination of 2D documentation and 3D visualisation. Other deliverables include basic data exports (ex: door schedules, concrete quantities, FFE costs...) and light-weight 3D models (ex: 3D DWF, 3D PDF, NWD, etc...) which have no modifiable parametric attributes.

Collaborative practices at Stage 1 are similar to pre-BIM Status and there are no significant model-based interchanges between different disciplines. Data exchanges between project stakeholders are unidirectional and communications continue to be asynchronous and disjointed. As only minor process changes occur at Stage 1, pre-BIM contractual relations, risk allocation and organisational behaviour persist. However, the semantic nature of object-based models and their ‘hunger’ for early and detailed resolution of design and construction matters encourage ‘fast-tracking’ of Project Lifecycle Phases (Fig. 10).

The Knowledge Model above hypothesizes how object-based modelling encourages fast-tracking — when a project is still executed in a phased manner yet design and construction activities are overlapped to save time [43]. The author argues that, after achieving maturity within Stage 1 implementations, BIM players will acknowledge the potential benefits of engaging other design and construction players with similar modelling capabilities. Such acknowledgement and subsequent action will lead these players to another revolutionary TPP change: model-based collaboration.

### 2.2.5. BIM Stage 2: Model-Based Collaboration synopsis

Having developed single-disciplinary modelling expertise in Stage 1 implementations, Stage 2 players actively collaborate with other disciplinary players. This may occur in many technological ways following each player’s selection of BIM software tools. Two different examples of model-based collaboration include the interchange (interoperable exchange) of models or part-models through ‘proprietary’ formats (ex: between Revit® Architecture and Revit® Structure through the .RVT file format) and non-proprietary formats (ex: between ArchiCAD® and Tekla® using the IFC file format).

Model-based collaboration can occur within or between two Project Lifecycle Phases. Examples of this include the Design—Design interchange of architectural and structural models [DD], the Design—Construction interchange of structural and steel models [DC] and the Design—Operations interchange of architectural and facility maintenance models [DO]. It is important to note that only one collaborating model needs to hold 3D geometric data to allow for semantic interchange between two disciplines. An example of this is the [DC] interchange between a 3D object-based model (ex: Digital Project®), scheduling database (ex: Primavera® or MS project®) or a cost estimating database (ex: Rawlinsons or Timberline®). Such interchanges allow the generation of 4D (time analysis) and 5D (cost estimating) studies respectively.

Although communications between BIM players continue to be asynchronous, pre-BIM demarcation lines separating roles, disciplines and lifecycle phases start to fade. Some contractual amendments become necessary as model-based interchanges augment and start replacing document-based workflows. Stage 2 maturity also alters the granularity of modelling performed at each lifecycle phase as higher-detail construction models move forward and replace (partially or fully) lower-detail design models (Fig. 11).

The Knowledge Model above hypothesizes how model-based collaboration is a factor in instigating fast-tracking and changing relative modelling intensity within each lifecycle phase. The author argues that the overlap depicted is driven by construction players increasingly providing design-related services as part of their Stage 2 offerings and design players increasingly adding construction and procurement information into their design models. Also, changes in semantic richness across lifecycle phases occur as detailed

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2 The graphical symbol used above represents 2D hand-drawn, 2D computer-aided drafting or 3D non-object based software technologies similar to AutoCAD®, SketchUp® and the like.
3 The graphical symbol used above represents a single-disciplinary 3D model exemplified by an architect’s ArchiCAD®, a structural engineer’s Revit® or a steel detailer’s Tekla® model.
4 The graphical symbol used above represents the interchange of 3D models between two different disciplines. This can be exemplified by two-way linking of Revit® Architectural and Structural models (a proprietary interoperable exchange) or the interchange of IFC-files exported out of multi-disciplinary BIM applications (a non-proprietary interoperable exchange).
5 Refer to IPD Guide and ConsensusDOCS 301: BIM Addendum.
2.2.6. BIM Stage 3: Network-Based Integration synopsis

In this stage semantically-rich integrated models are created, shared and maintained collaboratively across Project Lifecycle Phases. This integration can be achieved through model server technologies (using proprietary, open or non-proprietary formats), single integrated/distributed federated databases [6, 53] and/or SaaS (Software as a Service) solutions [81].

BIM Stage 3 models become interdisciplinary nD models [52] allowing complex analyses at early stages of virtual design and construction. At this Stage, model deliverables extend beyond semantic object properties to include business intelligence, lean construction principles, green policies and whole lifecycle costing. Collaborative work now spirals iteratively around an extensive, unified and sharable data model [22].

From a process perspective, synchronous interchange of model and document-based data cause Project Lifecycle Phases to overlap extensively forming a phase-less process (Fig. 12).

The Knowledge Model above hypothesizes how network-based integration causes ‘concurrent construction’ — a term used when “all project activities are integrated and all aspects of design, construction, and operation are concurrently planned to maximize the value of objective functions while optimizing constructability, operability and safety” [43].

BIM Stage 3 implementations necessitates major reconsideration of contractual relationships, risk-allocation models and procedural flows. The prerequisite for all these changes is the maturity of network/software technologies allowing a shared interdisciplinary model to provide two-way access to project stakeholders. The maturity of all these technologies, processes and policies will eventually facilitate an Integrated Project Delivery.

2.2.7. Integrated Project Delivery synopsis

Integrated Project Delivery, a term popularised by the American Institute of Architects California Council [2] is, in the author’s view, suitable for representing the long-term vision of BIM as an amalgamation of domain technologies, processes and policies. The term is generic enough and potentially more readily understandable by industry than “Fully Integrated and Automated Technology” [24] or “nD Modelling” [52] as two prominent examples.

The selection of Integrated Project Delivery (IPD) as the ‘goal’ of BIM implementations is not to the exclusion of other visions appearing under different names. On the contrary, the path from Pre-BIM (a fixed starting point), passing through three well defined Maturity Stages towards a loosely defined IPD is an attempt to include all pertinent BIM visions irrespective of their originating sources; some of these visions are quoted below:

- The “Integrated Project Delivery (IPD) is 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. IPD principles can be applied to a variety of contractual arrangements and IPD teams can include members well beyond the basic triad of owner, architect, and contractor. In all cases, integrated projects are uniquely distinguished by highly effective collaboration among the owner, the prime designer, and the prime constructor, commencing at early design and continuing through to project handover.”[2]
- The Integrated Design Solutions “are improved collaboration, coordination, communication, decision support, and other work processes enabled by increased horizontal, vertical, and temporal integration of data and information management to enhance the value added in whole network of shareholders throughout the building lifecycle.”[42]
- An nD model is an extension of the building information model by incorporating all the design information required at each stage of the lifecycle of a building facility [52, 51]. nD “is the parallel utilisation of building information for different analyses and evaluations...that will enable all stakeholders to experience the building, not just in a visual environment but in an information rich interactive system of all senses including acoustic (for ambient sound etc) and smell (to stimulate polluted environments) etc. nD modelling ‘... is a new approach orientated to integrate existing and non-existing modelling approaches into a new way to deal with the different dimensions of a project from a predictive perspective.”[52]
- FIATECH’s vision is of “fully integrated and highly automated project processes coupled with radically advanced technologies across all phases and functions of the project/facility lifecycle” [24].

2.2.8. Introduction to BIM Steps

The volume and complexity of changes identified in BIM Stages — at both organisational and industrial levels — are transformational
and cannot be implemented without traversing incremental evolutionary steps. The sections below identify BIM Steps which populate the passage from Pre-BIM to BIM Stage 1, through each of the three Stages and towards Integrated Project Delivery. Each step can either be a prerequisite for reaching a stage or a maturity level within each Stage.

2.2.8.1. Different Step Sets. The collection of steps required when working towards or within a BIM Stage — across the continuum from pre-BIM to IPD — is driven by different perquisites for, challenges within and deliverables of each BIM Stage. Steps can be identified in accordance with their location on the continuum (Fig. 13):

- A Steps: from pre-BIM Status leading to BIM Stage 1
- B Steps: from BIM Stage 1 maturing towards BIM Stage 2
- C Steps from BIM Stage 2 maturing towards BIM Stage 3
- D Steps are maturity levels within Stage 3 leading to Integrated Project Delivery

2.2.8.2. BIM Steps in relation to Fields. This paper has identified three BIM Fields: Technology, Process and Policy. The BIM Framework makes use of these subdivisions to distinguish between three types of steps leading to or transitioning between BIM stages (Fig. 14):

- Technology Steps in software, hardware and networks. For example, the availability of a BIM tool allows the migration from drafting-based to object-based workflow (BIM Stage 1)
- Process Steps in Leadership, Infrastructure, Human Resources and Products/Services. For example, collaboration processes and database-sharing skills are necessary to allow model-based collaboration (BIM Stage 2).
- Policy Steps in contracts, regulations and research/education. For example, alliance-based and risk-sharing contractual agreements are pre-requisites to achieving integrated practices (BIM Stage 3).

2.2.8.3. BIM Steps matrix. BIM Steps act as prerequisites of or maturity levels within BIM Stages. Steps will assist BIM implementation efforts by identifying activities, services and products necessary to fulfill Stage requirements. Representing these visually will also aid in assessing organisations’ maturity levels, what steps have been accomplished or are still required. Fig. 16 is a generic ‘knowledge visualisation’ (refer to Section 4) of BIM steps while Fig. 17 is a hypothetical view of an organisation’s BIM implementation efforts seen through the matrix.

It is important to note that BIM Steps, their number, delineation and maturity will be analysed against relevant maturity models including CMMI®7, P-CMM®8, ISO/IEC 155049, and BIM_CMM10 in future publications. An introduction to maturity models or an elaboration on concepts like ‘key’ and ‘non-key steps’ cannot be succinctly introduced in this ‘scene-setting’ paper.

2.3. BIM Lenses

BIM Lenses represent the third dimension of the Framework and generate its depth of enquiry. BIM Lenses are distinctive layers
of analysis (Fig. 18) applied to Fields and Stages to generate ‘Knowledge views’ (refer to ontology, Section 3). They ‘abstract’ the BIM domain and control its complexity by removing unnecessary detail [45]. Lenses allow the domain researcher to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not. In essence, all knowledge views are abstractions derived from the application of one or more lenses and/or filters.

2.3.1. Differences between BIM Lenses and Filters

Lenses and Filters are investigative tools of enquiry and domain analysis allowing the discovery of concepts and relations (more about that in the Ontology Section 3). The difference between Lenses and Filters can be summarised as such: Lenses are additive and are deployed from the ‘investigator’s side’ of BIM Field observation while Filters are subtractive and are deployed from the ‘data side’. Lenses highlight observables that meet research criteria and identify their relations; example, an infrared lens highlights heat sources in a scene. Filters remove observables that do not meet the research criteria; example, data filters hide non-conforming data within a spreadsheet. Fig. 19 below visually exemplifies the difference between Lenses and Filters:

There are three types of lenses/filters which can be applied individually or collectively to generate a knowledge view:

2.3.2. Disciplinary Lenses and Filters

Disciplinary lenses generate BIM views through the application of fields of knowledge. If a discipline is applied as a filter, it will hide all data not related to that discipline from view. Table 5 below lists some applicable disciplinary lenses/filters:

The application of different disciplinary Lenses and Filters generate distinct views of the BIM domain. For example, when applying two different Lenses/Filters to a Stage 2 collaborative effort, two distinctly different knowledge views emerge:

- The application of a ‘data management lens’ highlights data flows and controls while a ‘data flow filter’ isolates exchanged file types.
- The application of a ‘process management lens’ highlights roles, procedures and tasks while a ‘task filter’ isolates specific meetings and phone calls.

2.3.3. Scoping Lenses and Filters

This type of Lens vary the horizontal and vertical abstraction [45] of the intended view. Scoping Lenses abstract the knowledge view by changing its granularity and filtering out unwanted information through ‘rounding units of measurement’. Scoping lenses have three complexity levels [80]:

- A Macroscopic Lens: wide topical coverage but low in detail; example, a knowledge management lens depicting push–pull interactions between BIM Fields at industry level.
- A Mesoscopic Lens: medium coverage, focus and detail; example, a data management lens depicting inter-organisational data flows.
- A Microscopic Lens: narrow in focus but high in detail; example, a change management lens depicting the role of an individual driving BIM implementation within a team.

2.3.4. Conceptual Lenses and Filters

This type of Lens generates knowledge views by applying conceptual filters derived from the BIM Ontology — a specialised conceptual ontology developed by the author (refer to Section 3). Conceptual lenses/filters are not mutually exclusive and include: Agents, Constraints, Deliverables, Equipment, Tasks and Triggers to name a few.

In Summary, BIM Lenses and Filters — whether disciplinary, scoping or conceptual — can be applied individually or collectively to generate a host of views. This ability to extract knowledge views through abstraction and representation [61] provides the BIM Framework with flexibility and investigative granularity.

After introducing BIM Fields, Stages and Lenses, it is important to expand on the language employed by the Framework. Section 3 introduces a special ontology generated to ‘systemically’ expose the Framework’s underlying knowledge structures, allow its modification and enable its extension. Section 4 follows by expanding on the ‘visual language’ critical for Framework’s simplification, representation and dissemination.

3. An ontological representation of the BIM Framework

The BIM Framework aims to investigate and represent a host of concepts and relations. To reduce complexity, enable knowledge acquisition and validation of Framework’s topics, a specialised ‘conceptual’ BIM Ontology has been developed.

The term ontology comes from Philosophy and signifies a systematic account of Existence [31] and “defines a common vocabulary for researchers who need to share information in a domain” [64]. There are many types of ontologies ranging in their formality, structure and intended use. The two main uses are to generate a language for communication between people [73,79] or interoperability between systems [79].

As a language to represent the BIM Framework, a BIM Ontology will act as a “formal description of the elements and relationships

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**Fig. 12.** Project Lifecycle Phases at BIM Stage 3 — linear model.
The BIM Framework fall within the research area of knowledge visualisation, didactic techniques, visual cognition and visual communication [23]. Knowledge visualisation utilizes graphical means to explore, communicate or resolve logical problems [12]. Visualisation can generate models in different formats (examples in Fig. 20) but share the intent to communicate and re-construct meaning [23].

Each model format offers a unique way to represent meaning. The VENN format (refer back to Fig. 3) is deemed appropriate by the author to best represent the overlapping nature of BIM Fields. In other instances, ‘map-based’ visualisations are better suited to represent BIM Framework’s concepts, relations and ontological infrastructure (see Fig. 21). According to Tergan (2003), map-based visualisation is a “valuable cognitive tool for supporting knowledge use in a variety of learning and instructional settings”. Concept Maps — a specific type of map-based visualisations composed of nodes, links and labels — show high levels of acceptance when generated by domain experts [36]. Concept Maps are thus deployed to graphically represent the ontological relations between Framework parts. This combination of visual modelling driven by explicit ontological relations renders the Framework accessible to analysis, modification and extension.

After discussing the languages used — both ontological and visual — to expose, represent and communicate the BIM Framework, the next section explores some of its deliverables and research extensions.

5. BIM framework deliverables and extensions

The systemic subdivision of the BIM domain into Fields, Sub-Fields, Players, Deliverables, Stages, Steps, Lenses and Filters allow the generation of an array of deliverables. The Framework employs a simple yet specialised ontology to explore and ‘make explicit’ the relations between BIM concepts thus facilitating its semantic representation through a variety of mediums. The Framework also serves by a multitude of visual knowledge models which, in essence, simplify and clarify the overlapping BIM concepts to industry stakeholders. The Framework is arguably well placed to provide many deliverables — some of which are under development — classified by ‘target audience’ and ‘scale of application’.

- Target audience: the BIM Framework is of benefit to both Industry and Academia. It generates knowledge modules, templates and tools that can assist in implementing and teaching BIM respectively.
- Scale of application: The BIM Framework — by virtue of its generic and systemic nature — is applicable across disciplines and lifecycle phases. Its deliverables can be scaled to guide BIM implementations within organisations, at project and industry levels.

![Fig. 13. Step Sets leading to or separating BIM Stages — linear model.](Image)

![Fig. 14. Step Types leading to or separating BIM Stages — linear model.](Image)
Full exploration of Framework deliverables cannot be achieved within this 'scene-setting' paper. However, a summary of these deliverables is provided in Table 7 below:

5.1. Research extensions

The BIM Framework and its BIM Ontology provide an expandable base for knowledge acquisition, representation and sharing. Research extensions include generating visual knowledge models of many inter- and intra-organisational BIM Interactions. Push–pulls and Overlaps between BIM Fields can be visually and semantically represented and their knowledge components transformed into tools customised for different BIM Stages. The Framework can be contextualised to represent collaborative BIM relations between different industry players (ex: between an Architect and a Facility Manager) and extended to identify changing roles and emerging tasks.
within organisations and teams. Finally, the Framework can be independently and collaboratively extended by subject matter experts using the BIM Ontology as a semantic structure and Concept Maps (for example) as a visual language.

6. A brief note on the methodology underlying the BIM Framework

Building Information Modelling is an expansive knowledge domain. To allow the Framework to systematically investigate and represent domain players, deliverables, interactions and maturity levels and render itself accessible to multiple investigators, the research methodology is necessarily a mixed one. Depending on the Framework part being investigated, validated or extended, the investigator will adopt the most appropriate paradigm, method or strategy irrespective if its inductive, deductive, retroductive or abductive nature [10]. In essence, the BIM Framework is generated and delivered through a mixed-method study [74].

A discussion of theoretical frameworks [3], methodology and investigation strategies underlying the BIM Framework cannot be adequately addressed in this paper. Nevertheless, a sample strategy to define one of the Framework’s dimensions is briefly discussed below:

6.1. Sample research strategy: identifying BIM Fields

BIM Fields, one of three Framework dimensions, has been identified using ‘conceptual clustering’ of observable knowledge objects within the AECO industry. These clusters have been ‘inductively inferred’ through a strategy of observation and discovery [56].

Inductive inference is the “process of generating descriptions that imply original facts in the context of background knowledge” [56]. One key strategy to generate these descriptions is through observation and discovery where the observer analyses the background knowledge (the BIM landscape as an instance space) and determines that some observables can be usefully grouped. This act of grouping generates conceptual clusters of objects sharing common attributes.

According to Michalski and Stepp (1987), a ‘concept’ is an equivalence class of entities united by a common property or goal while ‘clustering’ is the act of grouping a collection of objects into classes [56]. Conceptual clustering thus signifies the identification of concepts, followed by classification of objects according to these concepts and, finally, the clustering of classified objects together. This process of identification, classification and clustering is goal-driven and attempts to simplify a large system by decomposing it into smaller sub-systems [57].

Inductive generalisation (whether instance-to-class or part-to-whole) and abduction (specific assertions based on background knowledge [56]) are two types of inductive inference techniques deployed to define some Framework concepts. For example, the AECO industry includes a great number of stakeholders. To cluster these stakeholders in a descriptive and useful manner, the Framework identifies a concept (BIM deliverables — a cluster in its own right), classifies stakeholders according to that concept and then, through an instance-to-class strategy, generates BIM Fields — a set of conceptual clusters (refer to Section 2.1).
Although inductive inference is a primary method for acquiring knowledge, creating new knowledge and even predicting future events [56], hypotheses generated by inductive inference need to be tested and verified before they become accepted theories.

6.2. Validation of the BIM Framework

The Framework aims to use multiple types of ‘triangulation’ — the observation of research issues from at least two different points [44] — to test and validate the accuracy of its subdivisions and their relations. Whether it is data, investigator, theory or methodological triangulation [19,66], the Framework will rely on available literature and new research (conducted by the author and others) using qualitative and quantitative paradigms, different methodologies and tailored investigative strategies.

7. Conclusion

Building Information Modelling is an expanding field of study incorporating many knowledge domains within the Architecture, Engineering, Construction and Operations industry. The divergence of study topics relating to BIM highlights the necessity of and need for a research framework to allow its systematic investigation. This paper has identified a research and delivery framework, specialised ontology and visual language tailored to investigate the BIM domain and provide actionable deliverables. This is a ‘scene-setting’ paper and many non-foundational framework parts have been excluded while others succinctly included; exclusions will be remedied in future.
publications. The BIM Framework is “an integrated framework [incorporating] different approaches to information within a consis-
tent whole. It might incorporate not only the information model but
also the reference process model and dictionaries. It is possible that it
may go further and also enable the inclusion of ontology/taxonomy
developments from the world of classification”[55].

In Summary, this paper has briefly introduced BIM Fields, BIM
Stages and BIM Lenses. It also identified Step Sets, Step Types — both
requisites of BIM implementation — and discussed many framework
deliverables. Further investigations and publications are needed to
generate a fuller understanding of the BIM domain and extend the
Framework’s research potential, academic standing and industrial
deliverables.

Acknowledgements

This paper is in partial fulfilment of the author’s PhD requirements
at the University of Newcastle, Australia. The author would like to
express gratitude to his supervisors Willy Sher, for his support and
substantive input, and Dr. Guillermo Aranda-Mena (RMIT University)
for his continuous encouragement. The author also acknowledges
Professor Ron Wakefield and research colleagues John Crawford and
Agustin Chevez for their generous feedback. Finally, the author
expresses his appreciation to the reviewers for their enriching
commentary which helped improve the quality of this paper.

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Table 5
A non-exhaustive matrix of BIM Lenses and Filters

<table>
<thead>
<tr>
<th>Disciplinary BIM Lenses</th>
<th>Disciplinary BIM Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change management</td>
<td>Change mechanisms, incentives, resistance,…</td>
</tr>
<tr>
<td>Construction/</td>
<td>Project planning, resources, activities,…</td>
</tr>
<tr>
<td>- project management</td>
<td></td>
</tr>
<tr>
<td>Data management</td>
<td>Data standards, security, flows,…</td>
</tr>
<tr>
<td>Design management</td>
<td>Design leadership, communication, creativity,…</td>
</tr>
<tr>
<td>Financial management</td>
<td>Financial strategies, controls, budgets,…</td>
</tr>
<tr>
<td>Knowledge management</td>
<td>Knowledge acquisition, representation, transfer,…</td>
</tr>
<tr>
<td>Organisational behaviour</td>
<td>Organisational culture, development, planning,…</td>
</tr>
<tr>
<td>Process management</td>
<td>Process roles, procedures, tasks,…</td>
</tr>
<tr>
<td>Risk management</td>
<td>Risk identification, allocation, mitigation,…</td>
</tr>
</tbody>
</table>

Plus many other Disciplinary Lenses— like Human Resource Management, Product
Management, Supply Chain Management, Quality Management — and their respective
Filters. Disciplinary Lenses inherently overlap in their terminology and fields of
application.

Table 6
Knowledge objects pertaining to BIM Ontology

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Events</th>
<th>Incentives</th>
<th>Mental concepts</th>
<th>Recommendations</th>
<th>Social</th>
<th>Knowledge objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agents</td>
<td>Constraints</td>
<td>Deliverables</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Examples</td>
<td></td>
<td>Functions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowledge areas</td>
<td></td>
<td>Knowledge areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical phenomena</td>
<td></td>
<td>Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Software agents</td>
<td></td>
<td>Software</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tasks</td>
<td></td>
<td>Triggers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Attributes

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Link</th>
<th>Text</th>
</tr>
</thead>
</table>

Relations

<table>
<thead>
<tr>
<th>Part of</th>
<th>Has part</th>
<th>Has expertise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performs</td>
<td>Performed by</td>
<td>Uses</td>
</tr>
<tr>
<td>Supplies</td>
<td>Supplied by</td>
<td>Located in</td>
</tr>
<tr>
<td>Resource for</td>
<td>Has resource</td>
<td>Produced by</td>
</tr>
<tr>
<td>Owns</td>
<td>Owned by</td>
<td>Caused by</td>
</tr>
<tr>
<td>Runs</td>
<td>Run by</td>
<td>Attends</td>
</tr>
<tr>
<td>Has function</td>
<td>Function of</td>
<td>Documented in</td>
</tr>
<tr>
<td>Requires</td>
<td>Required by</td>
<td>Consults</td>
</tr>
<tr>
<td>Made of</td>
<td>Material for</td>
<td>Followed by</td>
</tr>
<tr>
<td>Has role</td>
<td>Has contact</td>
<td>Applicable to</td>
</tr>
<tr>
<td>Affects</td>
<td>Linked to</td>
<td>Has authority over</td>
</tr>
<tr>
<td>Validates</td>
<td>Is validated by</td>
<td>Is empowered by</td>
</tr>
</tbody>
</table>

Knowledge views

<table>
<thead>
<tr>
<th>Knowledge document</th>
<th>Knowledge matrix</th>
<th>Knowledge model</th>
<th>Knowledge store</th>
</tr>
</thead>
</table>

Fig. 19. Difference between BIM Lenses and Filters — tri-pane model.
Fig. 20. Sample visualisation models — adapted from Eppler and Burkhard [23].

Fig. 21. Knowledge view using Concept Maps and BIM Ontology.
Table 7
Summary matrix of BIM Framework deliverables

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Macroscopic: industry level</th>
<th>Mesoscopic: project level</th>
<th>Microscopic: organisation level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Educational deliverables</td>
<td>Generating BIM Literacy Guidelines, producing learning tools and collating case studies — through publication of a BIM textbook</td>
<td>Identifying BIM Educational Deliverables according to organisational types and delivery modes — example: identifying vocational, tertiary, industry and industry associations’ BIM educational deliverables</td>
<td>Classifying and embedding BIM Educational Deliverables into different curricula and the generation of BIM educational tools — example: developing course outlines and learning plans for an undergraduate course</td>
</tr>
<tr>
<td>Industry deliverables</td>
<td>Setting an industry-centric BIM Knowledge Store catering for organisations and individuals — through the publication of industry papers and setting up a BIM-focused wiki and a weblog</td>
<td>Generating BIM Implementation Guidelines in modular format detailing BIM Maturity Steps within and across industry disciplines — examples: BIM leadership, risk management and HR development modules</td>
<td>Generating a BIM Implementation Handbook in modular format including implementation templates and change tools — example: a BIM Skill/Knowledge Competency Matrix for staff or a BIM Software Selection Matrix</td>
</tr>
</tbody>
</table>
B. Succar / Automation in Construction 18 (2009) 357–375


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