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Digital buildings - challenges and opportunities

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ABSTRACT

This paper considers the wider implications of digital buildings (as currently exemplified by building information models) becoming the norm within the building construction sector. Current deployment is reviewed and the growing opportunity to better address previously identified problems (both process and structural) within the construction industry is considered. Taking a twenty year perspective, the challenges and the opportunities that digital buildings will present to the construction industry - and to its IT suppliers - are explored against the context of needing to deliver greater value while also addressing sustainability, zero carbon and enhanced resilience objectives.

1. Introduction

Society currently faces many challenges dealing with the current economic conditions and the pressing need to address climate change (and its effects) together with the wider sustainability agenda. Considerable expectations will be placed on the construction industry to improve its efficiency and play a key role in addressing the environmental concerns. Yet construction has been widely recognised as an industry that exhibits many intractable problems. With support from its IT suppliers, the industry is currently making the transition to full digital model-based working, creating new opportunities and posing new challenges.

Modern buildings contain substantial digital infrastructure, both a communications infrastructure to serve the IT needs of the building occupiers and the digital systems that are increasingly being used to monitor, control and manage the building itself. Such infrastructure should be an integral part of the overall building design and provide a robust, secure and cost effective solution that is likely to be modular, adaptable and increasingly intelligent. However, the term *digital building* as used in this paper refers to the comprehensive set of highly structured information that potentially defines all aspects of the corresponding *real building* including its digital infrastructure. With the capability to be represented as-necessary as a fully attributed *virtual building*, such a digital building should mirror the lifecycle of the corresponding real building. (Being created when the need for the building is identified and subsequently capturing and retaining all relevant information until the physical building no longer exists.)

Figure 1 is a simple recursive four-phase representation of the lifecycle of a building that is employed within this paper. With design, construct, use, and modify phases, it seeks to convey the relatively long duration of the use phase (which implicitly includes manage and maintain the building). This representation does not show demolition which is included in the modify phase and would follow a decision not to adapt or redeploy the building.

Building Information Modelling (BIM) represents an imperfect first approximation to the concept of a digital building, this paper therefore starts by looking at the current state of BIM. It then examines some of the well documented problems within the construction industry and considers how BIM may help address these. The paper then looks forward some 20 years to consider the emerging challenges facing the building construction sector. The potential for digital buildings to help address these challenges is considered and some of the consequential IT challenges identified.

Clearly the context will include the pressures to mitigate climate change, to make buildings more resilient to its effects, to minimise pollution and to accommodate probable shortages of resources. Similarly the main socio-economic pressures will probably be increased economic uncertainty, the consequences of continued population growth and potentially political instability. Increasingly society will expect the construction industry and its clients to deliver infrastructure that is both *appropriate* and *resilient,* these terms being somewhat ill defined in this context. The key characteristics of the wider context are likely to be uncertainty and progressively increasing complexity, with the probability of significant changes occurring in the regulatory framework and fiscal constraints.

2. Building Information Modelling

2.1 Background

The term BIM has been adopted by the major vendors of CAD software and, in this context, it is now widely accepted as referring to a particular category of leading-edge software for building design and related applications. The computational foundation of BIM software is the object oriented paradigm for the design and implementation of software and, while BIM software builds on the success of more traditional CAD applications, the intellectual concept underpinning BIM is that of a *product model* for buildings.

A product model can be described as a formal information model that defines agreed data structures which provide a comprehensive ability to capture engineering information about a particular class of artefact. The concept of employing an underlying engineering product model was originally developed to enable the creation of more robust data exchange standards, the approach being refined and matured in the context of STEP (ISO 10303) [1]. In the 1980s these ideas were being adopted by researchers in the construction sector and being applied to buildings in particular. Some of the early work was associated with the creation of formal STEP standards for the construction industry, but more pragmatic STEP-based initiatives followed. These resulted in the establishment of important construction industry interoperability standards such as the CIS/2 for structural steelwork [2] and the IFC for buildings more generally [3]. These open data exchange standards are each underpinned by a published product model. Similarly BIM software applications are each underpinned by a proprietary information model and these are assumed to embody concepts drawn from the published product models. Both categories of models are designed to hold similar information but their objectives differ.

The *BIM Handbook* by Eastman et al includes several definitions of the term BIM plus a useful history of the term in the forward written by Jerry Laiserin. The authors themselves define BIM as “a modelling technology and associated set of processes to produce, communicate, and analyze building models” with building models being characterised by:

- Building components represented by digital objects that know what they are and can be associated with computable graphics,
- Data attributes and parametric rules,
- Components that include data that describe how they behave,
- Consistent non-redundant data so changes are propagated to all views and the presentation of all views of the model are coordinated [4].

Among those authors who have attempted to define the meaning of building information modelling there is considerable divergence. Some ambiguity is implicit within the phrase itself. For example, does the model refer to the underlying schema or to the instantiated model of a specific building, and is the term modelling intended as a noun or a verb? Today BIM is usually written as building information modelling (rather than model) and the term is generally regarded as having two distinct but complementary meanings: either to identify a particular category of engineering *software***,** or to denote a *process* view of the industry. In the limit, the latter can be characterized as the adoption of an information-centric view of the whole lifecycle of a building.

2.2 The software view

The software view of BIM can currently be characterised as referring to the (new) design and construct software platform. BIM *authoring* software is still (largely) being marketed as a more efficient means for designers to produce fully coordinated production information. This characteristic is derived from the fact that, unlike traditional CAD which stores and manipulates 2D or 3D geometry, BIM authoring software generates the currently required geometrical representations on-the-fly from the occurrences of the underlying building objects (such as beams and slabs) stored within the BIM. Each of these instances has a location and parameter values but no explicit geometry. Thus the underlying parametric building model is very much easier to manipulate than traditional CAD representations and, because they are all generated from a single database, the consistency of all graphical and non-graphical representations should be assured [5]. Critically, this consistency extends across all types and scale of representation. BIM authoring software employs a parametric object oriented architecture with change propagation, ensuring that a change made in any representation is propagated across the model and thus across all representations.

For the purpose of this paper **Table 1** defines four categories of engineering software: *BIM authoring software* as characterised in the previous paragraph, *applications* as all other engineering software**,** *BIM aware applications* as a subset of applications and *BIM software* as the superset BIM authoring software and BIM aware applications. Where the term BIM is used alone, this normally refers to the database that underpins a particular BIM authoring package.

Industry is currently transitioning from using traditional CAD to BIM authoring software and it is evident that the latter normally succeeds in delivering the primary objective of consistency across all representations. However, it is widely recognised that the potential of BIM software extends far beyond the immediate and substantial benefit of producing coordinated production information; the underlying model provides the basis for a more integrated multi-faceted approach to design and construction. Additionally, this functionality clearly has potential to extend beyond the construction phase through the full lifecycle of a building. It is the extended duration of the subsequent use phase that forms a barrier to the current generation of BIM authoring software evolving directly into the long-term digital building.

In terms of the realisation of BIM, current BIM software may be incomplete but a good foundation has been established on which to build increasing functionality.

2.3 The process view

The complementary process view of BIM looks beyond immediate attractions of the latest BIM software and focuses on the strategic value of having coherent structured digital information available throughout the building lifecycle. This process view informs the notion that the future role of the BIM is wider than that of the engineering information captured by a "traditional" product model. The produce in this context is a complex AEC artefact which has a lifecycle that may be measured in hundreds of years and information that might (for example) also include commercial, material testing, performance, maintenance, FM and recycling data. Clearly the progressive realisation of the digital building concept will effect existing construction industry processes; more immediately how things are done at a technical level but, increasingly, how the industry itself is organised.

At a tactical level there is the short to medium term impact of BIM software on the processes of building procurement. There are a relatively small number of particular BIM authoring packages and most of these are acting as a focus for (increasing) numbers of specialist applications. BIM aware applications generally have the ability to make API calls to a particular BIM authoring package to extract relevant information direct from the BIM. Some BIM aware applications are also able to directly update information held in the BIM, thus creating a *round-trip* of information flow.

Applications that are not BIM aware do not have an intimate relationship with a particular BIM authoring package. Thus data exchange can only be by means of a common file format that one programme is able to write and another read. Such an information transfer capability may arise by chance or be intended, and may involve a particular neutral data exchange file format (such as the IFC). Generally such information transfers are less robust than a particular transfer capability involving a BIM aware application because the latter transfers are implemented specifically and are more likely to have been extensively tested.

At a strategic level current BIM authoring software will have a short lifetime compared with that of a typical building. What ultimately matters will be the flow, preservation and aggregation of relevant information throughout the lifecycle of a building. This view is well articulated in the first US "*National Building Information Modelling Standard*" which is subtitled *transforming the building supply chain through open and interoperable information exchanges*. The document quotes the cost of current industry processes failure to adequately support such workflow as $15.8 billion per annum. Recognising that BIM authoring software has existed in different guises for 20 years, the standard argues that BIM is a fundamentally different way of creating, using, and sharing building lifecycle data Three categorisations for doing this are identified: (1) an intelligent representation of data – authoring tools, (2) a collaboration process, and (3) a facilities lifecycle management tool. It argues that the overall scope of BIM has yet to be defined, but that it will affect all stakeholders supporting the capital facilities industry who will need to share information via an information backbone [6].

In terms of the realisation of BIM, the process view is still relatively poorly developed. Interoperability between different vendors BIM authoring software is limited, while moving information further down the building lifecycle has not yet become the focus.

2.4 Current deployment

Software vendors

The BIM market leaders are the two dominant vendors of traditional CAD: (a) Autodesk with *Revit Architecture*, *Revit Structure* and *Revit MEP,* and (b) Bentley Systems with *Bentley Architecture*, *Bentley Structural, Bentley Mechanical Building Systems* and *Bentley Mechanical Building Systems*. Both companies offer a suite of sophisticated discipline-specific BIM authoring software that is built on a common BIM platform and thus is internally interoperable. Until about eight years ago neither company was marketing true BIM authoring software; Autodesk bought the start-up company Revit Technology Corporation in 2002 for $133m.

The other vendors have less comprehensive BIM offerings. *ArchiCAD* was first released in 1984 and was subsequently recognised as being the first real BIM authoring software. The latest release has an innovative BIM server to facilitate synchronisation across a distributed project team, but ArchiCAD lacks strength outside its core area of architecture. Similarly *Tekla Structural*, which was developed from of a leading 3D structural steelwork detailing application, is limited to the structural discipline.

Internationally Revit, Bentley, ArchiCAD and Tekla are the best selling BIM authoring platforms and currently there are few alternatives[1]. The most widely known alternatives are probably *Vectorworks* (from Nemetschek who also now own ArchiCAD) and *Digital Project* (from Gehry Technologies). The latter is unusual in that it was developed on top of the powerful CATIA environment whose origins lie outside the construction industry. The recent demonstration by Dassault Systems of *Catia Live Building,* a long rumoured new BIM product based on a future version of CATIA, may mark the emergence of a potentially important new BIM authoring platform [7].

The picture is similar in China where the move towards BIM is less well developed. Revit appears to be the most popular BIM authoring software (Autodesk has a tie-up with several universities) with ArchiCAD and Bentley also used. Over 20 design institutes are understood to be using BIM, but the most popular architectural “BIM” application is an AutoCAD-based Chinese application called *T-Arch* [8].

[1] *IDEA Architectural* was recently released by 4M Solutions based on the IntelliCAD platform suggesting the possible emergence of a second tier of competent but limited low-cost BIM authoring tools [9].

A key feature of current mainstream BIM authoring software is the ability to define parametric constraints to enforce relationships on the geometry of objects. This may be used quite simply within a model to ensure (for example) that certain localised geometric relationships hold true when more global changes are made. It can also be used to define self-configuring assemblies of objects that will automatically re-configure depending upon the context in which they are placed. This approach, which was pioneered by Bentley Systems *Generative Components* and is more generically known as *Smart Geometry* [10], is likely to become increasingly prevalent.

Industry usage

Other than producing fully coordinated production information and their inherent abilities as a design visualisation tool, the drivers for using BIM authoring software hinge on the utility of the underlying database. Critically, this enables such software to act as a design repository able to interoperate with other specialist BIM aware applications to perform tasks beyond the ability of the BIM authoring software – for example specialist analysis, detailed design, simulation or evaluation programmes. The increasing ability of specific BIM authoring packages to "round trip" information with selected BIM aware applications and thus act as an *information integrator* (able to merge additional data or changes originating from an external programme) is significant. Within a particular discipline it has been feasible for some time for BIM to lie at the centre of the design process [11], with the possibility of several designers working concurrently on different areas of that model [12].

Current BIM authoring software is discipline specific and complementary BIM models are normally created for each discipline. Cross-discipline coordination is often achieved using software tools such as *Navisworks* which have the ability to read BIM (and other) file formats from diverse sources and allow the models they contain to be compared visually. With facilities for problem detection (including automatic clash detection and interrogating the various models), problem recording and the tracking of problem resolution, such tools provide a popular and pragmatic approach. They can overcome incompatibilities between particular BIM authoring packages and support the staging of regular design review meetings, this without necessarily making significant changes to the nature of the relationship between the members of the design team. Other options are available, with similar problem identification and problem management support from within the BIM authoring software itself, but only when all parties are using the same vendor's BIM platform (and thus can read each others files). For example, discipline specific BIM files can be periodically be issued to all parties paralleling the traditional drawing-based approach. An alternative federated BIM deployment provides direct view-only linking to each others models [13], thus allowing design changes to be propagated at more of a micro level. This implies a significant shift from traditional industrial practice.

The usage of BIM authoring software during the design phase is already significantly impinging on processes. Some design companies are already 100% BIM and most of the larger companies are either rolling out BIM or are conducting serious evaluations. At least seven major BIM surveys have been conducted since 2005. In American a 2005/6 survey [14] suggested 16% of architectural firms had some BIM authoring software rising to 34% in a 2007 AIA/AGC survey [15] while a 2008 survey [16] suggested almost 33% of structural engineering firms were using BIM to meet client needs (with another 43% expected to be doing so within 5 years). A 2007 survey of Nordic countries [17] suggested that BIM software was being used by architects in about 20% of projects and by engineers and contractors in about 10%.

A 2008 survey of American architects, engineers, contractors and owners who are already using BIM software suggested that:

- 62% of BIM users would use BIM on more than 30% of their projects in 2009.
- 72% of BIM users said that BIM has had an impact on their internal project processes.
- 45% (up 10% on the previous year) of current adopters would be using BIM on at least 60% of their projects.
- As users gain experience with BIM, their view of its impact improves significantly.
- Contractors (61%) had the most positive view of BIM.
- 41% of owners reported that BIM has a positive impact on their projects (with 33% very willing to purchase BIM authoring software for other team members) [18].

Although contractors are not (yet) the primary target of the BIM vendors, it is evident that contractors see potential advantages in working from a BIM model. Wishing to access and evaluate these advantages, it has been reported that some contractors are already creating their own BIM models on projects where BIM has not been used by the designers. Others (such as Laing O'Rourke in the UK) are actively promoting the use of BIM by their design partners.

2.5 A disruptive technology?

Traditional 2D CAD was introduced into the construction industry over an extended period, with the uptake accelerating rapidly as costs fell significantly and manual draftsmen became hard to recruit. Some reorganisation within design offices was required but 2D CAD proved to be a largely incremental technology which delivered higher productivity than manual drafting and a useful degree of coordination.

With indications that the deployment of BIM software is now accelerating, the probability is that this will be a significantly more disruptive technology in terms of its consequences. This view is informed by the implicit rapid switch from 2D to 3D working and by the opportunities that the dual (software and process) view of BIM will create to further address some of the problems inherent in the construction sector. Others [19], [20] have highlighted the need for dramatic changes in current business practices.

3. The Established Challenges

3.1 Inherent construction industry problems

Much has been written about the economic importance and the inherent problems of the construction industry. In the UK this includes a significant number of official reports, the Business and Enterprise Committee [21] being one of the more recent. The underlying problems, including a contractual and confrontational culture and a fragmented structure, have been widely articulated. Initiatives have been launched and progress made, partnering and public private partnerships for example. However, further improvements are needed. The industry has embraced ICT but without the degree of transformation seen in many manufacturing and some services sectors. Does the switch to BIM present an important opportunity to address some of the challenges?

3.2 Egan project process improvements

Although the *Rethinking Construction* report [22] largely predates BIM, it was very influential and spoke of the project implementation team needing to work together from design to construction and commissioning and the use of computer modelling to predict the performance for the customer and minimise the problems of construction on site. The challenges that follow have been drawn from the *Improving the Project Process* chapter of that report.

Repeated processes

Significant inefficiencies in the construction processes suggested potential for much more systematised and integrated project processes, with significantly reduced waste plus quality and efficiency improvements. BIM provides a firm foundation for implementing a systematic and integrated approach to project processes [23 see Scenario VPD], [23 see Eagle Point], particularly for a sequence of similar projects [24 see Dianne Davis]. It also helps to reduce waste and improve quality and efficiency [25].

Integrated project processes

The full construction team should bring their skills to bear to deliver value to the client; efficiency being constrained by largely separate processes for planning, design and construction; learning, innovation and development of skilled and experienced teams is inhibited by a lack of continuity between jobs. BIM is increasingly supporting integrated project processes, involving all the participants including the client [24 see Keith Holloway], [26], allowing the bringing together of planning, design and construction [27]. It is also likely to evolve into a platform for learning from previous projects (for example) and should already be a substantial aid to innovation [28]. These characteristics may encourage project teams to stay together to address specific types of projects, but BIM may also provide an infrastructure that supports the efficient establishment of new project teams.

Focus on the end product

Egan envisaged continuous development of the product and supply chain allowing innovation and the elimination of waste, this being blocked by the lack of continuity of project teams. The potential of BIM in these areas has already been outlined above, with the rider that the reduction of waste is already being advanced as a particular advantage of BIM [29].

Product development

Egan also anticipated continuously developing a generic construction product, requiring detailed knowledge of client's aspirations plus effective innovation and learning from objective measurement of completed projects. This implies a project team that focus on a particular type of project. BIM has already been deployed in the domestic housing sector where the nature of the business and the product provides an early example of an integrated vertical market approach [30]. BIM has been identified as a future integrator of performance measures from completed buildings, this could provide a natural route into the retrospective re-evaluation of the actual performance of previous designs [24 see Ramtin Attar], [31].

Product implementation

The translation of a generic product into a specific project involving the full team in designing the engineering systems, selecting key components and pre-planning manufacturing, construction and commissioning; the use of standard components, precise engineering fit and extensive pre-assembly. BIM can make a major contribution by supporting the transformation of generic into particular solutions, by facilitating the active participation of the full project team (even when geographically dispersed) and by the selection of appropriate components via the internet [23 see Steve Jones]. Similarly, BIM provides a platform for the planning of manufacturing (the generation of reports and integration with external applications for example) [32 see Jennifer Knudsen], construction and commissioning [32 see Brian Kramer] - potential driving the latter process from information held within the BIM and storing the resulting data. BIM can actively encourage the use of standard components (component libraries) while its implicit unified geometric model provides the foundation for overall accuracy and accurate prefabrication and pre-assembly of components.

Partnering the supply chain

Not easy but critical to driving innovation and sustained improvements. BIM technology and particularly the associated philosophy can permeate along supply chains [33] making them more efficient and more stable.

Production of components

Detailed design of components and sub-assemblies, management and improvement of production processes, right-first-time, just-in-time delivery, ongoing improvements. The potential of BIM in these areas has already been outlined, with right-first-time [32 see Rick Khan] and just-in-time delivery [33] being substantial beneficiaries.

Health and Safety

Egan also highlighted the challenges of health and safety. This is an area where considerable progress has been made but BIM has the potential to facilitate a further step-change across all phases of a building's lifecycle by implementing an integrated approach to Health and Safety that permeates design, planning, simulations and execution and is assisted by greater awareness of the physical conditions [24 see Patrick Mays], [34].

4. The Emerging Challenges

We face very substantial challenges in the areas of sustainability, moving to a low carbon economy and creating more resilient infrastructure. The multi-faceted and frequently conflicting requirements, with significant uncertainties and often spanning the whole lifecycle, will require a substantial paradigm shift to engage them fully. Ultimately, the biggest challenge is likely to be identifying what is the most appropriate solution, given the environmental, political and fiscal risks and uncertainties plus the diversity of evaluations and simulations that will be required. Taking a twenty year forward view, these are the types of challenges that digital buildings will (hopefully) allow the industry to address.

The dual software and process view of BIM provides an appropriate context for starting to address them. The BIM authoring software vendors have been quick to recognise the commercial opportunity and useful evaluation modules are already available, particularly for the early stages of design [35]. A more comprehensive approach will necessitate many such tools, a high level of BIM integration and a design methodology that is able to locate optimal solutions in a very complex design space. This will require considerable investment and innovation and is likely to see optimisation and knowledge-based techniques fully integrated into the BIM concept.

4.1 Some key challenges

Environmental

The environmental requirements, including the more traditional sustainability issues such as pollution and diminishing resources, seem likely to be increasingly driven by the climate change agenda. This will include efforts to reduce the causes (such as designing carbon neutral low embodied energy buildings) and mitigate the effects of climate change (by designing buildings and their wider context to be more resilient).

Several challenges will flow from this seemingly inevitable trend. The number of aspects that have to be considered, assessed and evaluated during the design process may well increase significantly. It is unlikely there will be early consensus on the priorities and requirements relating to these design aspects, thus variations with geographic location and over time can be expected. Additionally, some requirements may conflict (for example, increasing resilience while also reducing embodied energy). Currently there is a proliferation of different sustainable building rating schemes [36] and clients are increasingly requiring a building to be designed to achieve a specific classification against a particular rating system (rather than the classification being an outcome of aspiring to achieve an excellent and highly sustainable solution).

Understanding Needs

Understanding the needs against which a building should be designed is a pivotal challenge that is becoming increasingly complex given the inevitable shift in perspective from a short-term view to *whole-life costing*. It can be difficult to establish the probable long-term needs of a single client, without the implied need to also consider the wider community of stakeholders:

- Cost and stakeholder value over time are clearly key, but what should whole-life costing really mean?
- Given the inherent uncertainty, how well can it be assessed?
- How to value additional inbuilt flexibility and adaptability against the future alternative of demolishing a redundant building?
- How to compare new-build against renovation?
- How in the longer term to value low maintenance and high availability?

A more probabilistic approach will probably need to be adopted both to define needs against the lifecycle processes and to underpin the design process itself. Two more immediate challenges from the client are:

- Achieving greater predictability in areas such as costs, construction programme and building performance, with the implied need to improving constructability and maintainability.
- The growing importance of knowing exactly what you own, future disposal liabilities for example.

Multi-aspect Design

The requirement to consider increasing numbers of aspects will result in an increasingly complex and probably unfamiliar design space. Simply finding and recognising a good solution may be difficult and finding an “optimal” solution may be very difficult, particularly if the evaluation criteria are not clearly defined. The future “designer’s workbench” is likely to be an increasingly sophisticated environment.

Building Lifecycle

Referring to the four-phase lifecycle model in **Figure 1**, it is the long duration of the use phase that creates an information discontinuity - the bridging of which may be encouraged by the current trend towards longer-term design, build and operate contracts. Clearly the role of the digital building must be to inform and interconnect the various activities that take place within these phases to enable more appropriate and longer-term decisions to be taken at each stage.

4.2 The potential of BIM

The nature of the challenges facing the construction industry implies increased use of IT tools and, for the building sector, BIM currently appears to be the way forward. Three particular aspects of the potential of BIM are considered below. The primary linkages between these three aspects and the four twenty-year challenges identified in section 4.1 are illustrated in **Figure 2**.

Driving Process Change

As a technology that is being promoted by the major software vendors, and is allied to a strategic process view of the construction industry, BIM has been widely recognised as a powerful agent for change.

This is best illustrated in the US by citing three highly influential reports and initiatives. The pivotal "*Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry*" [37] first reported that inadequate interoperability in the commercial, institutional and industrial facilities industries was costing the US economy $15.8 billion per annum. The subsequent publication of part 1 of the US "*National Building Information Modelling Standard*" [38] saw the adoption of a strongly process view of BIM and promotes the adoption of open (not vendor) information standards. In the same year version 1 of the "*Integrated Project Delivery: A Guide*" [39] was published. This has evolved into IPD, a radical new contractual framework for building construction that is effectively predicated on the use of BIM technology. As can be inferred, the deployment of BIM is being strongly promoted in the US.

Current BIM software is still mainly directed at the design phase where deployment is approaching a critical mass. As companies increasingly understand how best to exploit the software, and its capabilities continue to increase, rapid growth in deployment is anticipated. The widespread adoption of BIM for design will represent a substantial step towards full digital working within the industry.

Evolution of BIM

As the BIM vendor's focus starts to shift further down the building lifecycle, the capability of BIM software is already moving from design into detailing and fabrication.

In the construct phase some contractors are already making significant use of current BIM authoring software, using either the designer's model or one they have created themselves, to assess their options and to plan and control the construction. Those contractors who opt to create a new BIM model may be responding to contractual or technical concerns relating to the quality of the designer's model – something that needs to be addressed if the industry is to become more efficient. One of the construction drivers is the current availability of BIM aware applications that link BIM models to established construction management software for programming and estimating/costing, thus delivering to the contractor valued 4D [40] and 5D [41] capabilities. Also, by working direct from the model (rather than from predefined drawings of that model) it is anticipated that the contractor's staff will benefit from the same degree of interaction with the model currently available to designers. Recent technical developments [42] are confirming expectations that such access will become available to operatives while out on the site via mobile devices. This will have interesting implications both for communications in general and for areas such as health and safety, record keeping, checking work and the commissioning of equipment. Updating the BIM model to create a detailed *as-built* model incorporating any deviation from the *as-design* model plus the addition of substantial quantities of additional information arising from construction is likely to become the norm. These trends suggest that contractor specific versions of BIM software are likely to appear.

Similarly, in the use phase BIM aware applications are already starting to be used to extract information from BIM models into facilities management software [43]. It seems likely that the BIM authoring software vendors will also target this phase because of the potential richness of the BIM model compared with existing facilities management software. For example, maintenance staff could access all relevant information via mobile devices with potential to also make use of augmented reality. More strategically, an anticipated development is the onward updating of the BIM to capture building usage, performance and maintenance information.

Significantly, the vendors have already recognised the sales potential of the renovation market. Current design phase BIM authoring software is being deployed on a trail basis within the modify phase of existing buildings, necessitating that an *as-is* model first be created (frequently from scratch). The effort this involves is a substantial barrier to the deployment of BIM software in the modify phase or the use phase of older buildings. The automatic acquisition of the existing geometry by *laser scanning* and *point cloud* technologies [44] will soon help, but additional information acquisition tools will be needed to further reduce the barrier.

The current generation of BIM authoring software still reflect the traditional discipline-based divisions within the construction industry. A federated deployment was outlined in section 2.4 but, providing all disciplines use the same vendor's BIM platform, it is already possible to configure such tools to operate as a *unified* (i.e. cross discipline and location independent) BIM model [45]. This evolving *BIM server* approach currently requires the design team as-a-whole to adopt a more systematic approach to who can update which areas of the model[2]. While some major projects are already using a unified BIM model, as yet there is little published analysis of the practical implications. Further technology improvements may be required before unified BIM becomes the mainstream option, but this does appear inevitable. Unless a universal plug-and-play technology can be introduced for BIM aware applications, this will raise further concerns about restrictions on the choice of software that project participants can deploy.

[2] Bentley Systems BIM authoring software achieves scalability through a different approach: a federated BIM model is effectively defined by multiple distributed files which are in turn controlled by a powerful project and file management infrastructure.

Interoperability

Effective interoperability is critical to BIM-based working.

Consider the design phase. Today, within a particular discipline, a particular BIM authoring package is able to interoperate *directly* (in some cases both ways) with BIM aware applications that comply with that vendor's BIM interoperability standards. The BIM authoring package may also be able to interoperate *indirectly* via a file with a number of other applications. **Figure 3** represents a particular BIM authoring package which is able to interoperate directly with two BIM aware applications (BA#1) and (BA#2) and indirectly with another application (A). The large arrow representing the ability to pass the resulting discipline specific model downstream (also see **Figure 4**).

Unless a unified BIM model is being employed, when the design phase is completed the end result is likely to be several aligned but separate discipline-specific BIM models. Similarly, direct downstream interoperability with the next phase will only be possible if the same BIM vendor's software is employed in that phase. This fragmentation is illustrated in **Figure 4** which also uses shading to indicate the current degree of BIM software use in each phase.

The solution would be for all the BIM vendors to adopt a single set of BIM interoperability standards but technical and commercial considerations make this unlikely, at least in the near future. Potentially such a standard exists in the form of the IFC, with the former IAI apparently being rebranded as buildingSMART with this role in mind [3]. The BIM vendors currently support the IFC file format, but to differing degrees reflecting their particular commercial interests. The IFC might form the basis for any future universal plug-and-play specification for BIM aware applications but it seems more likely to play a longer-term role at the boundary between BIM domains. Specifically, the IFC could be used for interoperability between different BIM platforms - possibly between disciplines, but perhaps more likely when moving a model downstream. Additionally, it seems likely that the IFC will be used for the long-term archiving of models.

Interoperability considerations are fundamental to the practical realisation of the digital building concept. The importance and challenges of interoperability are currently reflected in (a) the progressive emergence of industry standards for the deployment of BIM [6], [46], and (b) the tools that are already embedded in BIM software for the pre-validation and monitoring of information transfers.

5. The IT Challenges

5.1 Some key challenges

It is evident that the construction industry will present its software vendors with business opportunities and some major challenges.

The growing breadth of the design processes will require additional applications to be developed to model and evaluate new aspects and present the results in a meaningful ways. These applications will need to be able to interoperate with the then current BIM models (which may well need to be extended in scope). They might become fully integrated within a particular BIM authoring package but, using the terminology in this paper, independent developers are probably more likely to package them as BIM aware applications able to interoperate directly with one or more BIM authoring packages. As usability expectations increase, developers may struggle to create applications that operate sufficiently consistently and seamlessly with more than one BIM authoring package.

The construction industry is likely to become increasingly concerned about BIM related limitations on the applications that they can deploy (and on the choice of BIM authoring software?), and about the implications for software innovation and costs. Given the growth in the number of applications required, and the desire to start aggregating additional information through the lifecycle, the BIM software vendors may struggle to deliver the level of interoperability and information management demanded by the industry.

Building owners and both the users and vendors of BIM software are likely to become increasingly exercised about which data standards should be employed (proprietary or open standards) and about the adequacy of current-generation standards.

Delivering IT solutions that extend over the lifetime of a building will pose new challenges to the BIM vendors and shift industry focus onto the information that is held within the BIM. While international software vendors are familiar with the need for localisation, this burden may increase significantly with the anticipated extension of supported design requirements from the implicitly more consistent hard aspects into softer aspects which are likely to be less consistently defined.

Mechanisms for supporting multiple uses working simultaneously on a unified BIM model will need to become increasingly flexible, transparent and scalable. Improved capabilities will be needed for the effective merging of models and for the aggregation of additional data into an existing model. The increasing scale of the information storage and management task suggests that BIM models may themselves be virtualised, with the underlying data being stored using traditional database technology.

With the potential for continued blurring of the distinction between applications and the BIM model, users are likely to demand a much greater ability to programme objects themselves (for example to create advanced self configuring and self-designing assembles). This challenge is likely to be increased by the proviso that explicit mechanisms are likely to be demanded to protect companies intellectual property rights a shared model environment.

Ultimately the greatest challenge may be to provide appropriate and effective support for what will increasingly become multi-aspect design. Requiring a highly configurable problem definition capability, an adaptive mix of algorithmic and knowledge-based techniques plus an innovative user interface to control what will probably become a raft of semi-automatic design processes that are likely to include probabilistic elements. The major software vendors will have the advantage that such design problems are more commonly in other engineering sectors, but the construction industry will have to adapt to new approaches to design.

5.2 Relevant technologies

Many technologies are likely to prove pivotal in addressing these challenges. At a basic level this includes existing capabilities such as databases, multi-core processors, the internet, mobile devices, GPS and radio frequency ID tags. At a higher level current BIM technology will need to be made scalable with seamless support for Smart Geometry and the incorporation of knowledge-based techniques (in the longer term case-based reasoning could be particularly important) and optimisation techniques. There is also considerable scope for developing a new approach to interoperability that overcomes the limitations of current approaches. In terms of physical delivery, it seems likely that cloud computing, in conjunction with fixed and mobile devices, will prove to be an appropriate delivery and collaboration platform [47].

5.3 Addressing the IT challenges

While section 5.1 directs the IT challenges towards the software vendors, the transformation of the building and allied sectors as-a-whole into full digital working will require the collective engagement of researchers, designers, contractors, building owners and operators together with all levels of government. The sector will ultimately be shaped by the nature and delivery of IT infrastructure upon which it relies, it thus needs to actively engage in the shaping of that infrastructure.

6. Discussion

The strategic challenges facing the building sector can be characterised as needing to give greater consideration to the wider (and long term) context of a building, to better justify the design prior to committing fiscal and physical resources and to more effectively deliver what the stakeholders and wider society require.

The increasing deployment and scope of BIM software and the wider implications of digital working (including the enhanced ability to create standard solutions and special solutions, greater use of automation, more off-site modularisation and an expectation of right-first-time) provide a trajectory for the industry. However, some unresolved questions remain. For example, who will ultimately control the IT tools, the information standards and even the processes employed in the building construction industry: will this be the industry, its clients, governments or the software vendors?

BIM is the current metaphor for the notion of digital buildings and inevitably a “beyond BIM” technology will emerge. Existing BIM solutions are just the start and major technical challenges and strategic issues have still to be addressed. However, it is clear that the successful introduction of a more unified BIM environment is likely to have significant implications for the future organisational structure of the building construction industry. Succar defines a series of (increasingly integrated) stages in the deployment of BIM and notes that the associated changes at an organisational and industrial level will be transformational rather than incremental [48].

The current evidence is that industry is rapidly adopting BIM software. Many firms are probably driven by the relatively immediate productivity advantages but BIM will soon be widely embedded as an agent for further change. There is already significant awareness of the strategic aspects of BIM and the desirability of open process and informatics standards to realize the full benefits [49]. A recent presentation at a conference [50] suggested that an UK government report, due early in 2011, will follow the lead in the US and recommend that the use of BIM technology effectively becomes mandated governmental contracts with a requirement to deliver models using open BIM formats [3].

7. Conclusions

The future building construction industry will be shaped by many forces including the commercial interests of the BIM vendors, pressure from clients to address the long standing challenges (see section 3) and the wider necessity to address the newer challenges such as sustainable and resilient design (see section 4). While it is not possible to predict just how this will resolve itself during the next twenty years and beyond, some form of advanced IT-based whole lifecycle integrated project delivery will be part of the solution. Similarly, the notion of digital buildings will evolve both to support the lifecycle of individual buildings and to play an increasing role in the wider operation of the industry itself.

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Category	**Informal Definition**
BIM authoring software	Software as described in the first paragraph of 2.2, a particular member of this class being referred to as a **particular BIM authoring package**.
Applications	Engineering software that is not BIM authoring software.
BIM aware applications	An application that has been written (or modified) specifically to communicate directly with one (or more) particular BIM authoring package(s).
BIM software	BIM authoring software and BIM aware applications.

Table 1: Engineering software categories (as used within this paper)

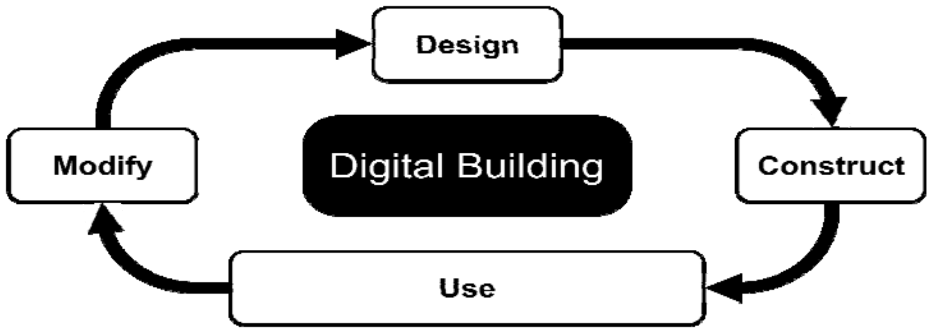

Figure 1: A four phase recursive representation of a building lifecycle

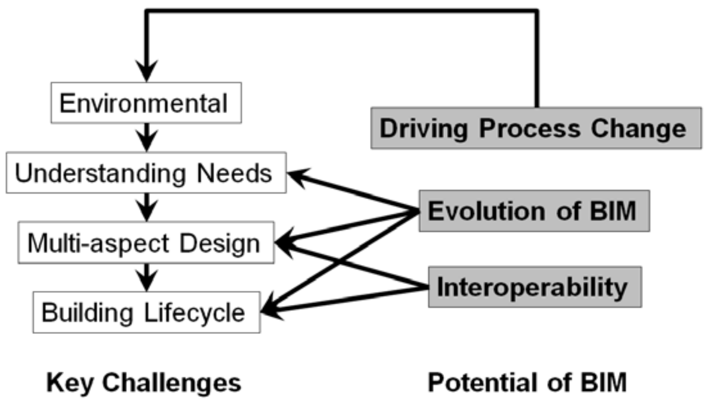

Figure 2: Primary Linkage between BIM Potential and Challenges

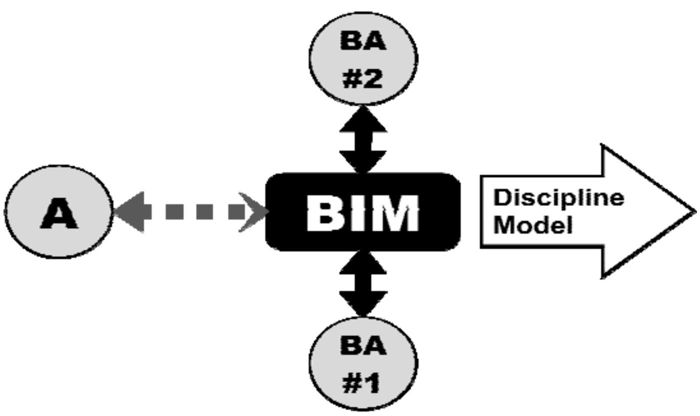

Figure 3: The interoperability of a particular BIM authoring package

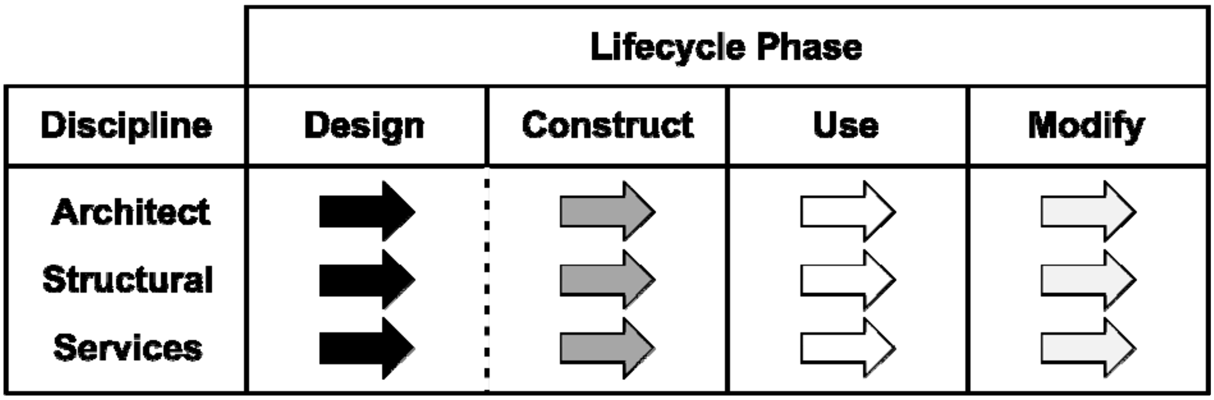

Figure 4: BIM authoring software: Typical current use and interoperability