Editorial: A PLM perspective of BIM research initiatives

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1 Introduction

Rapid technological changes, continuous innovation, global competition and low levels of productivity are some of the challenges that have recently compelled the architecture, engineering construction and operations (AEC/O) sector to react by focusing on improving the integration of people, processes, and information across the life of built assets. Developing and operating buildings and infrastructure in this scenario requires that data and information about a facility's delivery and operational processes are accessible to actors participating across the value network, including clients/developers, architects, engineers, contractors, suppliers, and facility/asset managers. Such levels of integration are often conceived around the concept of building information modelling (BIM). BIM is a 3D object-oriented approach to creating, managing and using product and product-related information. BIM not only supports virtual design and construction, but also provides a foundation for deploying information and knowledge management systems in the operations and maintenance (O&M) phase. Whilst many advances have been made in the application of BIM, limitations to managerial, technological and collaborative capabilities persist throughout project and operational phases of a facility's lifecycle. The continued evolution of BIM therefore relies on the development and adoption of new business models based on an integrated lifecycle approach (Jupp and Singh, 2014).

Such notions of BIM, as an integrated whole building lifecycle solution, reflects a relative proximity to the objectives of product lifecycle management (PLM). PLM is a "strategic business approach" (CIMdata, 2016) for the effective management and use of corporate intellectual capital, and has gained acceptance as a holistic business concept. In complex, discrete manufacturing industries, such as the aerospace and automotive sectors, being an innovative company, means not only designing innovative products, it also means improving the processes a business uses to realise its products and how these processes can support the product lifecycle (CIMdata, 2016). In complex manufacturing, PLM is therefore a business necessity capable of supporting innovation whilst meeting the associated challenges of product customisation and traceability, competition and globalisation, shorter product development and delivery timescales, and ever tighter regulations and legislation (Corallo et al., 2013).

The influence of PLM concepts, methods and technologies on the construction industry and recent maturity in the deployment of BIM in the AEC/O sector is stimulating changes in assumptions about data, information and knowledge management across the building lifecycle; as a consequence it is also changing the way that AEC/O companies approach business processes. Understandings of the PLM concept and its systems approach are also increasing across AEC/O research domains; for example, the integration of enterprise resource planning (ERP) and PLM systems via BIM (Holzer, 2014), industrialised construction (Bonev et al., 2015), BIM for O&M (Yalcinkaya and Singh, 2014; Codinhoto and Kiviniemi, 2014), and 'closing the loop' (Jupp, 2013) have been explored through the PLM lens. Whilst, these papers reflect a common end point with PLM – surrounding the management and traceability of information flows throughout lifecycle phases – the systems approach and level of integration achieved in PLM deployment has matured in the last decade; from a set of engineering-oriented tools into integrated enterprise-level solutions (Stark, 2015).

However, the proximity of BIM to PLM has not been realised in practice and remains largely an aspiration in the AEC/O sector. Applications of BIM are currently rooted at the project level and therefore a lack of strategic business perspective envisioned for the whole building lifecycle persists in industry. In contrast, PLM serves project, operations, and business objectives via consistent integration of different ICT systems (e.g., CAD, CAM, PDM, etc.) that contain data, information and knowledge about their products (Stark, 2015). PLM 'systems' are thus the enabling technology for PLM, serving as a central hub for product data so as to support collaborative design and production processes (PLM, 2016). This central information hub therefore supports the use, traceability and management of information across the extended enterprise, i.e., across all actors involved in the realisation, use and operations of the product (Stark, 2015). Unlike PLM, applications of BIM are not seen as a holistic business concept.

To advance BIM towards an enterprise-level solution requires a different approach to current business models. Such change is complex, and modifying or revolutionising AEC/O business models face numerous challenges. Challenges surround addressing how new business models will consider the whole building lifecycle – from procurement to schematic and detailed design, to fabrication and construction, to operations, maintenance, and decommissioning. Further, if AEC/O firms are to map, optimise and manage information flows effectively, new business models must also consider these phases relative to the multiple sources of data they generate. New approaches must also consider design, construction and operational data relative to project and organisational processes and different combinations of product and service offerings. Overlaid onto these challenges change must be considered relative to the structure of the industries.

Fragmentation across the AEC/O sector (e.g., between people, processes, protocols, information, tools, etc.) highlight the significance of the challenges to developing and implementing new approaches business.

2 Mapping PLM capabilities and BIM research initiatives

The AEC/O sector faces a range unique integration challenges relative to the creation, use, and management of building and building-related information. Project-centric and highly fragmented, companies in the AEC/O sector must overcome a range of barriers related to people, products, and processes that exist across multiple disciplines and organisational boundaries. Actors across the project enterprise at different phases of the building lifecycle will typically create, use and manage disparate forms of data, information, processes and workflows. Recent research efforts have advanced the concept and application of BIM at project and O&M levels, reflecting both enterprise and lifecycle perspectives. A useful categorisation of this research is based on the areas of development of BIM capabilities, including: managerial, technological; and collaborative. Within each area, a number of (inter-related) research topics are identified, including research that has advanced:

1. *Managerial capabilities* across the (extended) enterprise and/or lifecycle phases to support: integrated project and business processes/workflows, new business strategies and supply chain management (SCM), new approaches to data governance, and new ways to create value across the network of AEC/O actors.

2. *Technological capabilities* surrounding the: definition of the building information backbone, BIM tools and ICT infrastructures, advances in interoperability, information standards and requirements, definition of primary and secondary information types, as well as traceability and long-term archiving requirements.

3. *Collaborative capabilities* including the: integration of people, processes and information, processes supporting information sharing and coordination requirements, and cooperative relations across the extended enterprise.

Whilst a growing number of research efforts are taking an enterprise and/or lifecycle perspective of BIM and reflecting some of the defining aspects of PLM, there is still a lack of research that conceives of BIM in terms of a common, collaborative information hub. Previous research work surrounding BIM has largely focused on discipline-specific tools, representations and information, neglecting the integration of processes and workflows within companies as well as across collaborating firms from the perspective of through-life information management. By contrast, research on PLM in the complex discrete manufacturing sectors has focused on addressing the overall business process, identifying and streamlining workflows across the extended enterprise, and managing high-fidelity data throughout the life of the product. In the following review, we structure our discussion of BIM research efforts that relate to the following six defining aspects of PLM identified by Corallo et al. (2013); that is advancing the concept of BIM so as to better support:

1 strategic business approach
2 phases of the lifecycle
3 unique and timed data sources
4 consistency, traceability, and long-term archiving of data
5 integration of people, processes, and technologies
6 collaboration across the extended enterprise.

2.1 BIM as a strategic business approach

According to the most popular definitions and descriptions of BIM, it is not only as a technology but also as a process. For example, Azhar (2011, p.1) provides a definition of BIM, defining it as a "virtual process that encompasses all aspects, disciplines, and systems of a facility within a single, virtual model, allowing all design team members (owners, architects, engineers, contractors, subcontractors, and suppliers) to collaborate more accurately and efficiently than using traditional processes". In a similar vain, Eastman et al. (2011, p.8) describe BIM as "both as a multi-disciplinary design, analysis, construction, and facilities management technology, as well as the harbinger of dramatic process changes". Current approaches to BIM in practice are in reality more limited than these descriptions. Whilst the concept of BIM reflects similar lifecycle objectives to PLM, current approaches to deployment lack the technological interfaces and governance structures to support "a shared platform for the creation, organization, and dissemination of all product-related knowledge across the extended enterprise" (Ameri and Dutta, 2005). This highlights a significant differentiator between BIM and PLM.

The research literature surrounding BIM more commonly reflects integration relative to the sharing of information models during the project delivery phases, with all stakeholders editing or retrieving information from commonly shared models. To achieve this even at the project level, requires change to well-established processes, working routines, information infrastructures, organisational roles, contractual and collaborative practices, and importantly changes to mindsets (Gal et al., 2008). The building process has therefore largely been reconsidered, with the development of new models of project delivery based on higher levels of integration. For example, the American Institute of Architects (AIA) (2007) California Council's specification of the 'integrated project delivery' (IPD) model presents a method for integrating people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants. However, this level of project 'rethinking' does not account for AEC/O business processes beyond building handover and lacks a holistic approach to the building lifecycle. New approaches to 'service-led construction projects', have explored alternative business models but mostly relative to construction firms. Leiringer and Bröchner (2010) in their editorial of a special issue of construction management and economics discuss the strategic implications for construction firms shifting from product manufacturing to providers of through-life service offerings. Galera-Zarco et al. (2014) explore case studies in the servitisation of project-based construction firms via a knowledge management lens, where technological innovation is a key. The authors claim that a 'full' through-life approach can decrease the likelihood of problems stemming from a lack of information about previous stages.

However, Kiviniemi (2011) identifies two key obstacles to advancing BIM towards alternative business approaches that foster higher levels of integration through-life and across supply chains, including the barriers of old work processes and low-bid business models. Old work processes are based on “the use of documents, not on the necessary information flows between project participants” [Kiviniemi, (2011), p.133]. Mapping, optimising and managing information flows is crucial to process efficiency given the multiple sources of data that must be integrated throughout project and operational phases. To optimise information flows, project and organisational processes must be described, simulated and optimised. Further, low-bid business models “do not reward actual added value or optimisation of the whole project, but support sub-optimisation on the company level” [Kiviniemi, (2011), p.133]. An organisation’s internal processes are therefore strongly connected to the governance structures and technical interfaces that surround them and the changes to fundamental business processes require a new mindset and collaboration of multiple actors within the organisation to create what Kiviniemi (2011) terms a new ‘business eco-system’. This highlights the role of big data and business analytics (Whyte et al., 2016) in the AEC/O sector and the necessity for new technologies and capabilities in the way information is considered so that organisations can draw new insights from the flow of information as well as its content (Williams et al., 2014) relative to projects, people, products, and processes.

2.2 BIM and the building lifecycle

The value of BIM has long been argued to derive from its ability to support the whole building lifecycle by providing integrated and data rich visual environments (Azharet al., 2008). Managerial, technological, and collaborative capabilities spanning building lifecycle have been developed, including for example, model interrogation for compliance checking, fault finding and accurate reporting; greater levels of accessibility to product-related data including manufacturing, warranty, maintenance, legislative and statutory compliance data via the 3D model; automation of building management services; and 3D scenario analysis for design and refurbishment planning (López et al., 2016). Systems integration whereby the BIM model is integrated with O&M software, [e.g., with the building’s computerised maintenance management system (CMMS), computer-aided facility management (CAFM), building automation system (BAS), and ERP system] supports a range of benefits. In linking the model to these systems, the benefits of BIM to information management through-life surround increases in productivity, efficiency and effectiveness. They have been shown to include: e.g.,: accurate data management with low data capture and operational costs; O&M performance improvement where more effective and efficient data management has allowed the prevention of problems, faster analysis, and quicker responses in corrective maintenance; greater levels of coordination and communication; improvement in the accuracy of data (compared to manual) information handover processes; efficiency in the execution of corrective maintenance orders in terms of the speed of accessing data and locating interventions (López et al., 2016).

Thus, developing a holistic approach to BIM requires the capacity to create, use and manage information across all phases of the building lifecycle, and closing the loop between the asset’s ‘beginning of life’ and ‘end of life’ (Jupp, 2013). However, there are significant gaps in the technical interfaces between lifecycle phases to support the production, use, and reuse of data and information. In the PLM domain, this is known as the information 'backbone', and the structure of this backbone is conceived in a fundamentally different way when compared to BIM. In a recent article, Boton et al. (2016) explore this issue in a comparison between PLM and BIM from the standpoint of the 'product structure' as defined in discrete manufacturing, i.e., that the PS describes hierarchically, using items, how a product can be generated from assemblies, sub-assemblies, and components. The product structure is therefore able to store technical objects, associated product data and customised product families in a dynamic way according to different 'views' of or uses of the model. Two major shortcomings in current approaches to BIM are identified (Boton et al., 2016), namely:

1. that assembly data and product hierarchies are not typically linked or represented with product family data
2. there is a lack of capability in terms of representing (and modelling methods for representing) model progression with the corresponding development of product structure throughout lifecycle phases.

Boton et al. (2016) demonstrate the lack of an equivalent product structuring (and bill of materials) concept and the need to explicit a similar one to support an information-centric approach to management in the AEC/O sector.

Several authors have described the phases of the building lifecycle relative to the managerial, technological and collaborative capabilities surrounding BIM technologies and processes. A BIM framework developed by Succar (2009) is based on the definition of fields, stages, steps (across phases of the building lifecycle), and lenses is described. The AIA's conception of IPD (above) is another example aimed at managing a lifecycle approach to BIM. The AIA's conception of IPD details the integration of people, systems, business structures and practices into a collaborative process aimed at optimising project results, increasing the value to the owner, reducing waste, and maximising efficiency through all project phases (American Institute of Architects, 2007). Whilst acknowledging the O&M phase, IPD lacks detail in this regard. Other initiatives including the UK Taskforce Guidelines for Employer Information Requirements (BIM Task Group, 2013) define requirements and processes for 'delivery drops' across all phases of the project lifecycle, accounting for asset information requirements across planning, design, construction, and commissioning so as to provide information to facility owners and operators.

2.3 BIM and unique and timed data sources

One of the fundamentals of PLM solutions is ensuring robust integration and storage of product and product-related data in 'unique' and 'timed' sources (Corallo et al., 2013). Like PLM, BIM extends the scope of data and information management from 3D CAD data (and associated information) to a larger perspective, which may encompass, e.g., 4D, 5D, O&M, workflow and process related data. The need for 'uniqueness' therefore emerges from fragmented product data and information that resides not only in different AEC/O organisations and organisational departments (e.g., engineering, IT, sales, etc.). This means that information relating to the building's design and construction, as well as any product-related data connected to the 3D model (e.g., asset catalogues and O&M manuals, etc.), must be integrated and stored. Whilst BIM has sought to eliminate the amount of data duplicated and increase the consistency of information about the building, AEC/O organisations still model the same data in different formats. Data produced over the building's lifecycle can remain fragmented in separate information silos, with a particular inefficiency and disconnect between project and facility management phases (Lucas, 2015). Connecting and utilising this data is often hampered by difficulties in integrating, searching, and accessing (interrelated) data across different discipline-based datasets. Whilst not commonly referred to in the BIM related literature, the notion of 'uniqueness' reflects a common problem to data and information management in both sectors. Thus, useful data can be 'loose' and/or remained siloed, generating additional costs and slowing down the flow of information. In parallel with the issue of uniqueness is the ability to manage 'timed' data. In the PLM domain, timed data is used to refer to the "ability to trace the path of product data through time providing a reference period" (Corallo et al., 2013). This describes the problem of ensuring the integrity of building data within and across AEC/O organisations and also relates to the problem of 'traceability', see Section 2.4).

These issues relate to the interoperability challenge in the AEC/O sector, which in the past two decades has received much attention in the development of the standardised data exchange format known as Industry Foundation Class (IFC) (Liebich, 2013). The IFC format is modelled using EXPRESS information language (ISO, 2006) and standardised by buildingSMART International and the International Organization for Standardization (ISO). The IFC standard allows semantic description of a building as a digital building model, including element types (floors, walls, doors, windows, and spaces), complex 3D geometry, custom property sets and many more (Pauwels et al., 2011). Other proposals focus on making building data available online using semantic web and linked data technologies to address the issue of uniqueness, see Pauwels et al. (2011), Pauwels and Terkaj (2016), Törmä (2013, 2014), Hoang and Törmä (2015). The use of semantic web technologies enables the linking of building data with data from other sources, e.g., product manufacturer data, geographical data, regulation data, etc. This has evolved into the W3C Linked Building Data Community Group and the BuildingSMART Linked Data Working Group (2016). Recent research by Hoang and Törmä (2015) utilises linked data technologies to enable distributed online publication of structural and semantic data. Cross-dataset linking and granular access to objects is also supported. Hoang and Törmä (2015) approach therefore enables building data to be shared in a manner that is compliant with the fragmented and variable nature of construction projects with new capabilities to represent BIM models according to the IFC standard.

2.4 BIM and consistency, traceability, and long-term archiving

Like PLM, to data describing the building geometry and associated metadata contained within or linked to the model must be consistent, traceable, and available for long-term archiving. These aspects of data and information management underpin the issues mentioned above that relate to the uniqueness and timed aspects of data sources. According to Corallo et al. (2013), 'consistency' refers to the "capacity to maintain close links between different data in different versions". This capacity facilitates understanding of what information is being changed or impacted by a change in BIM datasets and also enables the search for information about a building object in any particular version of the model. Related to the consistency of the data, is the concept of 'traceability', which allows the history of the virtual design and construction model to be rebuilt. This capacity facilitates the tracking of model updates and revisions. 'Long-term archiving' then refers to the ability to "retrieve a particular piece of information even after a certain period of time" (Corallo et al., 2013). Whilst the concepts of traceability and long-term archiving may look similar, they have different scopes. Traceability is about "providing information about the evolution and changes in the product data during the whole lifecycle" (Corallo et al., 2013), whereas long-term archiving is related to the "capacity to store and recover useful information after many years" (Corallo et al., 2013). In the AEC/O sector, the building lifecycle is longer than 40–50 years during which it is necessary to guarantee the support of building assets and to respect legal requirements during demolition or refurbishment.

Issues of data consistency and traceability relate to data organisation and version management in multidisciplinary project teams. Gu and London (2010) identify data organisation and version management as two of the most important issues raised by survey respondents from the AEC/O industry in relation to BIM adoption barriers. Since their study in 2010, versioning of project data still remains a significant issue in industry. BIM implementations based on a centralised database where each discipline maintains, modifies and updates the data, require technical solutions (BIM-servers), workflows and processes to ensure data integrity, allowing different versions of project data to be managed throughout the project life-cycle (Gu and London, 2010). The challenges and complexity of system and sub-system integration in a centralised approach has resulted in the use of decentralised, distributed information management approaches to BIM (Törmä, 2013). In a decentralised approach, collaboration occurs at two levels: within a single organisation or discipline using similar tools, and across different discipline-specific models shared and combined using, e.g., the IFC data standard. To ensure data consistency throughout project delivery modelling procedures across project team members must be prescribed so that only one design team member can edit models or model objects at any one time. Model editing permissions must be specified and managed relative to discipline-specific datasets, with these permissions being controlled at the sub-model level. Technological solutions have also been proposed. Koch and Firmenich (2011) propose a model based on the integration of version-oriented building information with change-oriented descriptions. The approach provides information about both the state and change contained in the model, but does not address the issues surrounding interoperability and sharing changes among applications. Nour (2012) proposes an information management system that is aimed at addressing dependency management and access rights allocation at the object level. JalyZada et al. (2014) address the challenge of integrating object versions as a change management problem based on the IFC standard. JalyZada et al. (2014) propose IFC extensions for representing the history of changing objects contained with models and explore the merging of object-based change information with existing models so as to enable the representation of design intentions. The research initiatives documented above on the use of semantic web and linked data technologies also address data consistency, traceability, and long-term archiving issues.

The long-term preservation of building and meta-data is essential to a range of through-life services, including the ability to retrofit, preserve cultural heritage, ensure security, reuse design knowledge, and guarantee legal liabilities (Beetz et al., 2013). AEC/O data is particularly complex to preserve, as is the complexity of the range of individual file formats and large amounts of metadata required to understand how building assets, systems and sub-systems are connected, operated and maintained.

Methods, frameworks, guidelines and software systems for the digital preservation of information have matured rapidly since the recent uptake of BIM. Beetz et al. (2013) recently developed an approach to the long-term preservation of this new type of data by presenting the requirements for a secure solution covering a broad spectrum of 3D data and accounting for the demands of both the private sector (building industry SMEs, owners, operators) and institutional collectors (architecture libraries and archives). Their interdisciplinary roadmap accounts for a range of digital data types, including the consumption and storage of semantically consistent descriptions of heterogeneous building products to sets of low-level point-cloud data from laser scans.

2.5 BIM and the integration of people, processes, and technologies

The building lifecycle involves multiple people, processes, and technologies. At the same time, they are all highly related and fragmented, and can be best characterised as a wide net of interactions. Due to higher levels of consolidation within the discrete manufacturing industries, integration can be fostered more readily in applications of PLM. Other key contextual differences between the AEC/O sector and discrete manufacturing industries that influence on integration levels include the nature of the client base, lower levels of supplier specialisation, and lower levels of technological expertise (Green et al., 2004).

Without a holistic approach to the building lifecycle, applications of BIM at the project level are only able to provide a limited view of integration. Building data are created and managed by actors with different roles both internal to an organisation (i.e., employees of different units) and external (i.e., contractors, subcontractors, suppliers, partners, supplier's suppliers, clients, etc.). Each phase of the lifecycle is executed by people involved in processes may span many phases or limited to only one, where people are typically specific to a single building system or even component. The data and information generated across the building lifecycle are not all 'usable' or 'reusable' across different AEC/O processes. From the perspective of the building's lifecycle, the recent development of technological and managerial solutions (see Sections 2.3 and 2.4) have helped to assist in overcoming the range of data and information management issues surrounding the 30–40 year lifespan of a building. However these methods, frameworks and software solutions remain independent from the systems AEC/O companies use to manage communications and information with their customers (CRM – customer relationship management), their suppliers (SCM), and resources within the enterprise (ERP). From the project perspective, building design and delivery processes are one step removed from these ICT systems are instead integration focuses on project level data outputs (from CAD, CAE, and CAM tools, and electronic parts catalogues).

In a case study by Holzer (2014), integration is explored in an approach to linking PLM functionalities (via structured BIM data) to information systems (IS) supporting ERP. This pathway for PLM-ERP systems integration focuses on the needs of contractors, suppliers and manufacturers in their transition to a BIM-enabled PLM solution and associated ERP data requirements. Such levels of integration at both project and organisational levels highlights the opportunities for developing new business models in the sector and the potential for strategic repositioning of construction and manufacturing firms who utilise BIM data for supporting PLM functions within their organisation (Aram and Eastman, 2013).

2.6 BIM and collaboration across the extended enterprise

Like discrete manufacturing, designing and producing (constructing, manufacturing and fabricating) large complex buildings is a knowledge intensive process. In particular, the coordination of building engineering services, including structural, mechanical, electrical, hydraulic, and fire engineering, is challenging as it is carried out across network of firms so as to access the expertise required to realise the building's systems, sub-systems, and components. The design and production effort is fragmented between multiple disciplines and firms. In any one building project, the team is comprised of companies that specialise in the design and/or production of specific building systems, with firms operating in different locations, having distinct legal and organisational entities. This situation and context is similar to that of companies collaborating in discrete manufacturing industries. However in these industries, designers, manufacturers and suppliers combine their activities for periods that greatly exceed the lead-times associated with any one specific transaction (Corallo et al., 2013). With collaboration being characterised by persistence and continuity, the specification and implementation of PLM systems in this context finds an appropriate environment, where each company is able to build a "channel between themselves and their collaborators through which information and knowledge can be easily exchanged" (Corallo et al., 2013). With such longevity in collaborative relationships data and information exchange can extend beyond the exchange of geometric product data, (and information derived from that data such as specifications, drawings, etc.) to the exchange of metadata in a way that promotes data consistency and traceability.

In the AEC/O sector, a wide range of applications are available across the building lifecycle including design tools, analysis and simulation tools, document management systems, facility management tools, and so on. In current approaches to BIM-enabled projects, the scope, functionality, and value of collaboration are largely limited to the project phases and information sharing is restricted to geometric data. Standardised exchange formats, such as IFCs, support point-to-point exchange but on their own are insufficient for collaboration across the extended enterprise and throughout the whole building lifecycle (Tarandi, 2011) With this 'snap-shot' approach to information exchange, it is difficult to consistently integrate information about the building or project. Research suggests that to enable longer lasting collaborative processes throughout the life of a built asset, the use of a common information hub that supports higher levels of integration and consolidation of building information is required (Tarandi, 2011; Jørgensen et al., 2008; Singh et al., 2011; EPM Technology, 2002). The notion of a common information hub is manifest in BIM or model server approaches, also known as a 'model collaboration system' (MCS). A model server is a "database system built upon a set of server applications that host model data and allows multiple users to perform collaboration operations on model data using a common platform" (Jørgensen et al., 2008). MCS functionality enables information to be exploited and reused directly from models, facilitating changes to the type and length of collaboration from intra-disciplinary to multidisciplinary, and from short- to longer-term. The development of MCS over the past decade has therefore been aimed at facilitating information exchange in a multi-model environment and supporting the range of applications across a building project life-cycle (Singh et al., 2011). MCS functionality has largely been adapted from manufacturing industries. Tarandi (2011) advocates the application of the product life cycle support (PLCS) standard (ISO 10303-239 – REF) to projects in the AEC/O sector.

The PLCS standard was developed to support business needs in the implementation of enterprise-based collaborative initiatives, such as PLM, and for the past two decades, PLCS has enabled process improvements in service-focused discrete manufacturing industries. Tarandi's (2011) approached to an open BIM-based model server approach leverages Eurostep's share-a-space capabilities and the IFC standard to develop a web-based open ICT platform. Share-a-space is a standards-based data consolidation and exchange solution, built on the PLCS standard. A number of other research and commercial projects have developed MCSs for the AEC/O sector, including, e.g., IFC model server (Adachi, 2002), The Express Data Manager (EDM) database (EPM Technology, 2002), Eurostep, and BIMserver (Beetz et al., 2010). Development efforts by CAD and BIM tool vendors have also invested in the development of MCS technologies, including, e.g., Gehry Technologies, Onuma, and Autodesk 360.

Despite these development efforts, the implementation of MCSs in the AEC/O sector is limited due to a lack of industry awareness, lack of evaluation of available systems, and dependencies in the development paths of multi-model collaborative technologies and the evolution of BIM collaboration requirements. In a recent study, Shafiq et al. (2013) present a critical review and analysis of existing collaborative systems and their correspondence to AEC/O and BIM requirements. Shafiq's findings show that whilst the technology for multi-model collaboration is available in different capacities, a comprehensive custom built solution is required to address characteristics and work practices specific to construction. Jotne EDM and Eurostep share-a-space were identified as the most 'potent' MCSs based on their percentages of feature availability across all four requirement domains of BIM collaboration including: model content management, model content creation, viewing and reporting, and system administration (Shafiq et al., 2013).

3 Role of PLM in the evolution of BIM

Integrated solutions in complex discrete manufacturing have been serving these industries for the past decade at a relatively mature level. These solutions are based on the production of an integrated PLM system that links a number of IS as pieces of this complex puzzle; for example: CAD, CAE, and CAM tools, enterprise portals for collaboration, and dashboard business intelligence, which are then linked with ERP, SCM, and CRM systems. With such integration, companies must formalise and standardise the processes and data that they, and the numerous suppliers, customers, and partners, use. Fostering such an approach to formalising and standardising data and processes is arguably more difficult in the AEC/O sector than in discrete manufacturing due to high levels of fragmentation and low levels of technological sophistication. Further, for the AEC/O sector to achieve similar capabilities across the six defining areas of PLM, it must develop solutions to the range of managerial, technological and collaboration issues discussed in Section 2. The unique data and process integration requirements demands new technical interfaces to support information hubs and collaboration across the extended enterprise (Jørgensen et al., 2008), as well as innovative approaches to governance structures (Rezgui et al., 2013) at both the project and organisational level. A number of research areas are identified as significant to the evolution of BIM across the managerial, technological and collaborative capabilities of PLM systems.

3.1 Managerial capabilities

- Greater consideration of managerial challenges and requirements relative to the whole building lifecycle and extended enterprise.
- Process integration and consideration of related processes and activities of BIM (e.g., information, technology, and strategic points of view).
- Development of new business models and strategies so as to understanding how an organisation makes decisions and manages its resources to gain and maintain a competitive advantage over a period of time.
- Focus on value creation and the primary goals of businesses; including greater consideration of performance activities that increase the value of the products and services of AEC/O firms, and satisfying client expectations.

3.2 Technological capabilities

- Ongoing development of the building information backbone, MCS and the central hub for storing different data distributed among heterogeneous systems; including the creation a single view of product information that can be leveraged across the network of AEC/O actors.
- Development of ICT tools serving both project and organisational levels; encompassing the integration of a board range of software and IS used in all the aspects of building lifecycle (design, analysis, construction, collaboration, etc.).
- Definition of object libraries relative to meta-data and secondary information; including information indirectly connected to specific product knowledge (e.g., vendor application notes, manufacturer specifications, O&M feedback, marketing plans, archived project schedules, etc.).
- Increased focus on data traceability and the ability to chronologically interrelate building lifecycle information and track all changes to building data.
- Increased capacity for long-term archiving so as to meet AEC/O actors needs for long-term retention of older data, assisting in the maintenance of information integrity and demonstrating regulatory compliance and transparency.

3.3 Collaborative capabilities

- Increasing the integration of people, process, and technologies so as to combine different aspects related to BIM (business processes, human resources, data, etc.) so that they work together to better support and manage the building lifecycle.
- Improving sharing capabilities and the use of data and information jointly, supporting knowledge integration during collaborative activities across the building lifecycle.
- Increasing ability and ease of collaboration within and across extended enterprise; moving towards the notion of the ‘borderless organisation’ in the AEC/O sector

> whose processes are transformed and integrated with those of its partners, based on agile, cooperative and collaborative relations.

4 Contributions of this special issue

In the AEC/O sector, new methods, frameworks, processes and technologies are being developed and implemented in practice. This research work is evidence of the growing proximity of BIM with the PLM concepts. The four articles published in this special issue reflect the common end points between them. Whilst the articles included here are a continuation of the developments summarised in this review, they are collectively only a starting point and much remains to be done in terms of learning from and mapping the capabilities of PLM in the continued evolution of BIM. This issue seeks to advance the cross industry learning and lifecycle approaches to BIM by consolidating four contributions which focus on best practice in both the BIM and PLM domains.

The first article 'Principles and recommendations for client information requirements for BIM enabled construction projects in Qatar' by Hafeez et al. examines the need for context-specific information standards for BIM-enabled projects in the Qatar construction industry and issues surrounding the transfer of guidelines between countries. The basis for the research concerns the toolkits and guidelines developed for the UK's BIM mandate and the unique industry context that underpins this situation. The UK's recent development of a series of publicly available standards (PAS) surrounding information standards, information requirements, etc. (e.g., PAS1192-2) is aimed at supporting industry adoption of BIM technologies, processes and protocols. The BIM mandate has had some influence on countries looking to learn from UK adoption processes. Via an examination of the UK BIM Task Group's 'Employer Information Requirements' guideline or toolkit, the authors aim to understand how it can support key information deliverables in BIM-enabled projects in Qatar, and therefore its relevance in the context of the Qatari construction industry. The EIR toolkit is a new type of advisory guideline not previously seen in (or required by) the UK's AEC/O sector prior to the BIM mandate. Together with the required level of development (LOD), the UK EIR defines which models need to be produced at each phase according to the LOD. Models are specified as key deliverables in 'data drops' and help support decision making. The EIR therefore also specifies the standards and processes to be adopted as part of project delivery. Via interview-based case studies, the authors show that whilst BIM-enabled construction projects in Qatar are adopting various aspects of the UK's EIR guidelines relative to its technical, management and commercial elements, inconsistencies in addressing information requirements due to varied levels of readiness and competencies to deliver across all EIR items. The authors propose a number of context-specific recommendations for delivering what they refer to as 'Qatari Client Information Requirements' (QCIR). Due to a lack of BIM standards, dictionaries, project work phases, and capability assessment tools that are specific to Qatar, a QCIR that is specific to the requirements of its construction industry is seen as crucial to increasing adoption and maturity of BIM deployment efforts. A QCIR that can avoid the 'mixed requirements' that are typically 'imported' from different countries and used on the same project in Qatar due to the variety of multi-national companies operating in the region.

The research perhaps most influenced by PLM concepts is Oberoi and Holzer's article on 'Mechanical contractors: the key for supply chain integration in lifecycle BIM'.

The authors investigate the requirements for specialist trades in the construction industry to increase information integration and productivity when using BIM. The contribution focuses on the functional prerequisites that enable a whole-of-life approach in the project delivery phases from the perspective of a specialist (mechanical) trade. Drivers for innovation among specialist trades, and in particular mechanical contractors, are examined in conjunction with the implementation of bespoke policies, documentation standards, and BIM object libraries to support a whole-of-life approach. Using an example of the Australian BIM-MEPAUS initiative spear-headed by the Australian Air Conditioning and Mechanical Contractors' Association opportunities and challenges of BIM-use among specialist trades are examined. The paper illustrates the growing use of BIM by specialist trades and presents practical examples of the mechanical contractor's trade. This paper acts as a reference and example for other AEC/O specialist trade groups looking to develop and implement policies, documentation standards, and BIM object libraries to support a whole-of-life approach.

The research by Ran and Singh in the paper 'Building information modelling-enabled best practices in AEC and takeaways for Finnish shipbuilding industry' is perhaps the most 'comparative' of the four articles relative to the use of BIM and PLM tools in the construction versus the shipbuilding industries. The article explores the industry context that mediates the differences between the construction and shipbuilding industries and examines which, if any, BIM-based best practices can be transferred to shipbuilding. The outcome of interviews with AEC experts, identify four best practices including clash detection, visualisation, quantity take-off and scheduling. Following discussions with shipbuilding professionals on these topics, it was found that there are already several similar or more advanced practices enabled by 3D CAD in the shipbuilding industry. The four BIM-based best practices in the AEC were compared with corresponding 3D CAD enabled approaches in current shipbuilding practice. Collision detection, visualisation and quantity take-off methods in both industries were found to be of primary benefit and an essential practice for ensuring higher quality design, coordination, and successful integration. Whilst at comparative levels of technological maturity, the level of acceptance was perceived to be higher in the shipbuilding industry, with these aspects being perceived as routine or a norm. This was contrary to the authors' assumption that best practice could be transferred from the AEC industry into shipbuilding. However, 4D BIM was identified as a significant innovation in the evolution of construction scheduling by both AEC and shipbuilding experts. This was one key feature that differentiated BIM-enabled best practice from the use of conventional 3D CAD in the shipbuilding industry. Although some aspects of 4D scheduling and simulation were found to be present, overall 4D was not integrated in the 3D CAD systems used in the shipbuilding industry.

Finally the article 'Cross industry learning: a comparative study of product lifecycle management and building information modelling' by Jupp presents a review of the constructs, systems and applications of PLM and BIM. The paper is based on the premise of PLM's contribution to productivity improvements over the last two decades in discrete manufacturing. Jupp's motivation for the comparison is therefore based on the AEC/O sector's need to achieve similar improvements and the potential of BIM to evolve in much the same way that PLM has in manufacturing. In this light, the article focuses on the potential for BIM to move towards a common end point with PLM. A comparative typology of the review is based on four aspects of PLM/BIM, namely the scope of their conceptual framework, objectives, technologies and impacts on industry practice. Jupp identifies differences between PLM and BIM as well as their main similarities. The articles main contribution lies in the extrication of the significance of these differences and similarities relative to the characteristics defining their application domains. Jupp shows that whilst the differences are significant, particularly in light of context-based variances, five key similarities merit further research into the transfer of managerial and technological knowledge surrounding approaches to:

1 product data requirements
2 functional data requirements
3 information standards and data exchange
4 increased focus on relationships management
5 IT transition strategies and processes including legacy systems
6 configurations management.

The cross industry learning that can be supported by Jupp's research is however largely one-way – with the experiences and advances in the managerial and technological capabilities of PLM systems standing to benefit the AEC/O sector and the continued development and evolution of BIM. The comparison is therefore most valuable to BIM researchers and industry practitioners; whilst also being useful in continuing to open up a dialogue between PLM and BIM communities.

5 Conclusions

The papers in this special issue bring into focus a common end point that can be fostered between BIM and PLM. The articles provide a considerable research contribution to advancing BIM relative to understanding client information requirements and context dependant variables (Atif et al.), supply chain integration and specialist trade requirements (Oberoi and Holzer), its tools and best practice (Ran and Singh), and ultimately relative to PLM's objectives, technologies and impacts on practice (Jupp). BIM and through-life information management are two very broad areas of research but we believe this special issue provides a sampling of efforts that can help advance understanding and progress towards transferring best practice and lessons learned from the PLM domain into AEC/O applications of BIM. Despite the AEC/O sector producing complex products and operating in complex contractual and supply chain scenarios, the tendency is to use BIM not as a strategy to integrate all elements (people, processes, business systems, and information) thereby enabling greater support across the building lifecycle and value chain, but as a tool that resolves more immediate issues during project delivery phases. Given the increasing importance of BIM within AEC/O sector, the need to develop a more holistic and strategic approach is apparent.

It is clear from this special issue and the research efforts highlighted here that there is a growing need for further research in the six areas addressed in this discussion, i.e., advancing BIM relative to: its implementation as strategic business approach requiring new approaches to business models and processes across the extended enterprise; greater consideration and integration of phases of the (building) lifecycle; furthering approaches to managing unique and timely (building/asset) data; developing technologies and technical interfaces to support consistency, traceability, and long-term archiving of data; improving the level of integration of people, processes, and technologies; and increasing collaboration across the extended enterprise. Our hope is that this issue will create a dialogue among various stakeholders of the BIM and PLM communities of researchers and industry practitioners to solicit the state-of-the-art approaches and methods that address the issues outlined above. We believe these four articles make important contributions to the problem of an integrated, strategic, and holistic approach to BIM. They continue to draw attention to the managerial, technological and collaborative capabilities enabling AEC/O actors and the support required of a lifecycle approach to building data and information management. Specifically, AEC/O actors need to pay attention to the importance of the flow of information in decision making across the building's design, delivery and operations.

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