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

Bilal Succar

University of Newcastle, Australia
RMIT University, Australia

ARTICLE INFO

ABSTRACT

Building Information Modelling (BIM) is an expansive knowledge domain within the Architecture, Engineering, Construction and Operations (AECO) industry. To allow a systematic investigation of BIM's divergent fields, its knowledge components must be defined and expanding boundaries delineated. This paper explores some of the publicly available international guidelines and introduces the BIM Framework, a research and delivery foundation for industry stakeholders. This is a 'scene-setting' paper identifying many conceptual parts (fields, stages, steps and lenses), providing examples of their application and listing some of the Framework's deliverables. This paper also identifies and deploys visual knowledge models and a specialised ontology to represent domain concepts and their relations.

© 2008 Elsevier B.V. All rights reserved.

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].

1.2. Differences between terms

Some researchers have opted to differentiate between the many available terms [51] but the extensively overlapping boundaries render the uniqueness of each term questionable. From conceptual to descriptive in nature, these terms can be attributed to research or industry bodies as well as software developers. Table 1 sets out some of the more widely used terms in both research and industry literature while Fig. 2 presents some common connotations of the BIM term.

Some of the underlying knowledge and computational structures represented by these terms has shifted from research circles to the industrial realm [46] while many efforts could not attract the interest of the industry [33].

1.3. The need for a framework

In many writings, seminars and workshops, BIM is argued to be a catalyst for change [7] poised to reduce industry's fragmentation [17], improve its efficiency/effectiveness [34] and lower the high costs of inadequate interoperability [62]. These assertions — abridged as they may be — include several mental constructs derived from organisational studies, information systems and regulatory fields. Such divergence and coverage highlights the *lack of* and the *necessity for* a research framework to organise domain knowledge which, in turn, requires a systematic investigation of the BIM domain.

Additionally, the need for a systemically-defined BIM Framework extends beyond knowledge enquiry and organisation. Practitioners and educators alike will arguably find value in the delineation and

E-mail address: bsuccar@changeagents.com.au.

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
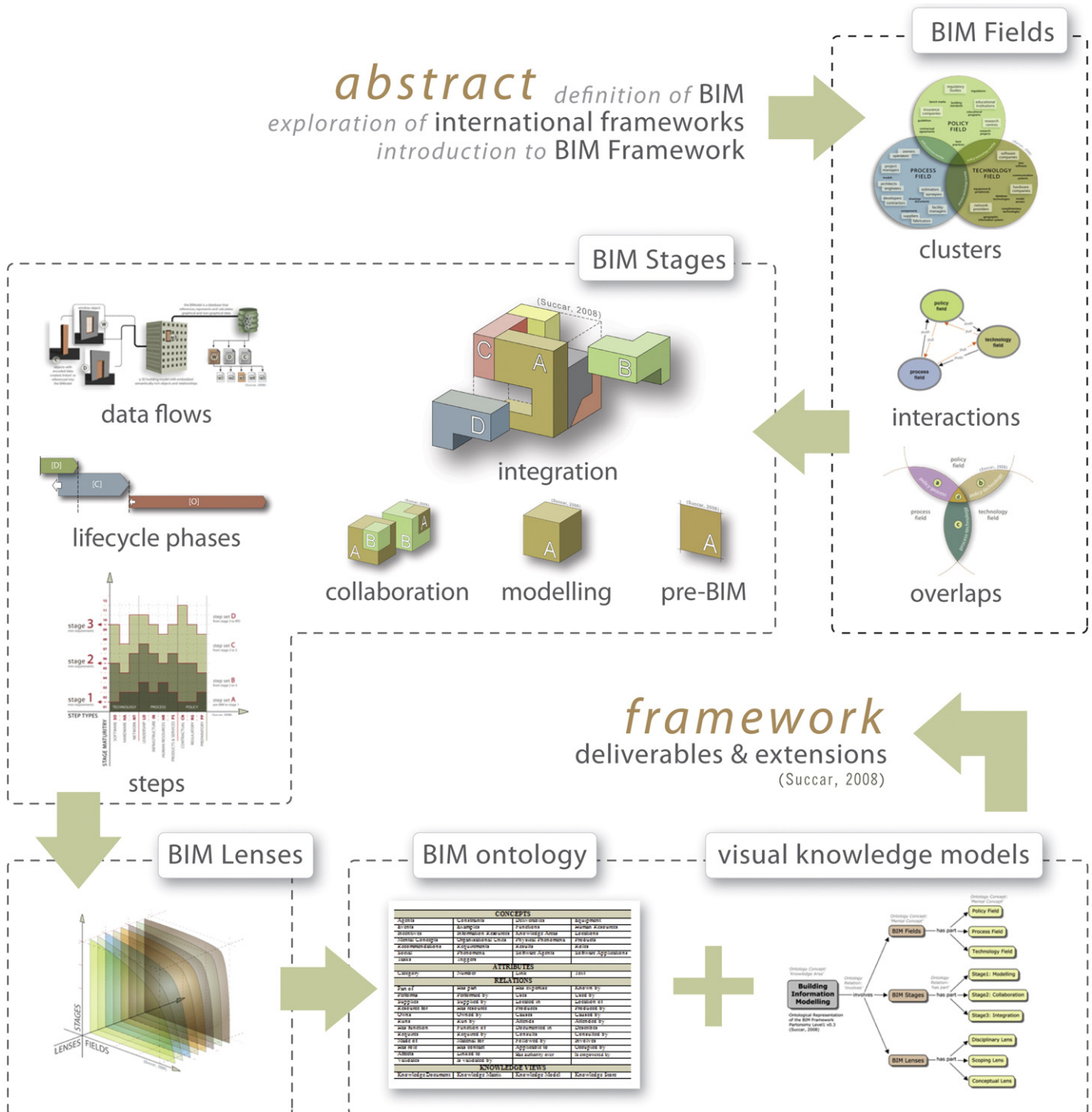

Fig. 1. Visual abstract of this paper.

Table 1
Widely used terms relating to Building Information Modelling

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

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

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 operations process.
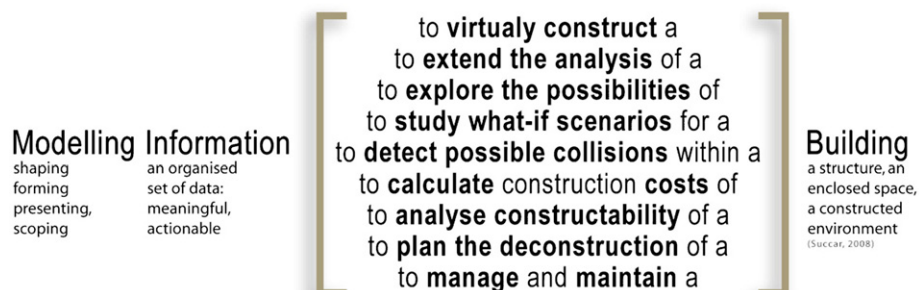
Fig. 2. Some common connotations of multiple BIM terms.

Table 2
A non-exhaustive list of publicly-available guides, reports and visions relating to BIM

Origin	Organisation	Project	Type and date	Description	Ref and link
Australia	CRC-CI	National Guidelines & Case Studies	Guidelines and six case studies — 2008.	"The guidelines will highlight open and consistent processes and test selected softwares compatibility"	[16] 5h95p5
Denmark	BIPS	Digital Construction	Guidelines 2007 in 4 parts (251+ pages)	A guide made of 4 components: 3D CAD Manual, 3D Working Method, Project Agreement and Layer — and Object Structures	[9] bipsBIM
Finland	SENATE Properties	BIM Requirements 2007	Guidelines — 2007 in 9 volumes (200 pages) subdivided by discipline	General operational procedures in BIM projects and detailed general requirements of BIModels — focuses on the design phase	[71] 63btnq
Netherlands	TNO	E-BOUW	Framework —2008 presented through a wiki	"a BIM Framework consisting of seventeen orthogonal Dimensions that describe in general the Building Information Modelling world constituting a "Way of Thinking" about BIM	[20] tnowiki
Norway	STATSBYGG	HITOS	Documented Pilot (52 pages). sections based on modelling roles	A 'full-scale IFC test' documenting experiences gained on a collaborative project	[50] 62kmd3
United States	AGC	Contractor's Guide to BIM	Guidelines — version 1, September 2006 (48 pages)	"This guide is intended to help contractors understand how to get started (with BIM or VDC)	[1] 695hjq
	AIA	Integrated project Delivery (IPD)	Guide — 2007 (62 pages)	"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 & construction"	[2] 6kadgh
	GSA	3D–4D-BIM Program	Guidelines —2006 in 7 series	A guide "intended for GSA associates and consultants engaging in BIM practices for the design of new construction and major modernization projects for GSA"	[32] GSABIM
	NIST	NBIMS National Building Information Modelling Standards	Guidelines — 2007 (183 pages)	"NBIMS establishes standard definitions for building information exchanges to support critical business contexts using standard semantics and ontologies…(to be)..implemented in software"	[63] NBIMSpdf
	USACE	US Army Corps of Engineers	BIM — A roadmap for Implementing BIM to solve the Time and Cost Challenges of MILCON Transformation (96 pages)	"The scope of this plan is to focus on the implementation of BIM in the U.S. Army Corps of Engineer's civil works and military construction business processes, including the process for working with the USACE Architectural Engineering Construction (AEC) industry partners and software vendors"	[77] 6qzpe9
	USCG	U.S. Coast Guard	BIM User Guides and Standards (partial publicly-available information)	"The aim is to develop and maintain a BIM standard"	[78]
European	Consortium of organisations	InPro	Report — 2006 till 2010 (131 pages in 4 or more parts so far)	"The Open Information Environment is a set of results due to the junction of two approaches: on one hand business processes and the required organisation and on the other hand the underlying technologies supporting the business processes."	[68] 5ref9c
	Consortium of organisations	CONCUR Concurrent Engineering in Building and Civil Engineering	Demonstration Project — 2002	"CONCUR has demonstrated concurrent working in construction engineering and design between project partners using advanced web based ICT"	[14] 6pst5l
	Consortium of organisations	ERABUID	Report — 2008	Review of the development and implementation of BIM: technology, standards and necessary future steps	[48] Erabuild
	Consortium of organisations	STAND-INN	Development Process — Quick Guide 2007	"Integration of performance based building standards into business processes (and manufacturing processes) using IFC standards to enhance innovation and sustainable development"	[72] STAND-INN

Note 1: It's worth mentioning that the efforts of the International Alliance for Interoperability (http://tinyurl.com/iai-int) are a basis for many guidelines and reports listed above.
Note 2: For web addresses, please add http://tinyurl.com/ in front of the code. Example (http://tinyurl.com/2sjlg9).

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
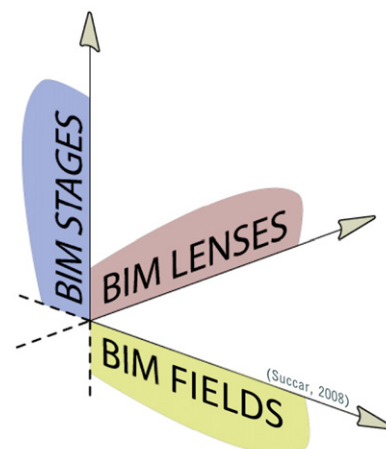

Fig. 3. BIM Framework: Fields, Stages and Lenses — tri-axial model.
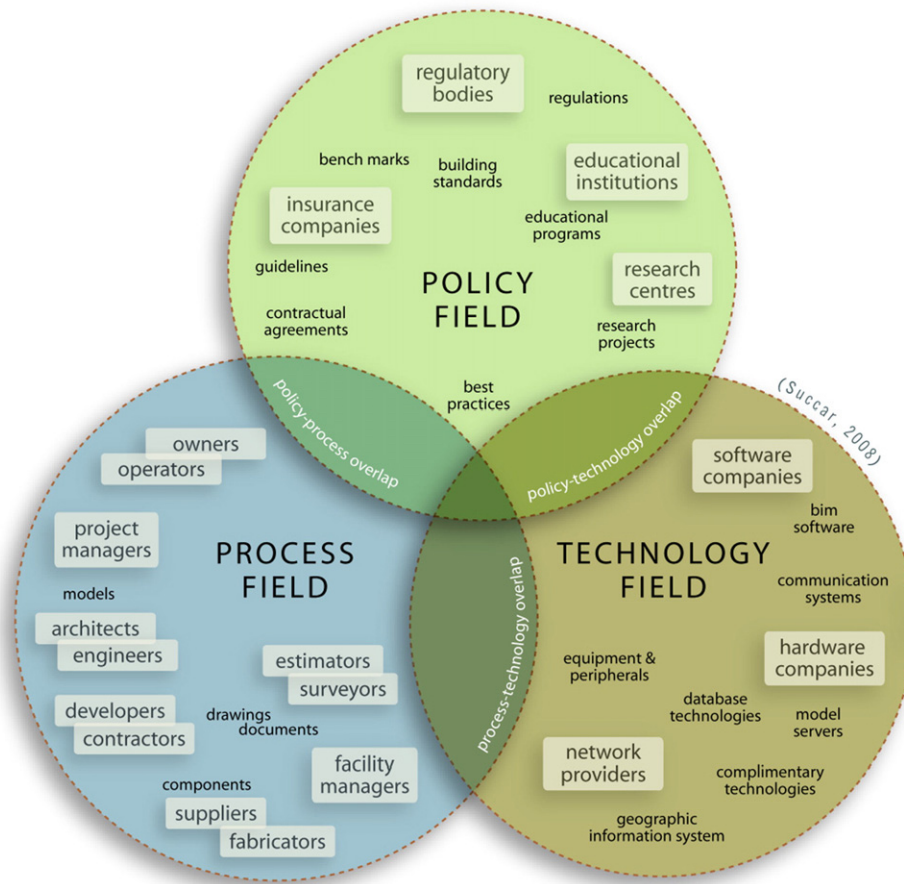
Fig. 4. Three interlocking Fields of BIM activity — venn diagram.

(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 unforseen future advancements in technology. This paper uses the term Pre-BIM to represent industry status prior to BIM
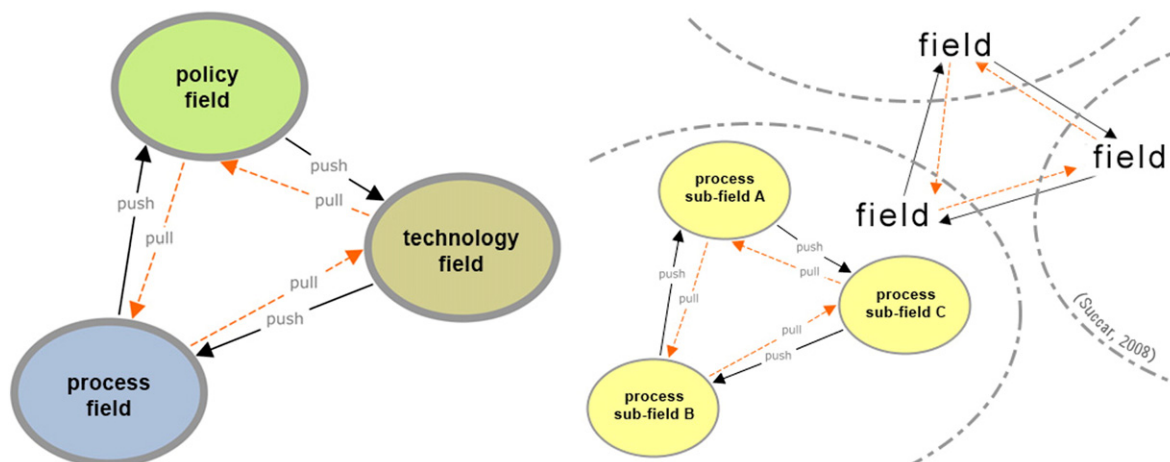

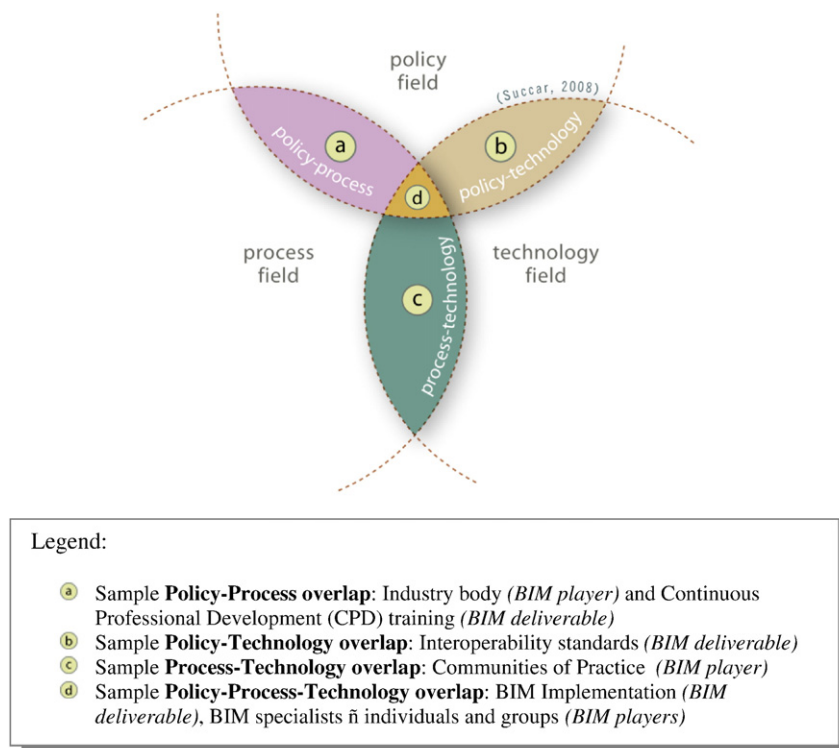**Fig. 5.** BIM Interactions between and within Fields — combined view.

Table 3
BIM Fields — players, deliverables and interactions

		Policy Field	Process Field	Technology Field
Definition		Policies are "written principles or rules to guide decision-making" [13]	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]	Technology is "the application of scientific knowledge for practical purposes" [65]
Extended Field Definition		The field of interaction generating research, talents, standards and best practices for the purpose of safeguarding benefits and minimizing contestation between AECO stakeholders	The field of interaction between design, construction and operational requirements for the purpose of generating and maintaining structures and facilities	The field of interaction between software, hardware, equipment and networking systems for the purpose of enabling or supporting the design, construction and operations of structures and facilities
Players (sub-field)		Governments, researchers, educational institutions insurance companies and regulatory bodies, …	Owners, operators, architects, engineers, estimators, surveyors, developers, contractors, sub-contractors suppliers, fabricators, facility managers, …	Software, hardware, network and equipment companies plus their development and sales channels
Deliverables (sub-field)		Regulations, guidelines, standards, best practices, bench marks, contractual agreements, educational programmes	Construction products and services including drawings, documents, virtual models/components, physical components, structures and facilities	Software, hardware, peripherals, network solutions, and office/ site equipments
Sample interactions between fields and sub-fields	Push into other fields	– Skilled graduates, standards, guidance into Process – Concepts, mathematical solutions into Technology	– Case studies into Policy – Feedback to Technology	Innovative solutions and new equipment into Policy and Process
	Pull from other fields Push–pull within the same field	– Subject matter experts from Process – Interoperability from Technology Interchanges between research, education and accreditation boards	– Development of solutions from Technology – Standards, guidelines and graduates from Policy Architect's Instructions (AI-push) and Request Further Information (RFI-pull)	– Standardisation efforts from Policy – Requirements and experiences from Process Hardware capabilities (push) and software requirements (pull)

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

Legend:
- a Sample **Policy-Process overlap**: Industry body (*BIM player*) and Continuous Professional Development (CPD) training (*BIM deliverable*)
- b Sample **Policy-Technology overlap**: Interoperability standards (*BIM deliverable*)
- c Sample **Process-Technology overlap**: Communities of Practice (*BIM player*)
- d Sample **Policy-Process-Technology overlap**: BIM Implementation (*BIM deliverable*), BIM specialists ñ individuals and groups (*BIM players*)

Fig. 6. BIM Fields' overlapping players and deliverables — fan model.

Fig. 7. BIM maturity is subdivided into three stages — linear view.
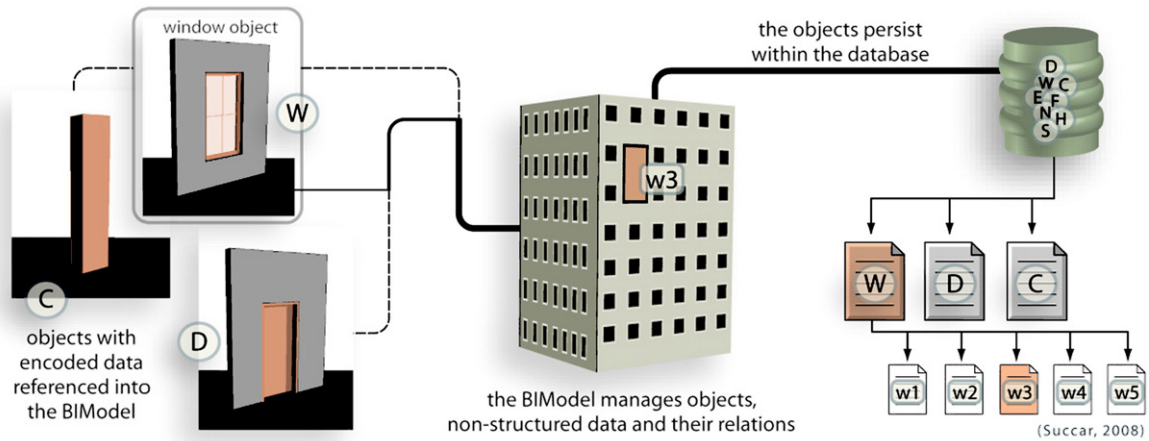

Fig. 8. Building Information Models and their objects — flow diagram.

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 BIModels — 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-proprietary[1] (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

---

[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[2].

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[3]
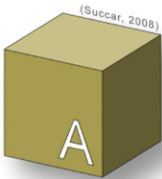
BIM implementation is initiated through the deployment of an 'object-based 3D parametric software tool' similar to ArchiCAD®, Revit®, Digital Project® and Tekla®. At Stage 1, users generate single-disciplinary models within either design [D], construction [C] or operation [O] — the three Project Lifecycle Phases. BIModelling 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 allocations 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 acknowledgment and subsequent action will lead these players to another revolutionary TPP change: model-based collaboration.

Table 4
Project Lifecycle Phases and sub-phases

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

2.2.5. BIM Stage 2: Model-Based Collaboration synopsis[4]
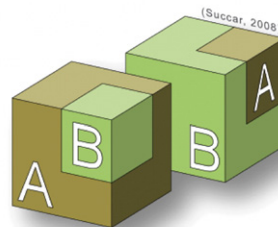
Having developed single-disciplinary modelling expertise in Stage 1 implementations, Stage 2 players actively collaborate with other disciplinary players. This may occur in many technological ways following each player's selection of BIM software tools. Two different examples of model-based collaboration 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 one* 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[5] 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

---

[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).
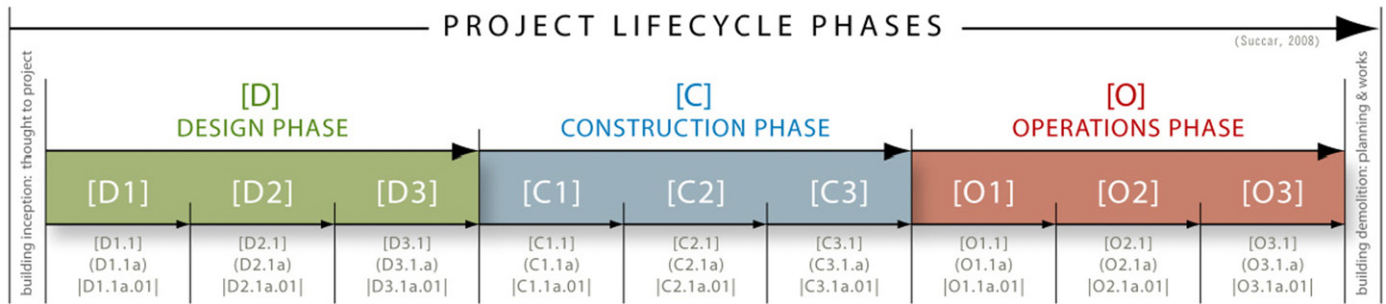[5] Refer to IPD Guide and ConsensusDOCS 301: BIM Addendum.

Fig. 9. Phases, sub-phases, activities, sub-activities and tasks — linear visual model.

construction and fabrication models (ex: steel detailing and duct fabrication models) partially replace the more generic upstream structural and mechanical design models.

2.2.6. BIM Stage 3: Network-Based Integration synopsis[6]
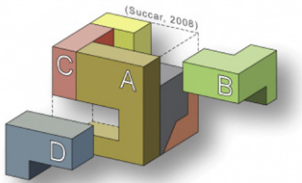
In this stage semantically-rich integrated models are created, shared and maintained collaboratively across Project Lifecycle Phases. This integration can be achieved through model server technologies (using proprietary, open or non-proprietary formats), single integrated/ distributed federated databases [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

---

[6] The graphical symbol used above represents the integration of 3D models using a network-based technology. Each of the single-disciplinary models is an integral part of the resulting inter-disciplinary model.
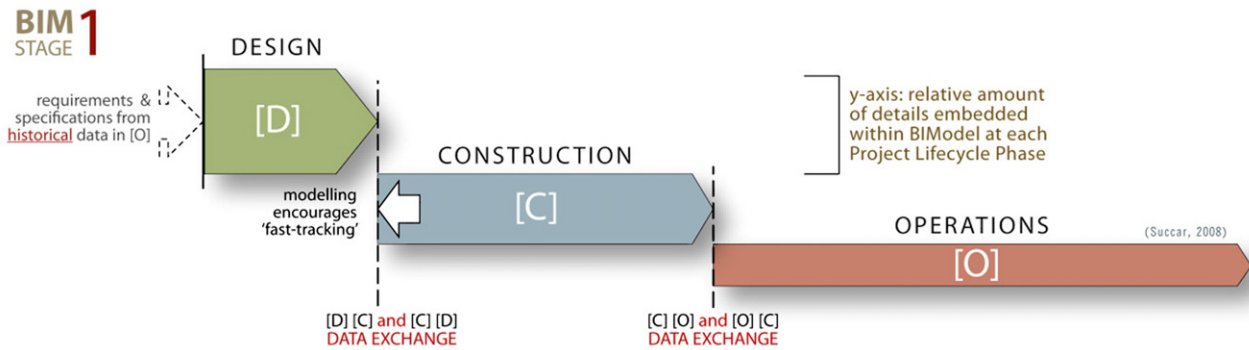
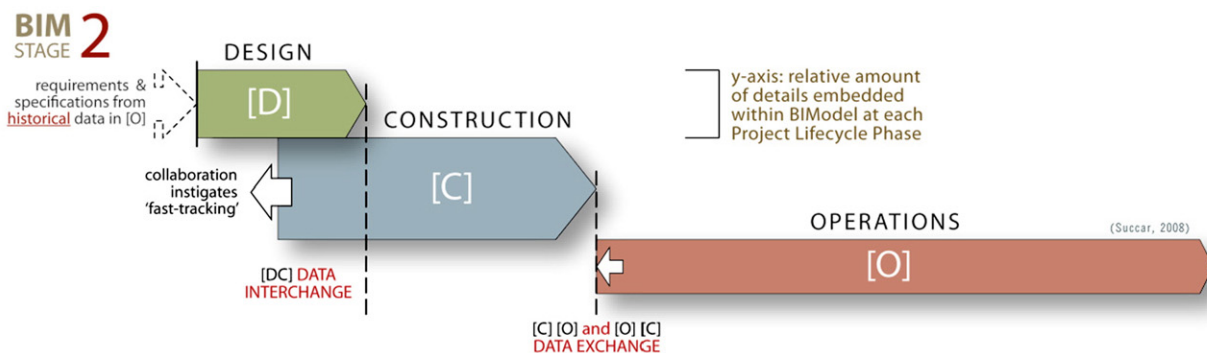**Fig. 10.** Project Lifecycle Phases at BIM Stage 1 — linear model.

Fig. 11. Project Lifecycle Phases at BIM Stage 2 — linear model.

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).

Fig. 15 below identifies some of these BIM Step types in an indicative and non-exhaustive manner.

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 fulfil 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 15504[9], and BIM_CMM[10] 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

---

[7] Capability Maturity Model Integration, refer to http://www.sei.cmu.edu/cmmi/index.html.

[8] People Capability Maturity Model, refer to http://www.sei.cmu.edu/cmm-p/version2/index.html.

[9] ISO/IEC 15504-4:2004 Information technology - Process assessment - Part 4: Guidance on use for process improvement and process capability determination, refer to http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=37462.

[10] The National BIM Standard Capability Maturity Model – BIM Capability Maturity Model, tool can be downloaded from http://www.facilityinformationcouncil.org/bim/pdfs/BIM_CMM_v1.8.xls.
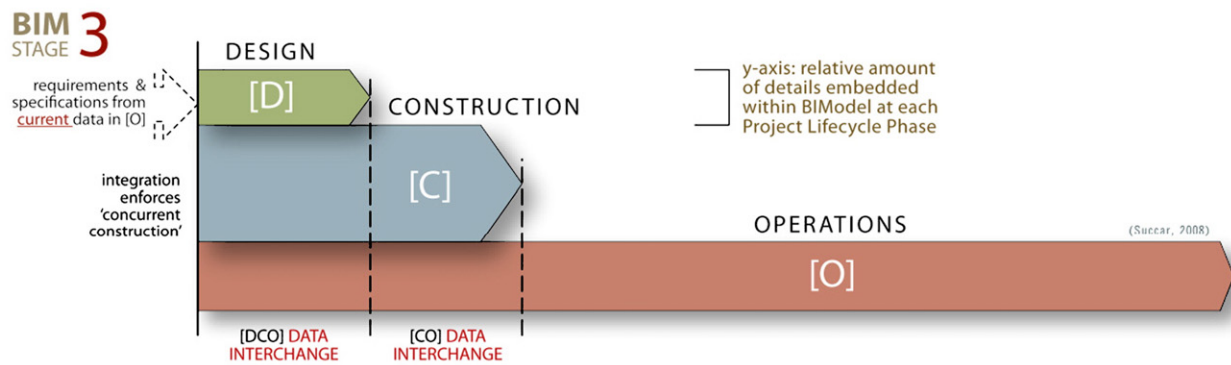
Fig. 12. Project Lifecycle Phases at BIM Stage 3 — linear model.

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 hides 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, Stags 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

Fig. 13. Step Sets leading to or separating BIM Stages — linear model.

between elements" within the domain [30]. It will also assist in the application of knowledge acquisition tools, techniques and methodologies [15], facilitate construction of domain models [73] and knowledge re-use across domains [30].

3.1. The BIM Ontology

For the purpose of representing the BIM Framework, the author has generated a specialised BIM Ontology by amending and reusing existing ones as recommended by Noy and McGuiness (2001). The selection of an existing ontology followed Gruber's criteria for shared ontologies — clarity, coherence, extensibility, minimal encoding bias and minimum ontological commitment — those intended for sharing knowledge and interoperation [30]. Based on these criteria, the BIM Ontology has been developed out of the General Technological Ontology [58,59] and the General Process Ontology [15].

The BIM Ontology comprises of four high level knowledge objects: concepts, attributes, relations and knowledge views (Table 6). This paper briefly discusses these levels in an effort to introduce — without fully exploring — the ontology's role in exposing, representing and further developing the Framework.

This BIM Ontology will be utilised to "analyse domain knowledge, make domain assumptions explicit, separate domain knowledge from the operational knowledge and enable reuse of domain knowledge" [64]. In addition to the specialised ontology, the BIM Framework will utilise 'abstracted representation' [45] to visualise BIM concepts and relations.

4. Visualising the BIM Framework

Driven by the expanse of knowledge domains covered by the BIM research framework, the knowledge transactions are necessarily numerous and complex in nature. Such a wide and varied knowledge scope necessitates the use of visualisation to cope with the amount and complexity involved [76] and offers a systematic way to transfer knowledge to others [23]. Using visualisation or 'graphical representation' expands the usability of data/information/knowledge following "universal laws that are unavoidable and undisputable but can be learned and taught" [8].

4.1. Using knowledge visualisation to represent the BIM Framework

Building Information Modelling includes transactions at the *data*, *information* and *knowledge* semantic levels. Representations of the BIM framework fall within the research area of knowledge visualisation; a merger between information visualisation, didactic techniques, visual cognition and visual communication [23]. Knowledge visualisation benefits from cognitive sciences' experimentation within the field

of expertise and qualitative reasoning. It builds on the depiction of subject matter experts structuring their knowledge through qualitative mental models [69].

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 is also served 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.
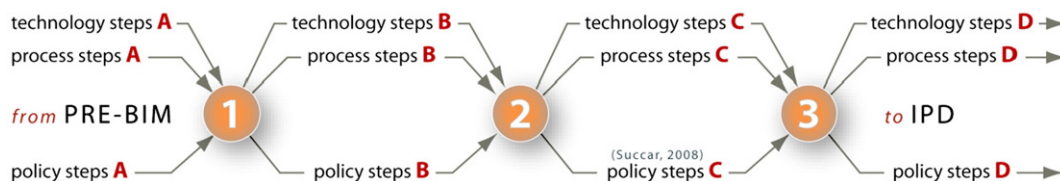

Fig. 14. Step Types leading to or separating BIM Stages — linear model.

BIM Step Types

Steps are identifiable changes and milestones within each BIM Field necessary to meet the requirements of a BIM stage, v1.6 (Succar, 2008)

Technology Step Types

Software te-SO
- Delivery Modes
- Software Prerequisites
- Semantic connectivity
- Main Deliverables
- Modelling and Visualisation levels
- Clash-Detection between drawings files or models
- Code Checking and Compliance (Accessibility, Fire...)
- Plant Design & Construction Sequencing (4th Dimension)
- Product Quantities and Project Costing (5th Dimension)
- Construction and Fabrication Prototyping
- Engineering Analyses: Thermal, Acoustic...
- Interoperability: Proprietary, Open and Non-Proprietary
- Discipline Specific Steps

Hardware te-HA
- Computer hardware - Minimum Requirements
  - Processing power
  - Storage capacities
  - Display properties
- Office Equipment and Peripherals
- Site Equipment (if different from above)
  - Mobility
  - Connectivity

Network te-NT
- Network prerequisites
  - Bandwidth
  - Access control
  - Security
- Information Direction
- Web technologies

Process Step Types

Leadership pr-LD
- Management decisions
  - Vision
  - Culture
- Organisational processes
  - Programme Management
- Communication activities
  - Internal
  - External

Infrastructure pr-IN
- Physical infrastructure
  - Spaces
  - Equipment (non-IT)
- Technological preparations (activities)
- Knowledge assets (non-human)

Human Resources pr-HR
- Knowledge resources
- Skill resources

Products & Services pr-PS
- Products
  - Structured Output
    - Physical Components
    - Virtual Components
  - Non-Structured Output
- Services
  - Modes of delivery

Policy Step Types

Contractual po-CN
- Responsibilities
- Rewards
- Risk allocation
  - Insurance

Regulatory po-RG
- Building regulations
  - Codes & Standards
  - Performance
  - Sustainability
- Project guidelines
  - Best practices
  - Bench marks
  - Classification Systems

Preparatory pr-PP
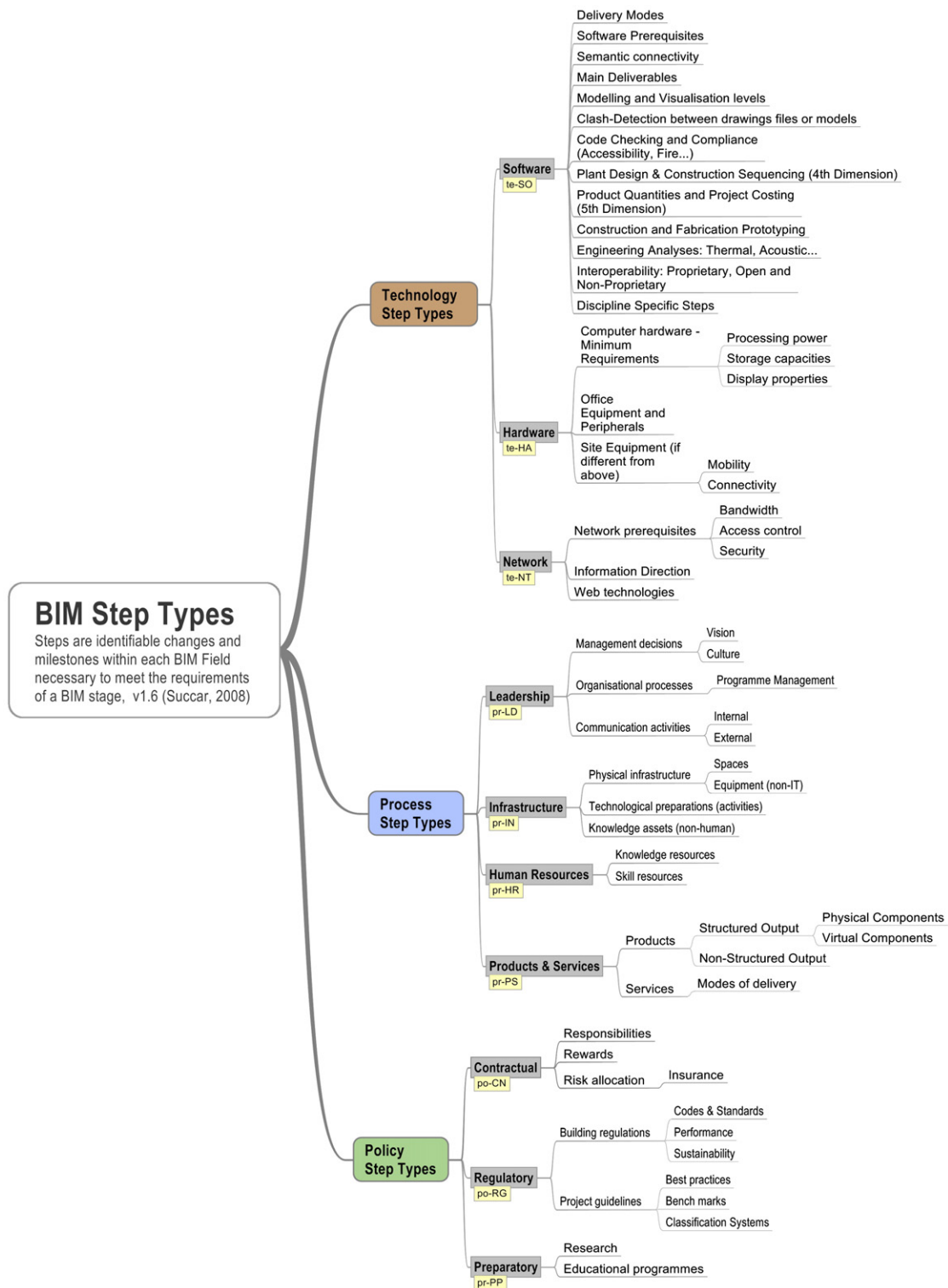- Research
- Educational programmes

Fig. 15. Indicative and non-exhaustive list of BIM Step Types — mind map view.

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
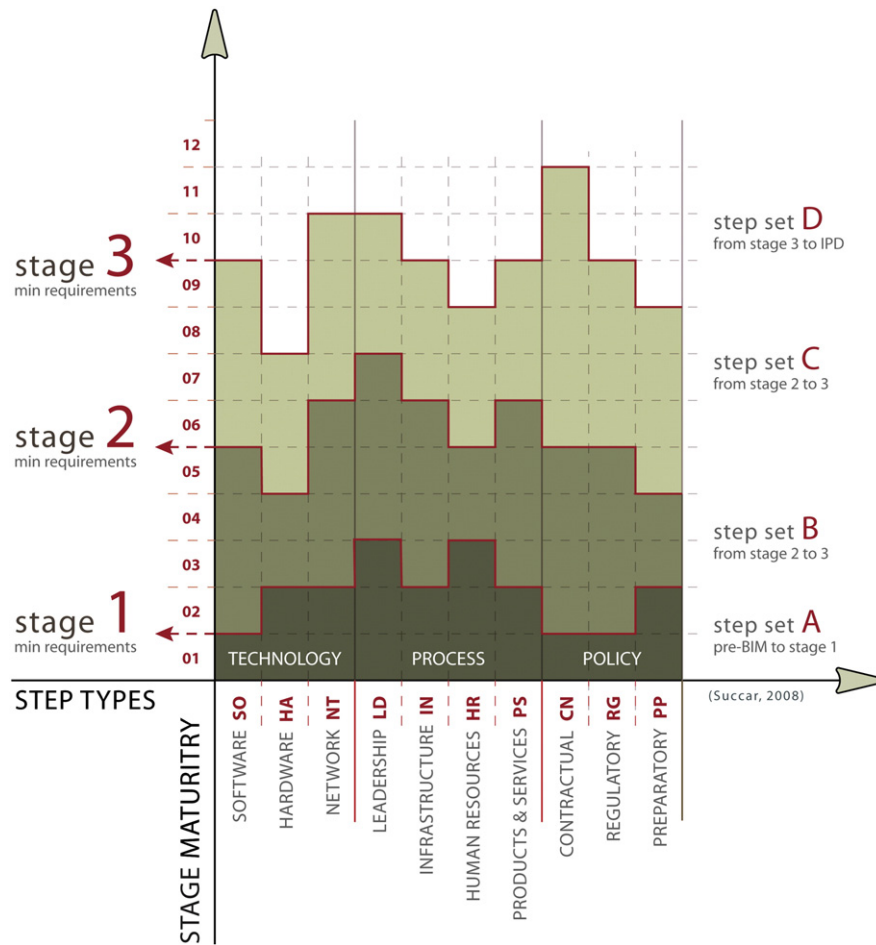
Fig. 16. Generic BIM Steps requirements for a BIM Stage — matrix view.

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).
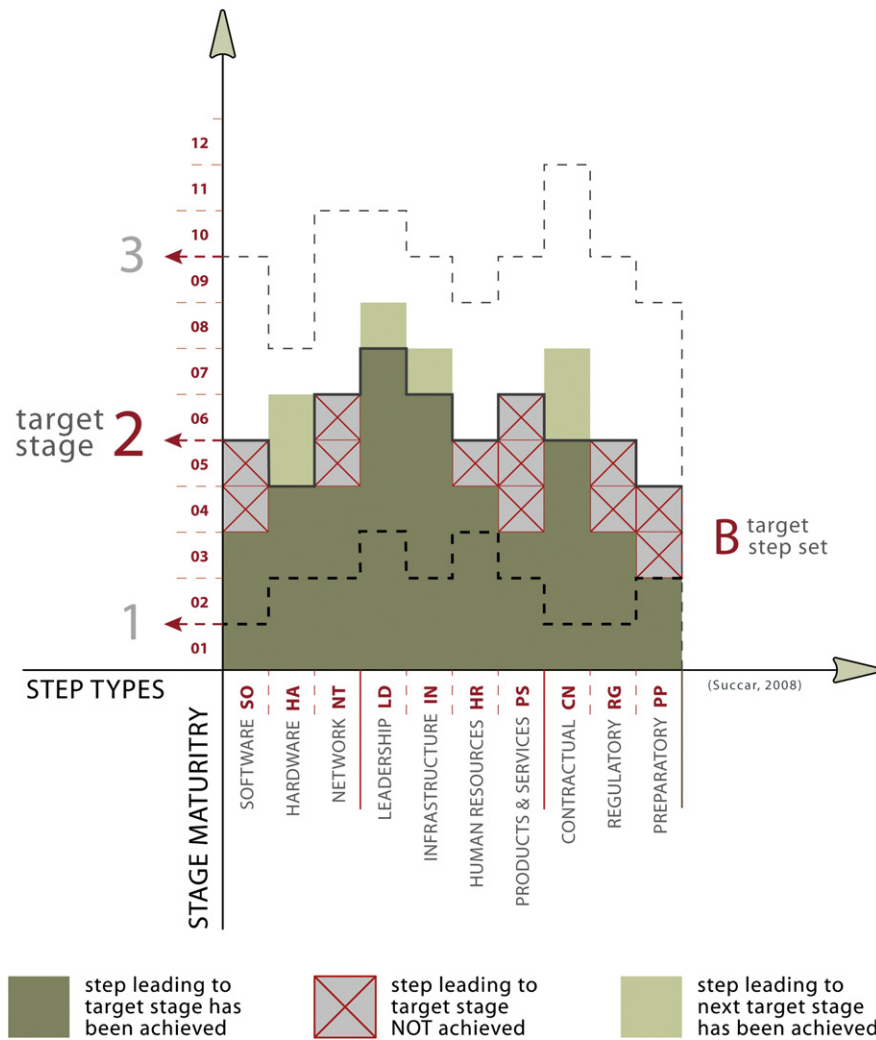
Fig. 17. Hypothetical assessment of an organisation using BIM Steps — matrix view.

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
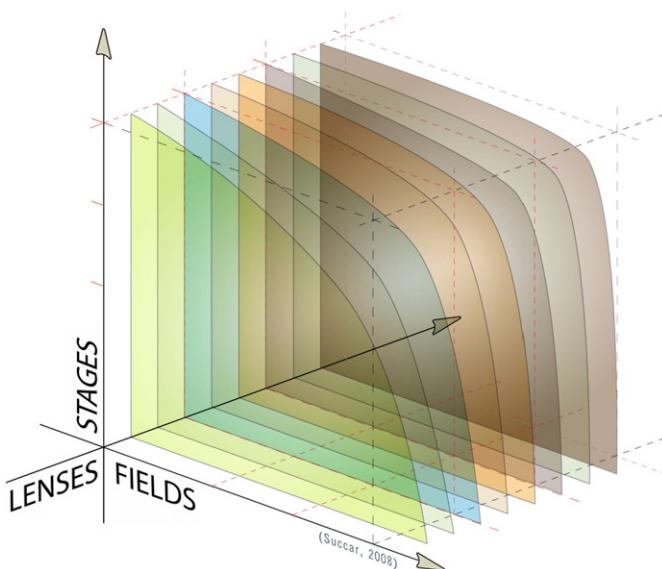

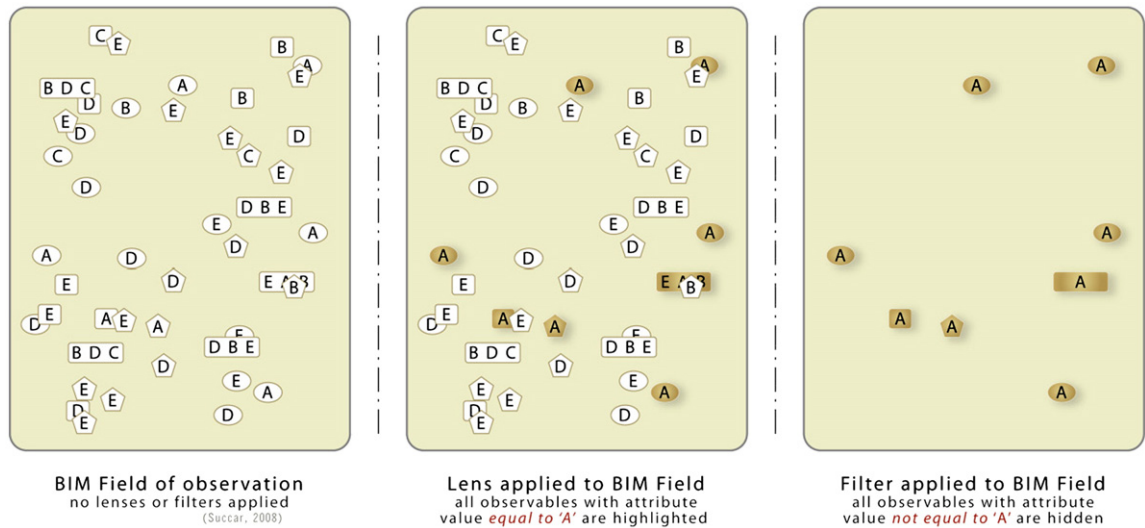**Fig. 18.** BIM Lenses — tri-axial model.

Fig. 19. Difference between BIM Lenses and Filters — tri-pane model.

publications. The BIM Framework is "an integrated framework [incorporating] different approaches to information within a consistent 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

References

[1] AGC, The Contractors' Guide to BIM — Edition 1, Associated General Contractors of America, 2006 (AGC).
[2] AIA, Integrated project delivery: a guide, AIA California Council, 2007.
[3] V.A. Anfara, N.T. Mertz, Theoretical frameworks in qualitative research, SAGE Publications, 2006.

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

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

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.
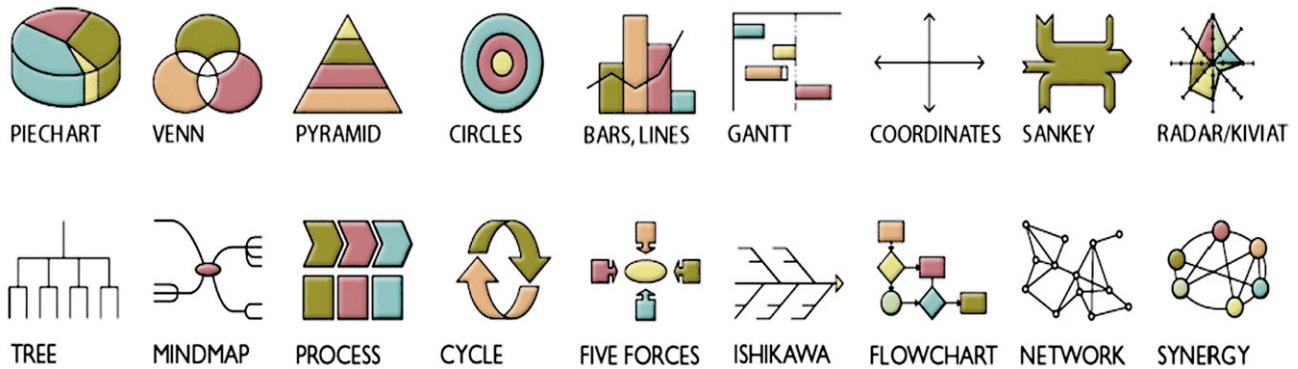
Table 6
Knowledge objects pertaining to BIM Ontology

Concepts			
Agents	Constraints	Deliverables	Equipment
Events	Examples	Functions	Human resources
Incentives	Information resources	Knowledge areas	Locations
Mental concepts	Organisational units	Physical phenomena	Products
Recommendations	Requirements	Results	Roles
Social	Social phenomena	Software agents	Software applications
Tasks	Triggers		
Attributes			
Category	Number	Link	Text
Relations			
Part of	Has part	Has expertise	Known by
Performs	Performed by	Uses	Used by
Supplies	Supplied by	Located in	Location of
Resource for	Has resource	Produces	Produced by
Owns	Owned by	Causes	Caused by
Runs	Run by	Attends	Attended by
Has function	Function of	Documented in	Describes
Requires	Required by	Consults	Consulted by
Made of	Material for	Followed by	Involves
Has role	Has contact	Applicable to	Occupied by
Affects	Linked to	Has authority over	Is empowered by
Validates	Is validated by		
Knowledge views			
Knowledge document	Knowledge matrix	Knowledge model	Knowledge store

Fig. 20. Sample visualisation models — adapted from Eppler and Burkhard [23].

[4] Autodesk, Parametric Building Modeling: BIM's Foundation, http://images.autodesk.com/adsk/files/Revit_BIM_Parametric_Building_Modeling_Jun05.pdf, last accessed 12 June, 2006.
[5] Bentley, Build As One — BIM is a new way of approaching the design and documentation of building projects, http://www.bentley.com/en-US/Promo/Build+As+One/What+is+it/, last accessed 12 June, 2006.
[6] Bentley, Does the Building Industry Really Need to Start Over - A Response from Bentley to Autodesk's BIM-Revit Proposal for the Future, 2003, Last accessed July 12, 2008, from http://www.laiserin.com/features/bim/bentley_bim_whitepaper.pdf.
[7] P. Bernstein, Integrated Practice: It's Not Just About the Technology, 2005, Last accessed 9, 2008, from http://www.aia.org/aiarchitect/thisweek05/tw0930/tw0930bp_notjusttech.cfm.
[8] J. Bertin, Matrix theory of graphics, Information Design Journal 10 (1) (1997) 5–19.
[9] BIPS, Digital construction, 3D Working Method, Danish Government, 2008.
[10] N.W.H. Blaikie, Designing Social Research: The Logic of Anticipation, Polity Press, 2000.
[11] E.D. Bono, Lateral Thinking; Creativity Step by Step, Harper & Row, New York, 1970.
[12] S.K. Card, J. Mackinlay, The structure of the information visualization design space, IEEE Symposium on Information Visualization, Phoenix, AZ, USA, vol. 125, 1997, pp. 92–99.
[13] Clemson, Definition of Policy, Clemson University — Office of Research Compliance, Definitions of Research Compliance Terms, 2007, Last accessed 14 April 2007, from http://www.clemson.edu/research/orcSite/orcIRB_DefsP.htm.
[14] CONCUR, Concurrent Design and Engineering in Building and Civil Engineering — A project sponsored by the European Commission under Brite-Euram 3 (GROWTH) programme, 2001, Last accessed July 11, 2008, from http://cic.vtt.fi/projects/concur/.
[15] H. Cottam, Ontologies to assist process oriented knowledge acquisition (draft), SPEDE, Rolls-Royce plc 1999 covered by SPEDE IPR agreement, 1999.
[16] CRC-CI, National Guidelines and Case Studies 2007-002-EP, http://www.construction-innovation.info/index.php?id=1083, last accessed July 8, 2008
[17] CWIC, The building technology and construction industry technology roadmap, in: A. Dawson (Ed.), Collaborative Working In Consortium, Melbourne, 2004.
[18] T.H. Davenport, Process Innovation: reengineering work through information technology, Harvard Business School Press, 1992.
[19] N.K. Denzin (Ed.), Sociological Methods: A Sourcebook, 2nd ed., McGraw-Hill, New York, 1978.
[20] E-BOUW, BIM — Building Information Model(ling), http://wiki.e-bouw.org/index.php?title=BIM_—_Building_Information_Model%28ling%29, last accessed July 10, 2008.
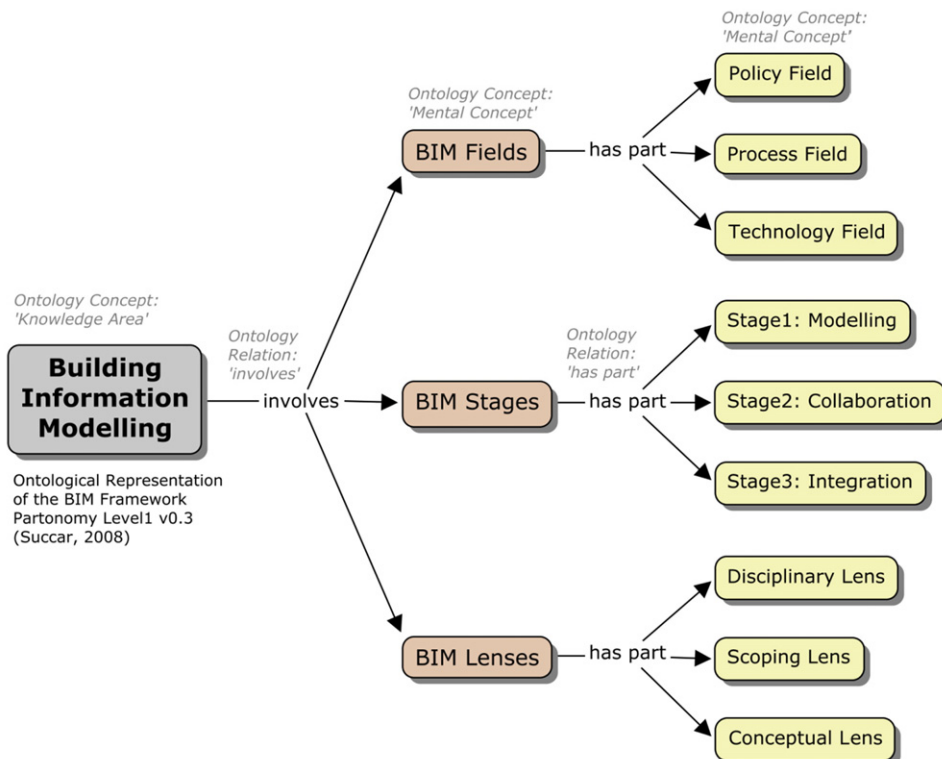
Fig. 21. Knowledge view using Concept Maps and BIM Ontology.

Table 7
Summary matrix of BIM Framework deliverables

Deliverables	Macroscopic: industry level	Mesoscopic: project level	Microscopic organisation level
	Multiple disciplines	Multiple organisations	Individuals and teams
Educational deliverables	Generating BIM Literacy Guidelines, producing learning tools and collating case studies — through publication of a BIM textbook	Identifying BIM Educational Deliverables according to organisational types and delivery modes — example: identifying vocational, tertiary, industry and industry associations' BIM educational deliverables	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
Industry deliverables	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	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	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

[21] C. Eastman, Building Product Models: Computer Environments Supporting Design and Construction, CRC Press LLC, Florida, USA, 1999.
[22] A. Edgar, NBIMS — Overview of Building Information Models presentation, 2007, Last accessed July 12, 2008, from http://www.facilityinformationcouncil.org/bim/docs/BIM_Slide_Show.ppt.
[23] M. Eppler, R. Burkhard, Knowledge visualization, in: D.G. Schwartz (Ed.), Encyclopedia of Knowledge Management, Idea Group Reference, 2005, pp. 551–560.
[24] FIATECH, Capital Projects Technology Roadmap, http://www.fiatech.org/projects/roadmap/cptri.htm, last accessed April 04, 2007.
[25] M. Fischer, Introduction to 4D Research, 2001, Last accessed June 11, 2006 from http://www.stanford.edu/group/4D/.
[26] M. Fischer, J. Kunz, Virtual design and construction: themes, case studies and implementation suggestions, Center for Integrated Facility Engineering, Stanford University, California, USA, 2005.
[27] T. Froese, Future directions for IFC-based interoperability, ITCON 8 (Special Issue IFC — Product models for the AEC arena), 2003, pp. 231–246.
[28] T. Froese, in: K.R. Molenaar, P.S. Chinowsky (Eds.), Future directions for model-based interoperability, Construction Research 2003, vol. 120, ASCE, 2003, p. 101.
[29] Graphisoft, Virtual Building concept, http://www.graphisoft.com/products/virtual_building/, last accessed June 12, 2006.
[30] T.R. Gruber, Toward principles for the design of ontologies used for knowledge sharing? International Journal of Human–Computer Studies 43 (5–6) (1995) 907–928.
[31] T.R. Gruber, A translation approach to portable ontology specifications, Knowledge Acquisition 5 (2) (1993) 199–220.
[32] GSA, The national 3D–4D-BIM program, U.S. General Services Administration — Public Buildings Service, Office of the Chief Architect, Washington, DC, 2006.
[33] M.R. Halfawy, T. Froese, Modeling and implementation of smart AEC objects: an IFC perspective, CIB w78 conference — Distributing Knowledge in Building, Aarhus School of Architecture, Denmark, 2002, pp. 1–8.
[34] K. Hampson, P. Brandon, Construction 2020: A Vision of Australia's Property and Construction Industry, CRC Construction Innovation, Australia, 2004.
[35] R.M. Henderson, K.B. Clark, Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms, Administrative Science Quarterly 35 (1) (1990) 9.
[36] R.R. Hoffman, G. Lintern, Eliciting and Representing the Knowledge Experts, The Cambridge Handbook of Expertise and Expert Performance, Cambridge University Press, New York, 2006.
[37] C.W. Holsapple, K.D. Joshi, Knowledge Management Ontology, in: D.G. Schwartz (Ed.), Encyclopedia of Knowledge Management, Idea Group Reference, 2006, pp. 397–402.
[38] IAI, Building Smart: Project Collaboration through Virtual Design and Construction, 2005, Last accessed 12 June, 2006, from http://buildingsmart.org.au/.
[39] M. Ibrahim, R. Krawczyk, The level of knowledge of CAD objects within the building information model, ACADIA 2003 Conference, Muncie, IN, USA, 2003, pp. 173–177.
[40] M. Ibrahim, R. Krawczyk, G. Schipporeit, A web-based approach to transferring architectural information to the construction site based on the BIM object concept, CAADRIA 2004 Conference, Seoul, South Korea, 2004, pp. 1–10.
[41] IEEE, IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries, Institute of Electrical and Electronics Engineers, New York, 1990.
[42] M.E. ILAL, The quest for integrated design system: a brief survey of past and current efforts, Middle East Technical University Journal of the Faculty of Architecture (METU JFA) 24 (2) (2007) 10.
[43] A. Jaafari, Concurrent construction and life cycle project management, Journal of Construction Engineering and Management 123 (4) (1997) 427–436.
[44] V. Jupp (Ed.), The Sage dictionary of social research methods, SAGE, Lomdon, 2006.
[45] D. Kao, N.P. Archer, Abstraction in conceptual model design, International Journal of Human–Computer Studies 46 (1) (1997) 125–150.
[46] L. Khemlani, Academic Research in Architectural Computing, 2005, Last accessed November 14, 2008 from http://www.aecbytes.com/buildingthefuture/ArchComputingResearch.htm.
[47] A.G. Kimmance, An integrated Product and Process Information Modelling System for On-Site Construction, Thesis (Ph. D.) — University of Loughborough, UK, 2002.

[48] A. Kiviniemi, V. Tarandi, J. Karlshøj, H. Bell, O.J. Karud, Review of the Development and Implementation of IFC compatible BIM, , 2008 Erabuild.
[49] B. Kosovac, T.M. Froese, D.J. Vanier, Integrating heterogeneous data representations. Model-Based AEC-FM Systems, CIT 2000 — The CIB-W78, IABSE, EG-SEA-AI International Conference on Construction Information Technology, vol. 2, Icelandic Building Research Institute, Reykjavik, Iceland, 2000, pp. 556–567.
[50] M.A.T. Le, F. Mohus, O.K. Kvarsvik, M. Lie, The HITOS project — a full scale IFC test, ework and ebusiness in architecture, Engineering and Construction: Proceedings of the 6th European Conference on Product and Process Modelling September 13–15 2006, Taylor & Francis Group, Valencia, Spain.
[51] A. Lee, S. Wu, G. Aouad, R. Cooper, J. Tah, nD Modelling Roadmap: A Vision for nD-Enabled Construction, University of Salford, Salford, 2005.
[52] A. Lee, S. Wu, A.J. Marshall-Ponting, G. Aouad, R. Cooper, I. Koh, C. Fu, M. Betts, M. Kagioglou, M. Fischer, Developing a Vision of nD-Enabled Construction, University of Salford, Salford, 2003.
[53] J. Liaserin, Building Information Modeling — The Great Debate, 2003, Last accessed July 12, 2008, from http://www.laiserin.com/features/bim/index.php.
[54] J. Liaserin, Comparing Pommes and Naranjas, 2002, Last accessed November 12, 2005, 2005, from http://www.laiserin.com/features/issue15/feature01.php.
[55] T. Liebich (Ed.), Standard analysis — Current AEC situation — Building Models, European network for product and project data exchange, e-work and e-business in Architecture, Engineering and Construction, IST — 2001–32035, January 2002.
[56] R.S. Michalski, in: S.S. Shapiro (Ed.), Concept Learning, Encyclopedia of Artificial Intelligence, vol. 1, Wiley, New York, 1987, pp. 185–194.
[57] R.S. Michalski, R.E. Stepp, in: S.S. Shapiro (Ed.), Clustering, Encyclopedia of Artificial Intelligence, vol. 1, Wiley, New York, 1987, pp. 103–111.
[58] N.R. Milton, Knowledge Acquisition in Practice: A Step-by-step Guide, Springer, London, 2007.
[59] N.R. Milton, Specification for the General Technological Ontology (GTO), 2007, Last accessed 24 September, 2007 from http://www.pcpack.co.uk/gto/notes/files/GTO%20Spec%20v4.doc.
[60] M. Minsky (Ed.), A Framework for Representing Knowledge, McGraw-Hill, New York, 1975.
[61] S. Mustière, J.D. Zucker, L. Saitta, Cartographic generalization as a combination of representing and abstracting knowledge, Proceedings of the seventh ACM international symposium on Advances in geographic information systems, 1999, pp. 162–164.
[62] NIST, Cost analysis of inadequate interoperability in the U.S. capital facilities industry, in: A.C. Gallaher, J.L. Dettbarn Jr., L.T. Gilday (Eds.), M.P.O.C, National Institute of Standards and Technology, 2004.
[63] NIST, National building information modeling standard — version 1.0 — part 1: overview, principles and Methodologies, National Institute of Building Sciences, 2007.
[64] N.F. Noy, D.L. McGuinness, Ontology Development 101: A Guide to Creating Your First Ontology, 2001, Last accessed 15 April, 2007 from http://www.lsi.upc.edu/~bejar/aia/aia-web/ontology101.pdf.
[65] Oxford, "Technology" — Compact Oxford English Dictionary, http://www.askoxford.com/concise_oed/technology?view=uk, last accessed 15 April 2007.
[66] M.Q. Patton, Qualitative evaluation and research methods, 2nd ed.Sage, Newbury Park, California, 1990.
[67] H. Penttilä, Describing the changes in architectural information technology to understand design complexity and free-form architectural expression, ITCON 11 (Special Issue The Effects of CAD on Building Form and Design Quality), 2006, pp. 395–408.
[68] M. Pfitzner, M. Bög, F. Neuberg, M. Bögl, H. Jan Tulke, O. Nummelin, Y.I.T., P. Benning, Bouygues, European integrated project inpro — overview, A consortium of participants, 2007.
[69] Z.W. Pylyshyn, in: S.S. Shapiro (Ed.), Cognitive science, Encyclopedia of Artificial Intelligence, vol. 1, Wiley, New York, 1987, pp. 120–124.
[70] S. Santini, Using language more responsibly, Computer 35 (12) (2002) 126, 128.
[71] Senate, SENATE Properties BIM Guidelines, http://www.senaatti.fi/document.asp?siteID=2&docID=588, last accessed July 10, 2008.
[72] STAND-INN, Integration of performance based building standards into business processes using IFC standards to enhance innovation and sustainable development, http://www.standards.eu-innova.org/Pages/StandInn/Reports.aspx, last accessed 11 July, 2008.

[73] R. Studer, V.R. Benjamins, D. Fensel, Knowledge engineering: principles and methods, Data & Knowledge Engineering 25 (1–2) (1998) 161–197.

[74] A. Tashakkori, C. Teddlie, Mixed Methodology: Combining Qualitative and Quantitative Approaches, Sage, 1998.

[75] J. Taylor, R.E. Levitt, Inter-organizational knowledge flow and innovation diffusion in project-based industries, 38th International Conference on System Sciences, IEEE Computer Society, Hawaii, USA, 2005.

[76] S.O. Tergan, knowledge with computer-based mapping tools, in: D. Lassner, C. Mc Naught (Eds.), ED-Media 2003 World Conference on Educational Multimedia, Hypermedia & Telecommunication Honolulu, HI: University of Honolulu, 2003, pp. 2514–2517.

[77] USACE, US Army Corps of Engineers, Engineer Research and Development Center - Building Information Modeling: A Road Map for Implementation To Support MILCON Transformation and Civil Works Projects within the U.S. Army Corps of Engineers, USACE, Washington, DC, 2006.

[78] USCG, BIM user guides — presentation from the 2nd congress on digital collaboration in the building industry, AIA Buiding Connections, 2005.

[79] M. Uschold, Building ontologies: towards a unified methodology, expert systems '96, the 16th Annual Conference of the British Computer Society Specialist Group on Expert Systems, Cambridge, UK, 1996.

[80] R. Van der Brugge, H. De Haan, Complexity and Transition Theory, Lof der Verwarring, Engels, Rotterdam, 2005.

[81] P. Wilkinson, SaaS-based BIM, 2008, Last accessed July 12, 2008 from http://www.extranetevolution.com/extranet_evolution/2008/04/saas-based-bim.html.

Bilal Succar is an integrated practice consultant and the director of ChangeAgents AEC, an organisation specialising in BIM strategies, process change and knowledge management within the Architecture, Engineering, Construction and Operations (AECO) industry. He is currently pursuing a PhD in Building Information Modelling, Interoperability and Process Integration at the University of Newcastle, Australia. Bilal is also a researcher at RMIT University and is part of a team working to advance the research, education and delivery of BIM concepts. Bilal is a member of the Conseil International du Bâtiment (CIB) and an associate member of the Australian Institute of Architects (AIA).