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BIM for Infrastructure: An Overall Review and Constructor Perspective

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Abstract

The subject of Building Information Modelling (BIM) has become a central topic to the improvement of the AECOO (Architecture, Engineering, Construction, Owner and Operator) industry around the world, to the point where the concept is being expanded into domains it was not originally conceived to address. Transitioning BIM into the domain of infrastructure projects has provided challenges and emphasized the constructor perspective of BIM. Therefore, this study aims to collect the relevant literature regarding BIM within the Infrastructure domain and its use from the constructor perspective to review and analyse the current industry positioning and research state of the art, with regards to the set criteria. The review highlighted a developing base of BIM for infrastructure. From the analysis, the related research gaps were identified regarding information integration, alignment of BIM processes to constructor business processes & the effective governance and value of information. From this a unique research strategy utilising a framework for information governance coupled with a graph based distributed data environment is outlined to further progress the integration and efficiency of AECOO Infrastructure projects.

Key Words: Building Information Modelling (BIM); BIM for Infrastructure; constructor perspective; AECOO

1. Introduction

Building information modelling (BIM) has emerged into the mainstream bringing a different process of collaboration and a new way of working transforming current AECOO industry structures and practices, with the aim of improving efficiency & environmental objectives [36]. The subject of BIM has become a central topic to the improvement of the AECOO industry, to the point where the concept is being expanded into domains it was not originally conceived to address. Transitioning BIM into the domain of infrastructure projects has provided challenges and emphasized the constructor perspective of BIM. Many different countries across the world, including Norway, Singapore, Canada, the US and the UK have adopted BIM; and surveys conducted by McGraw-Hill Construction [48] revealed that western Europe was trailing behind north America which had a BIM adoption rate of 49% compared to an adoption rate of just over a third (36%) in western Europe. Of these adopters, 47% were Architects, 38% were engineers and 24% were contractors. This demonstrated the lack of adoption within the contracting sector due to a possible lack of understanding of the contractor role within BIM.

On a UK perspective The National Building Specification have conducted annual BIM reports and surveys, the latest NBS BIM report 2015 [65] depicts an expanding outlook, showing that BIM adoption in the UK has gained traction, increasing its adoption level from 13% in 2010 to 40% in 2012 and continuing to 50% in 2014 a substantial increase in a short period of time. In Contrast, similar Surveys conducted by McGraw Hill Construction [47] for the United States show that BIM use for Infrastructure is about 3 years behind that of buildings, only reaching a 50% adoption rate in 2013. These levels will continue to rise as further academic research is undertaken and the UK industry reaches the government mandated BIM level 2 and continues on through to level 3.

Construction industry is one of the key industries in the UK in meeting the requirements of the Climate Change Act 2008 that legalised the target to reduce CO_2 emissions by 80% by 2050 [29]. This culminated in the issuing of a UK government mandate for the use of ‘Maturity Level 2’ fully collaborative BIM by 2016 [11]. The mandate has specified BIM to be used on *all* public works, meaning a mandated use within the infrastructure sector such as rail, road, utilities and energy projects that are longitudinal in nature compared to the generally vertical nature of building projects. Infrastructure contractors & engineers have found themselves having to begin an accelerated BIM deployment in the form of both design BIM and field (site) BIM in a sector that is known for its heavy use of 2D based design and large volume of static documentation. Adaptation of the BIM concept to suit the specific requirements of infrastructure projects will be a key aspect in effective BIM deployment & UK contractors' ability to meet the 2016 requirement.

In view of the potential benefits of BIM for the Infrastructure construction industry, this study aims to provide a review of existing research and industry development on the use of the BIM concept within the Infrastructure sector and its application by the contractor role. In order to achieve the above target, this review collects more than 250 key publications in the relevant area, and analyses the trends for BIM development for infrastructure according to publication year, publication origin, project phase in question and publication scope. The review highlighted a developing base of BIM for infrastructure. From the Analysis, the related research gaps were identified regarding information integration, alignment of BIM processes to contractor business processes & the effective governance and value of information.

The following contents are organized as follows. A brief explanation of BIM and the Infrastructure sector is give in section 2.The review methodology is explained in section 3; Section 4 presents the main statistical contents of the review; followed by section 5 – discussion & gap identification. The conclusion is given in section 6.

2. BIM & The Infrastructure Sector

BIM is defined as the art of information management & collection by CPIC (Construction Project Information Committee); a process that runs through the entire asset lifecycle[32,57]; and a Digital representation of physical & functional elements of an asset used for decision making[53]. What is common from these definitions is that the BIM concept is made up of four key elements; collaboration, representation, process & Lifecycle which all interact

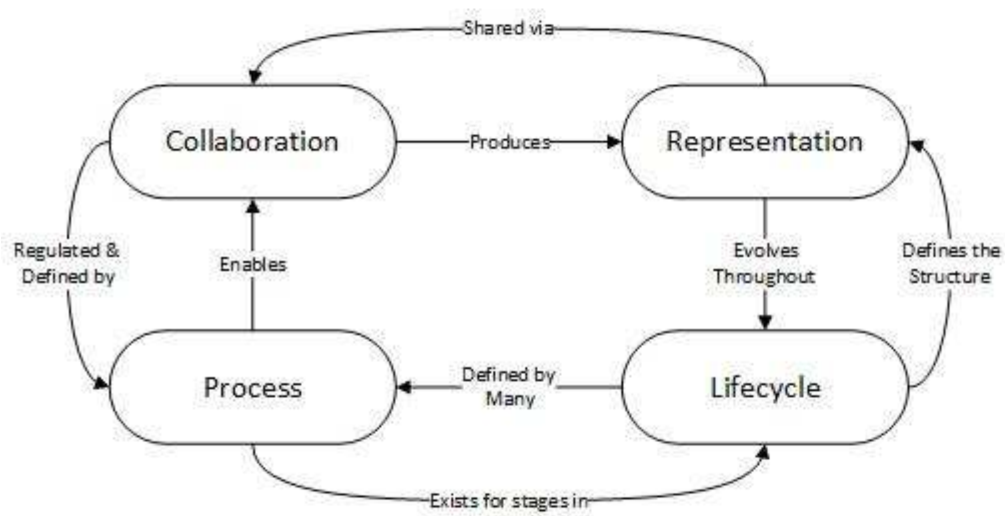

Figure 1 'BIM in a Nutshell' 4 key elements of the BIM concept

with each other to create an innovative and efficient project environment (Figure 1).

Infrastructure is defined by the oxford dictionary as 'the basic physical and organizational structures and facilities needed for the operation of a society or enterprise'[56]. Therefore, Infrastructure assets can be broken down in to 5 main domains[14]:

- Transportation infrastructure - roads, railways, bridges, tunnels and mass transit hubs (such as airports, ports & harbours)
- Energy infrastructure – power generation plants (nuclear, wind, tidal etc.), oil & gas (storage/distribution terminals, refineries, wells etc.) and mining.
- Utility infrastructure – networks/pipelines for the delivery and removal of electricity, gas, water & sewage
- Recreational facilities infrastructure – Parks, Stadiums etc.
- Environmental infrastructure – Structures for managing flood and coastal defence such as dams, levees, weirs or embankments.

3 out of 5 (road, environmental & utility) of the domains are formed of a mesh network of assets, longitudinal structures connecting point structures. This generates differences in project breakdown structures compared to buildings, greater usage of GIS due to the expansive size of networks, a more mature asset management process, creating a greater value focus on non-graphical data and its meaningful connection into a project model. In relation to BIM this provides mark differences in data structure, connectivity and variety and collaborative team and project size that is far more expansive than traditional building projects.

3. Review Methodology

In order to produce a comprehensive review on the subject of BIM for infrastructure, this review has 2 components:

- Research Publications & Projects – consisting of journal articles and conference papers. Informing on research topics under investigation and existing state of the art work already completed. This information is collected via systematic literature research using keywords and content criteria.
- Industry Standards & Procedures – consisting of international, national & commercial standards created to guide or govern the use of BIM within the AECOO industry. These standards heavily influence each other but still remain unique to their geographical domain. This information is collected through online resources such as The International Standards Organisation (ISO), British Standards institute (BSi), etc.

The literature search was conducted on 4 academic databases selected for their comprehensive coverage on the subjects of engineering, construction & computing in construction, and combined cover the majority of major journal and conference publications. These were Scopus, Engineering Village, Science direct & Web of Science. The subject of this study considers the intersection of building information modelling (BIM) and the infrastructure sector, supplemented with transferable construction phase (main part of constructor/contractor role) content. To capture literature relating to BIM in construction and/or infrastructure the following search criterion was devised: ((*BIM* **OR** *Building Information Modelling*) **AND** (*Infrastructure* **OR** *Construction)*) within (*Title* **OR** *Keyword*)).

The use of the 'OR' operator instead of 'AND' between infrastructure and construction is due to the generality of BIM across different project types allowing the collection of BIM components applied to other sectors that are applicable and transferrable to Infrastructure projects. The results of the initial search (raw findings before removal of duplicates) and breakdown into the specific subject domains are depicted in Table 1. Duplication was addressed leaving a final volume of 1080 unique entries.

Table 1 Initial Volume returned for the literature search exercise

	Scopus	*Engineering Village*	*Science Direct*	*Web of Science*	*Totals*
BIM Infrastructure	50	71	11	46	178
BIM Construction	1057	901	183	675	2816
Totals	**1107**	**972**	**194**	**721**	**2994**

Following steps involved the removal of irrelevant publication types leaving only journal articles and conference papers, rating of the literature based on the criterion in Table 2, removal of literature rated 2 or less with ratings of 3 reviewed further for relevant to infrastructure. Leaving a final literature volume of 259 papers. A combined quantitative and qualitative approach was taken to further classify and analyse the literature presented in section 4.

Table 2 Descriptions of ratings criteria

RATING	DESCRIPTION OF CRITERION
5	Focuses on the Construction phase of infrastructure projects/domain
4	Focuses on BIM in infrastructure projects OR a highly transferrable BIM construction application/review
3	Generalised non-specific work on BIM in infrastructure OR construction BIM research that is considered relevant to the infrastructure domain
2	Relevant BIM subject but is not transferable or relevant to Infrastructure
1	Irrelevant literature that does not concern BIM, infrastructure or Construction

Standards relating to BIM were sourced from the relevant national and international governing bodies (e.g. British Standards Institute (BSi), The International Standards Organisation (ISO), National Institute of Building Sciences (USA), BuildingSMART Institute (bSi) etc.). Selection of the required standards was guided by industry resources and knowledge gathered at various conferences and events, along with information from the literature reviewed.

4. Statistical overview of BIM for infrastructure development

The aim of this section is to provide a quantitative analysis and qualitative discussion of the reviewed research literature and industry standards

4.1 Distribution of Publications over Time

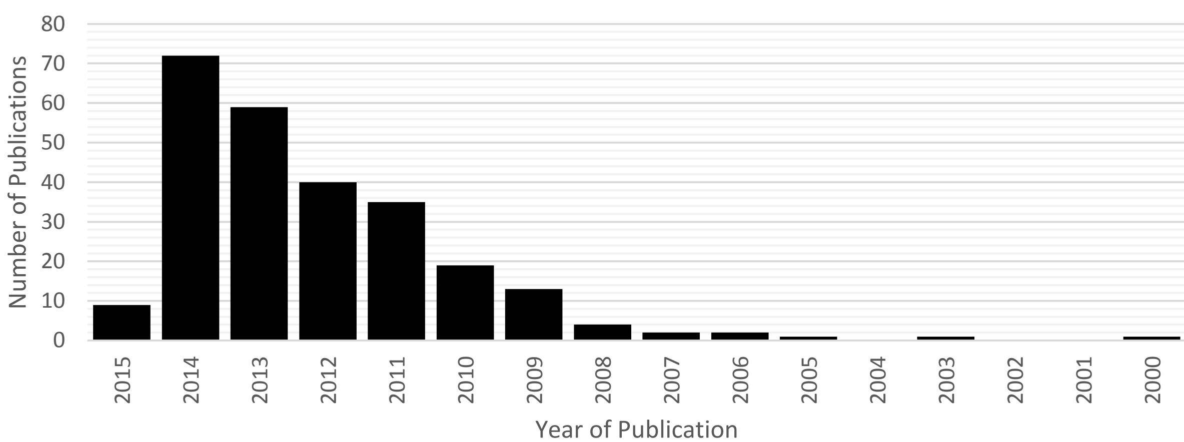

Figure 2 Distribution of publications over time (2015 not complete year)

As can be observed from Figure and observations made during the literature review process, BIM development has been explored since the late 90s and early 2000s.In 2000, Shi and Deng [59] developed an object orientated resource-based planning method, one of the first object based methods for planning of construction. This was followed by work conducted by Fu, et al. [21] and Gökçe, et al. [23] which used the developing IFC standard to explore IT supported life cycling costing and project management (respectively). It can be observed that from 2008 a large upward trend in the volume of published work in the field of BIM (relating to Infrastructure & Construction) emerged with over 70 papers published last year (2014) and over 50% of this study's literature volume emerging in the last 2 years (2013-2014). The increasing complexities and decreasing time and capital of AECOO projects has resulted in a greater reliance on information and communication technology (ICT), and transition to new object-orientated processes such as BIM. Thus it is expected that the requirement and demand for research into BIM will continue to rise and will include expansion into infrastructure projects and the entire lifecycle of built architecture.

4.2 Distribution of Publications by industry Sector

The Literature volume consisted of papers focusing on the infrastructure sector, buildings sector and generic work that has no specific sector focus (Left Figure 3). The presence of building sector work in this infrastructure BIM review is due to the inclusion of construction BIM studies that are considered to be transferable to infrastructure projects.

Focusing on the infrastructure sector publications the prominent sectors are general infrastructure research (25), Highways & Bridges (23) and the Alignment of Geographical Information Systems (GIS) with BIM (22). Also, the transport domain makes up ~40% of Infrastructure research, the majority of which is highways & bridges, though this research is highly transferrable to rail and tunnelling due to the similar information structure and processes. It

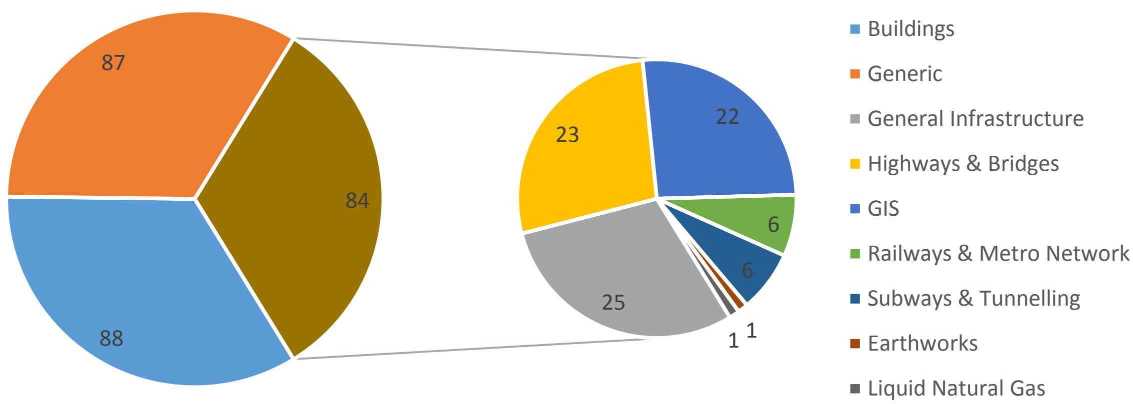

Figure 3 Distribution of publications by Industry Sector

must be noted the lack of utilities and environmental infrastructure domain research.

4.3 Distribution of Publications by Country

A Total of 27 different countries produced the 259 literature volume displaying the truly international scope of BIM. Of the total volume the United States, Korea and China contributed 40+, with the UK (23) and Germany (20) forming the majority of European contributions, plus notable additions from Canada (14) and Australia (13). In Regional terms, China, Korea and neighbouring states account for ~40% (102), with Europe and North America providing ~25% each.

In infrastructure (Figure 4) Korea and China are responsible for over 40% of the work with a high percentage of the Highways & bridges work conducted here. In reference to the study subject of Infrastructure & Construction BIM, it was observed that eastern Asia countries are producing a high volume of work on infrastructure subjects where as in Europe the focus was on buildings and design with a growing shift towards infrastructure subjects.

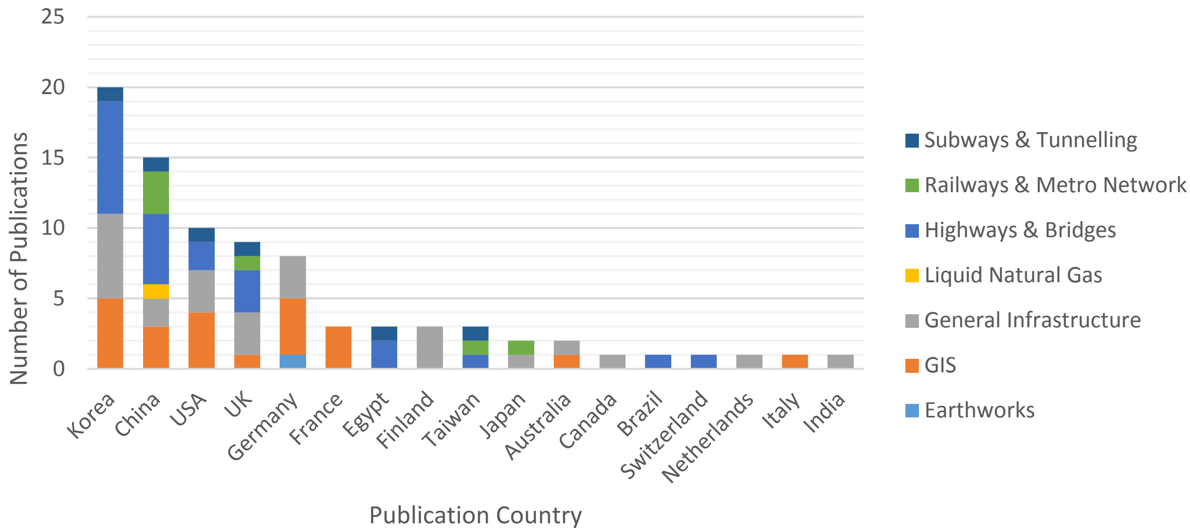

Figure 4 Distribution of Infrastructure publications by Country & industry sector

4.4 Distribution of Publications by Project Phase

Figure a displays the distribution of publications by the project phase being addressed. It must first be noted that a publication can focus on more than one phase. For example, papers often address both the Design and Construction phases when the subject is around project collaboration, whereas the term life-cycle refers to papers that address all phases in a cyclic unending fashion. The phases concerned are procurement, design, construction, handover, operation and maintenance and the unifying Life-Cycle concept.

In terms of the total volume, The construction phase is the most common phase addressed with 182 papers, this is in part due to the inclusion of transferable construction BIM subjects within the volume reviewed limiting the insights that can be gained. The next most common phase work has been conducted on is the life-cycle level (47), and design (32).

Focusing on the 84 publications that address the infrastructure sector. Figure 5b Shows the majority of research is concerned with the construction (32) and the Life – cycle concepts (29). Design forms a smaller volume in infrastructure possible due to the fact that the bulk of the work has been completed via the buildings domain, but this work still needs to be transitioned to infrastructure projects. Operation & Maintenance features in a notable volume most probably due to the advanced and mature nature of Infrastructure asset management.

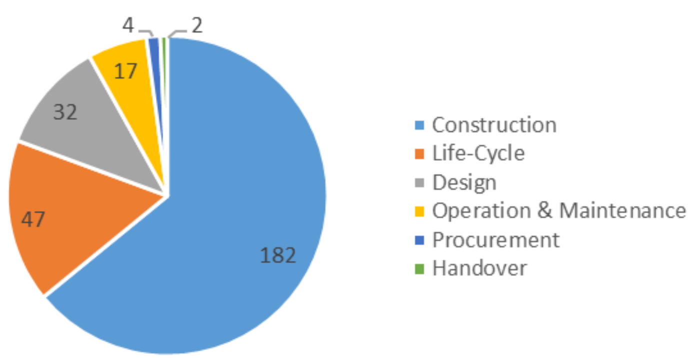

Figure 5a Publications by project phase addressed (total volume)

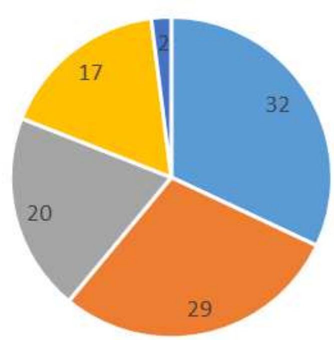

Figure 5b Publications by project phase addressed (Infrastructure publications)

4.5 Distribution of Publications by organisational level

Infrastructure and BIM research can be conducted at different organisational levels within the AECOO Industry, these levels are depicted in Figure 6 and defined as sub-project - research on a very specific task or subject that can exist as a silo of work within a project. Project level - address subjects that are present throughout an AECOO project but entirely encapsulated within it, ending when a project ends and starting new during the next project. Company - research that spans many projects conducted by a single company usually involving iterative learning processes to improve outcomes as each project is conducted. Lastly industry refers to studies relating to industry standards, data structures and perceptions that are applicable to the entire industry.

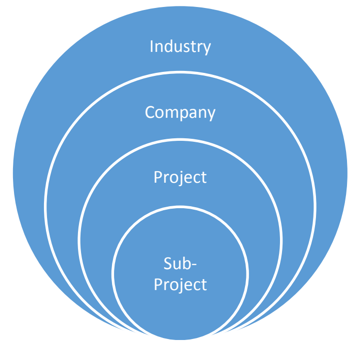

Figure 6 structure of organisational levels

From Figure 7 it is clear to see that the majority of the literature volume is focused at the project level with 144 papers (68%), generating systems that refer to dimensions and processes that exist throughout the entire project, some interesting examples are a case study of a steel bridge project by Liu, et al. [41] utilising 5D integrated design and construction and Cho, et al. [16] review of the BIM-based integrated construction management system utilised on a complex 10km rail project. Company level (44 papers) examples include integrating resource production and construction activities [4]. While industry level research (41) is mostly development of industry data standards such as development of a BIM ontology standard [37], Connecting IFC and CityGML [30], Interoperability between GIS and BIM [50] or an extension of the IFC to incorporate road drainage[25]. Sub-project level work involving specific isolated tools or systems is currently limited at the moment most probably due to the fact that researchers are still trying to understand the larger problems relating to projects and life cycles. Interesting examples include integrating barcodes and QR codes within BIM systems for construction management [42,63] and different automated methods for quantity take-off such as knowledge-based ontology reasoning [3].

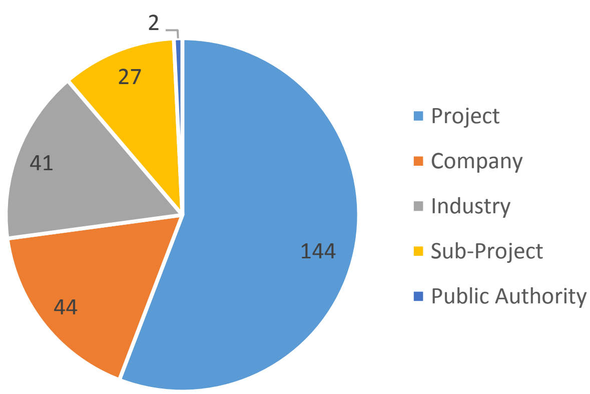

Figure 7 Distribution of publications by organisation level

4.6 Research Themes & Products

From Figure 8 the 2 most common research themes encountered within the literature volume involved ICT system Development with 79 publications and the modelling of AECOO information or processes including methodologies for using the information (76). The development of frameworks to describe specific subjects or integration of components was prominent with 38 publications. With the rest of the main body taken up by case studies for example use of BIM on the heads of the valleys project in the UK [60] and the Northern Hub Rail Improvements [61], subject analysis themes such as an analysis of BIM implementations in infrastructure [68] and literature reviews.

From these research themes many different types of products or deliverables emerged (figure 9), the most common of which was ICT system prototypes such as the system by Sulbaran and Strelzoff [64] for integrating BIM software and costing software to generate estimates or Braun, et al. [7]'s system for determining progress monitoring using photographs and 3D point clouds.

As would be expected these system prototypes emerge from papers with a system development theme, but also several papers on frameworks and information modelling have yielded practical system prototypes. 34 publications generated tool prototypes which involve smaller ICT applications such as Cao and Zheng [12]'s Revit plugin utilising a cost decision model for design insights or Moon, et al. [52]'s BIM genetic algorithm tool for minimising workspace interference in the construction sequence. Study analyses (61 publications) outcomes form a large volume of research outcomes as these stem from subject analyses, case studies and literature review themes, providing valuable knowledge on industry implementations such as Mäki and Kerosuo [44]'s case study on the daily use of BIM by Site managers, to the comparison of the accuracy of new and old strategies such as McCuen and Del Puerto [46]'s comparative case study on BIM based and traditional Estimation. Other notable studies include Hajian and Becerik-Gerber [26]'s review of current field data acquisition technologies a subject that is being utilised in generating as-built models and also deducing the progress of the works. The last type of outcome is data models or data methodologies (41 Publications) these outcomes result in a new data structure or data mapping to either integrate or connect data sources. Examples consist of IFC extensions for GIS [6], the creation of query languages such as a spatial query language for BIM [5] or query methods for extracting

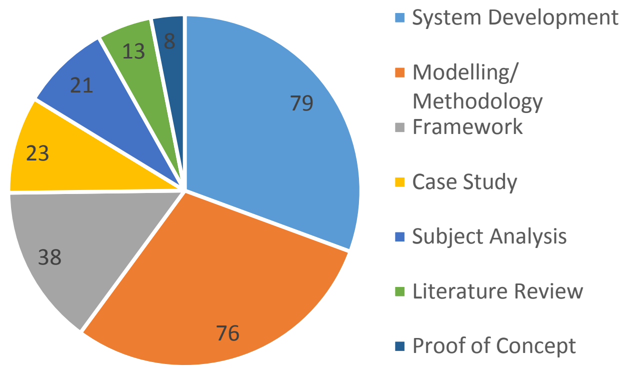

Figure 8 Publication research themes

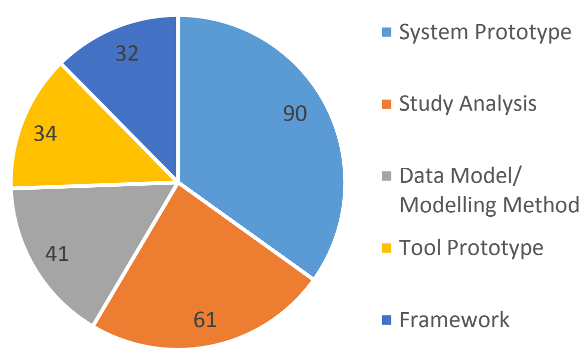

Figure 9 Publication research outcomes

construction information from IFC based models [55].

4.7 Business Dimensions/Processes

A business dimension/process in this paper refers to the grouping of project processes into domains or departments and mainly refer to the activities of the constructor role. Of the 259 publications 211 address 1 or more business processes. Cost management involving the generation of estimates and accounting onsite and time management involving the generation/update of 4D schedules and time simulation of the works were the most addressed processes with 53 publications each. Integration of many systems for overall project management and methods/systems for the progress monitoring of works were the next common with 28 publications each. Health and safety (25) integration within BIM is becoming a growing subject along with the leveraging of BIM for enterprise resource management (ERM) (22). Figure 10 also highlights the under development of quality management (6) a major business process and one of the 4 components of the Project management 'triangle' (Cost, Time, Quality, Health & Safety). Other emerging areas include the leveraging of 4D BIM models to analyse constructability (6), for example Chen, et al. [13] analyses space utilisation to improve construction sequencing and to perform time based clash detection in addition to the traditional static clash detection.

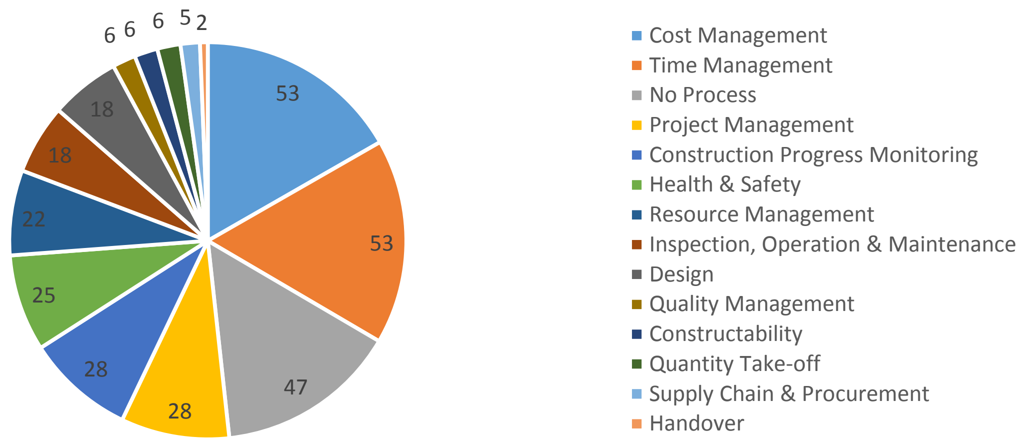

Figure 10 Business Processes/Dimensions addressed

4.8 BIM standards

Standards exist to provide guidance and best practice on a particular subjects and are effective within a particular domain. These domains usually refer to the geographical scope of the standard. From this study the most relevant standards on the subject of BIM in infrastructure and construction were found and reviewed.

IFC-IDM-MVD (ISO 16739 & 29481)

BIM as a process involves the generation and management of data and information associated with an AECOO industry project over its entire lifecycle from brief to decommissioning [32]. Therefore, to facilitate this consolidation of knowledge over multiple disciplines each utilising specialist BIM tools, a common data format/structure for information transfer is required. Industry Foundation Classes (IFC) is an example of an open common data format. It is an open data model schema for the definition of components' geometry and other physical properties to allow the transfer of data between CAD applications [32]. It provides a rigid and authoritative semantic definition of the asset elements and associated relationships, properties and descriptive information. IFC is developed and maintained by BuildingSMART and is documented as an international standard (ISO16739:2013 [35]), the latest release of IFC is named IFC4 Add 1 (released July 2015) and will replace the existing current release of IFC2x3-TC1.

The IFC by nature is a large and complex data schema (data format) designed to comprehensively store all aspects of an AECOO industry project and the resultant asset [10]. Therefore, complete implementation is not viable by software vendors. To address this the IDM-MVD methodology (Information Delivery Manual & Model View Definition) was developed which in simplistic terms is a targeted exchange of project information working on the premise to only exchange what is relevant and required for specific activities, using the IFC as the parent data schema. Briefly IDM defines an industry process that requires the exchange of information between two software packages, defining the process and exchange requirements. Coupled with this is the MVD (Model View Definition) which is the technical implementation of the exchange requirements in the form of a subset of the overall data schema. Figure 11 shows the interaction between IDM and MVD.

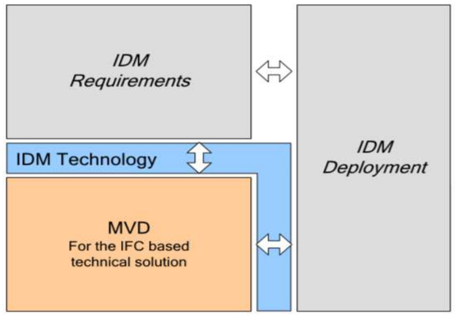

Figure 11 The role of MVD (with IDM for requirement and deployment Description) extracted from buildingSMART website

UK BIM Industry Standards

The United Kingdom's strategy for BIM standardisation currently involves around 8 documents. 5 of these form the main 1192 series of BIM standards, along with the CIC BIM Protocol, the digital plan of works and the Uniclass classification system.

The 1192 series of standards forms a set high level processes for the collection, specification and transfer of information throughout the lifecycle of built assets. Each standard addresses different processes within the project lifecycle. The earliest standard BS1192: 2007 collaborative production of AEC information, focused on the process of authoring and sharing information through collaborative environments, such as shared file systems such as network accessible storage and cloud technologies or document management systems such as SharePoint. The standard assigns shared information with specific states to describe its completeness and relevance. These states help share information sooner but still allows for the information to change before it is fixed as a binding issued design.

PAS1192-2: 2013 specification for information management during capital/Delivery phase of construction projects using BIM is the second standard in the series and the first true BIM standard. 1192-2 lays out the high level process for the planning and generation of the Project Information Model (PIM) containing graphical, non-graphical and document type data. Its main strength and BIM enabling aspect lies in a series of 3 documents namely the Employer's Information Requirements (EIR), BIM Execution Plan (BEP) and Master Information Delivery Plan (MIDP), which in combination specify the who, what and how for all project information explicitly specifying roles, responsibility and information ownership to facilitate the use of a singular integrated or federated PIM.

The follow on standard from 1192-2 is PAS1192-3:2014 Specification for information management for the operational phase of assets using BIM. Similar to 1192 part 2, part 3 lays out high level processes for the management, generation and maintenance of information. The difference lies in the purpose of the data being used. This data forms an Asset Information Model (AIM) used to monitor, analyse and cost effectively improve the performance of a built asset. The processes are tightly interlinked with part 2 forming a iterative loop of 'Plan - Design - Construct – Operate'. The PIM of a capital project contributes to the information stored within the Asset Information Model and is specified by the Asset information requirements. The AIR is also used to inform and cis integrated as an element of the EIR in the event of a new project being commissioned on an existing Asset. This standardised method of project management and asset management helps to seamlessly integrate information throughout the cyclic lifecycle of built assets, and provides a means for the efficient generation and reuse of information.

BS1192-4: Collaborative production of Information part 4: fulfilling Employer's information Exchange requirements using COBie, in simplest terms can described as the connection mechanism between Client and employer or construction to in-use phase. It is a methodology for the structured exchange of information relating to built assets. The code of practice details the use of the COBie format (Construction Operations Building infromation exchange) to exchange the information specified via the processes and documents detailled in 1192 part 2, assisting the demand (client) side in specifying and using relevent and accessible data, while allowing the information providers a mechanism to extract and prepare concise, unambiguous information that can be easily checked and interpreted on the client side. with this massive uptake of active collaborative data production, storage and transfer it has become apparent that the issue of data integrity and security needs to be addressed.

PAS1192-5: Specification for security-minded building information management, digital built environments and smart asset management, addresses the security issues relating to asset and built environment data produced and utilised throughout the project life cycle. It will outline steps to create a Security mind-set facilitating the safe and secure use of the information generated by a project enabling the full utilisation of the BIM Concept with out restrictions being emposed due to security issues and threats. In this ever more digital age the security of data is ever more apparent and is in direct opposition to data availability.

US standards

The central BIM standard for the USA is namely the US BIM Standard version 3 (NBIMS v3). NBIMS v3 differs to the traditional standards produced by entities such as ISO and BSi. It is the first open consensus BIM standard, developed by allowing anyone to submit changes and recommendations, which were then reviewed and voted on by the project committee. The standard is a collection of other standards and guidance that have been deemed as vital to conducting a BIM approach. The collection includes reference standards for Omniclass, IFC and the BiuldingSMART Data Dictionary, an extensive section on terms and definitions and a set of recommended Information Exchange Standards, along with a set of practice documents designed to inform practitioners on the correct and efficient use of BIM on projects. Similar to the stance of the UK BIM standards NBIMS address AECO projects in a generic sense considering both buildings and infrastructure projects.

European Standards

Several European countries have either mandated BIM use on projects or released formal Standards. Two Similar examples are Finland's Common BIM Requirements (known as COBIM) [9] and Norway's Statsbygg BIM Manual [62] which take the approach of specifying an extensive set of BIM Requirements, forming the general project requirements as well as topic specific domain model requirements (such as structural model requirements, as-built requirements & quantity Take-off). In addition the Statsbygg BIM manual also provides information in how the model will be analysed by the client and best practices the supplier will be expected to follow. These examples take on a checklist/requirement and instruction style of standardization compared to the Informative procedural frameworks and conventions defined in the UK and US standards. Procedural frameworks provide a methodology for the tailoring of a BIM solution to a specific project. Another European Example is the Netherlands Rgd BIM Standard [58] that provides a framework of specific subjects that must have an agreed convention or protocol for the project, it attempts to merge the specifics of a requirements based standard with the tailoring ability of the framework approach without specifying a formal BIM definition process (usually culminating in the production of a BIM Execution Plan or similarly named document). Noticeably all these standards have a narrow scope only focusing on buildings and do not address the use of BIM for Infrastructure.

Asia & Australia Standards

Mature examples of BIM standards from the Asia & Australia continents come in the form of Singapore's BIM Guide [8] which is coupled with their integrated e-information platform CoreNet, and Australia NATSPEC National BIM Guide [54]. Singapore's BIM Guide is very much a procedural framework for producing a BIM Execution Plan with the addition of examples of how to specify information requirements. It considers and provides aspects related to a civil project, but does not address them specifically, but like the UK standard remains open enough to facilitate its use on Infrastructure projects. Australia's National BIM Guide is a fusion of a procedural framework and requirements definition. If provides a similar framework methodology to the BIM execution Plan (calling it a BIM Management Plan) but also states minimum requirements related to specific subjects that form the base for the defined project BIM requirements. More recently (September 2015) Hong Kong have released their CIC BIM standards [31] these are heavily based on Pennsylvania State University's BIM Execution Planning Guide [17] using a modified version of their procedural framework for defining a BIM Execution Plan, with the addition of a level of detail specification and definition matrix.

4.9 Implications & common themes

In its current state IFC is 'able' to act as a full scale transfer mechanism for infrastructure project data. The drawback is that infrastructure specific objects and types are not recognised and are transferred as unknown elements leading to loss in semantic meaning. Certain aspects such as IFC for bridges and the recently released IFC alignment extension is well developed and has begun the steps required to incorporate linear assets within the IFC environment, but further development to fully incorporate road and rail is under development [25].

Common themes among countries producing BIM standards and documentation revolve around the BIM execution plan which has become the staple document defining the usage of BIM on AECOO projects. All standards and supporting documents emphasise the definition of data to be produced and made available throughout the project striving to encourage project stake holders to define the who, what, where, why and how for all information in an effort to improve efficiency and applicability of the work undertaken. The themes addressed can be broken down into 5 categories each addressing different types of datasets and processes:

- General Project Information
- BIM Deliverables
- Data Composition, Segregation & Linking
- Modelling Standards
- Collaboration Among Participants

Project Information –consists of data such as the basic project details, client details, project stakeholder information such as the designer or principal contractor and information about project programme and procurement type. The content of this information has not changed much with the advent of BIM but the use of collaborative environments has provided the means to centralise this information, and most importantly requires the explicit definition of stakeholder roles and responsibilities to facilitate effective BIM usage. All standards address this subject well providing processes for the definition and use of project information.

BIM Deliverables – All Standards emphasise the explicit definition of what information needs to be produced and who need to contribute this information into the central project information model. This definition is provided either by a requirements based BIM standard, or produced as part of a procedural framework. The definition of deliverables at the start of the project is key to the reduction of wasted working time producing information that will not be used or is irrelevant to the client and will provide direction and targets for the project participants to work towards. The best example that is often referenced by other standards is the processes implemented by PAS1192-2 & 3.

Data Composition, Segregation and Linking – another key topic that has emerged in the standards is the specification of how data is both isolated and connected. Isolation is key to maintaining data integrity and security while linking is one of the key concepts of BIM and where many of the gains are derived from. This balancing act can prove the defining factor in the effective use of BIM on a project.

Modelling standards – another common theme is the definition of how models are constructed, which includes the explicit definition of what software will be used, co-ordinate systems with a single project origin, levels of model definition (LOMD) and volume division. The aim of defining these points is to facilitate efficient Collaboration and data transfer. Also via LOMD plan the development of the model over time so that information is available when required reducing delays. The American NBIMS standard addresses the area of model definition in detail, and NBS's implementation of the digital plan of works facilities a process and toolkit for the planning and checking of model development us LOMD as its key parameter.

Collaboration among participants – One of the main points addressed within the standards is the definition of how data will be shared the process for sharing that data. This theme ties in with modelling standards and BIM deliverables. Defining the means by which the information will be delivered and also how the information produced to the modelling standards will be passed between participants. It is expected that the transfer of data between participants will be predominantly in the form of IFC, though other methods such as vendor proprietary data formats are still used. All standards facilitate the definition of a common data environment (CDE) and collaboration procedure.

It is clear by the variety of standards available both for specific regions and internationally that a considerable amount of work is being done to standardise and facilitate the use of BIM. Most standards address the same areas in the application of BIM though more needs to be done on the specification and standardisation of BIM subjects relevant to the construction phase of projects as most standards are heavily bias towards the production of the design model, and do not directly address the 4^{th} and 5^{th} dimensions of cost and programme.

Though these standards have made strides to improve BIM implementations the key to effective BIM usage lies in their correct use and understanding by project participants and the willingness to move away from traditional practices embracing the BIM concept.

5. The constructor perspective of BIM for infrastructure development

From the investigation into infrastructure projects and current BIM concepts it can be seen that some aspects are very similar to their building sector counter parts such as the design review process, collaboration methodology, and to some extent the co-ordination of the works which can take the same approach as building sector BIM. The main difference comes with the consideration of advantage, modelling in buildings is very component based and provides advantages in clash detection, clarity of information and visual aids during the design stage. In contrast a highways project has minimal need for clash detection and extensive modelling during the design stage as other than providing advanced visualisation does not add much value. The advantage in highways comes from the co-ordination and visual integration of non-graphical data into the model, and will be used most efficiently during the pre- construction and construction phase, linking field gathered information into a site (field) BIM modelling approach, generating accurate and data rich Project Information models (Figure 13) to be transferred to the operating agents in a form that can be automatically integrated into their network dataset. As with any BIM approach the effectiveness and usefulness of the data revolves around the ability to specify what data to collect, who will collect it and how it will be utilised, along with the provision of technologies to capture and transfer the data between participating parties (Figure 12Figure).

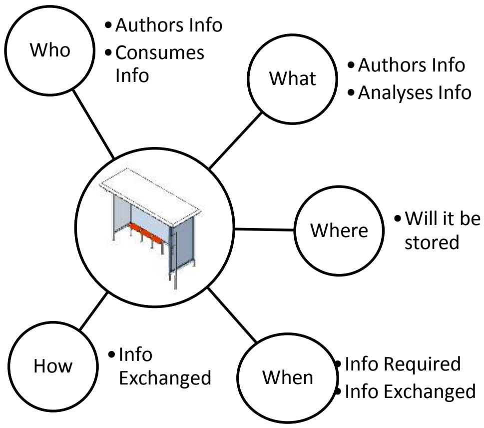

Figure 12 BIM Object Information Definition

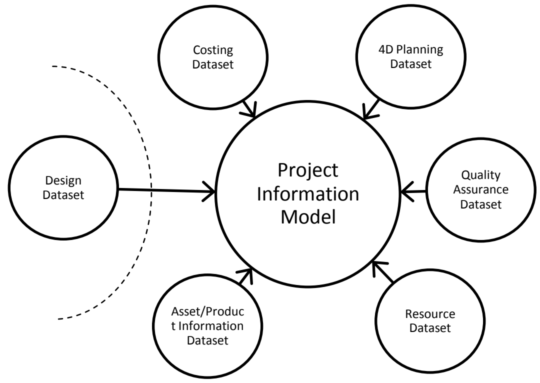

Figure 13 Contractor Datasets contributed to Project Information Model

5.1 Infrastructure BIM

The use of BIM in the infrastructure domain is a subject growing rapidly in conjunction with the traditional BIM concept. As analysed previously infrastructure BIM research is focused mainly on the integration of GIS, its use on highways and bridges and the general implementation process (Figure). The limited research into design is most probably due to the fact that most of the major transferable BIM research (research that can be applied in the infrastructure sector) has already been completed in the build hnyings domain. Other factors include the direction of the driving forces for BIM adoption in Infrastructure coming from the operational phase working backwards, due to the advanced asset management capabilities of infrastructure clients, compared with buildings where the BIM driving force started from the design practitioners and has been driven forwards through the phases. Most of the infrastructure design phase research within this study is concerned with case studies of practical examples or the design and representation at an object level of the unique linear structure of infrastructure projects such as roads, rail or tunnels. The level of O & M research also shows that the industry and researchers believe BIM can be leveraged in the integrated management of entire asset networks such as highway networks, rail networks and utilities. By using integrated information databases and mappings to external data sources it would be plausible to manage a network of assets more effectively and provide the optimal application of capital, time and resources to meet defined objectives.

The large volume of construction phase research also provides evidence to the concept that the 4th (time) and 5th (cost) dimensions of BIM will provide major efficiency and quality gains within the infrastructure sector from ideas such as space conflict checking on bridge projects [51], the use of aerial and satellite images for construction monitoring [27], or the use of integrated cost and schedule models for fast evaluation of highway alignments [38].

From the literature volume a few initial concepts can be described comparing building IM and infrastructure IM. When it comes to buildings, detailed geometry and component data can be said to be the most useful, providing the ability to perform clash detection, co-ordination and generate linked costs and tasks. Whereas in infrastructure detailed geometry data is less important as the analysis it makes possible (e.g. clash detection) is of less benefit and is reliant on accurate data from other domains such as utilities. The most beneficial data on an infrastructure project comes from what can be termed non-graphical data such as cost information, material specifications, and component performance data.

What this can all be broken down to is a concept of 'data usefulness', involving the modelling and inclusion of information that can be leveraged for the most effective gains and discarding or not producing information that will be either be unused or has no value adding capability. Therefore, utilising this concept designers and constructors can specify what information is needed for what tasks and produce models with varying levels of model definition to be fit for purpose reducing both development time and capital expenditure.

5.2 Data/process Models

As described previously in section 4.6, 38 different data/process models were developed. The most relevant of these are concerned with IFC extensions to cover infrastructure domains, mappings for linking domain models and lastly process models for the use and correct production of AECOO data.

Examples of projects to create IFC extensions were uncovered within the literature volume. Ha, et al. [25]'s work developing IFC for roads/drainage defining the elements, objects and relationships required to represent road systems is key to the continuing expansion of IFC and also the collaborative use of BIM for highway design and its use in Network management. Other key developing points include Borrmann, et al. [6]'s work on multi-scale tunnel modelling which in turn discusses the extension of IFC for use on tunnelling including the definition of GIS style multi-scale representations a kin to those found in formats such as CityGML. Unique points include the ability to cascade updates between scales meaning updates on the model at a coarse level automatically updates at the finer levels. This work is promising and while providing an initial foray into IFC for tunnelling it also completes some of the work required to extend IFC for GIS purposes. Other work includes Zhiliang, et al. [69]'s development on the IFC information requirements for cost estimating, utilising the information delivery manual technique. Defining information requirements is key to providing correct and relevant data at different stages within a project. Lastly spatial query languages have been developed to better interpret and extract construction information that is hidden or only defined implicitly within the IFC model. The approach provides a richer more usable representation of construction information by layering additional graphical information on top of the model removing the need to manually extract the information.

Mapping between different data sources and data models is becoming common place mostly due to the ever expanding number of data formats and sources available and interest in utilising ontologies for knowledge bases and information connection. From this the most interesting piece of literature by Karshenas and Niknam [37] involves using a conversion of the widely used IFC format into an ontology schema to aid in the cross domain information sharing by mapping elements and properties from one domain to another via SWRL Rules (semantic Web Rule Language). This method is interesting as it provides a rule based process to actively update connected properties but still maintaining the information separation between domains. Other interesting uses of data mapping involves the mapping of building information models to a cost information model. Lawrence, et al. [39] developed a generic approach to create flexible mappings between BIM objects and cost items using a query based approach to populate views which are then associated to one or more cost items. The benefits stated are the flexibility of the mappings allowing encoding of a variety of relationships between the design and cost estimate and removes the need for using a common standard for designers and estimators. This approach has its merits but will require a level of programming knowledge on the estimator's part to write and implement the required queries.

Along with data formats and mappings, data linked process models have become popular to both specify the correct procedures for today's IT and data driven activities and to provide innovative solutions to tedious activities. The most notable example in the literature volume is Ajam, et al. [1]'s augmented process model for electronic tendering. The objective of the process model is to integrate the information exchange via Web Collaborative Extranets (mainly document based information) with data in the project integrated database (the element based model data) the process model serves as a basis for the development of the system architecture to integrate these elements for tendering during a traditional procurement scenario. This research shows promise in the efforts to merge document and element model data to improve data transfer and integrity between project organisations.

It is clear to see that a substantial amount of work is being done with regards to data and process models and the expansion of IFC to the infrastructure domain is a key component along with the creation of information webs via cross domain and cross format mappings.

5.3 BIM for Constructor Business processes/dimensions

The most cost effective uses of BIM in practical applications lie in the improvement and streamlining of business processes and logic. Therefore, one of the components of this study has focused on the business processes/dimensions addressed by the literature volume (with a focus on constructor processes). The processes of most importance constitute the project management triangle of Cost, Time, Quality and Health & Safety. Other important functions include progress monitoring (considered a specialist division of time management) and resource management.

Most of the work hours involved in cost management are accrued in the generation and update of quantity take-offs and cost estimates, therefore any process or computerised system that can automate or streamline this process will generate a huge advantage and improve turnover times for bidding. With this in mind a few interesting studies have been found. A study by Al-Mashta and Alkass [2] developed a cost budgeting and estimating model that integrated multiple cost databases within BIM geometrical data to render cost estimates using varied work breakdown structures (WBS), and crucially these estimates complied with national classification standards. Variable WBS allows estimates to be generated by the system at different phases from concept design (assembly based) to construction (object and Trade based). If connected to cost databases that are able to implement a feedback loop constantly improving their cost values this system could both improve estimate accuracy and streamline the process. Other projects include studies such as Aram, et al. [3] work developing a knowledge based framework designed to both assist the estimator in quantity take-off and cost estimation activities and use reasoning and rule libraries to intelligently interrogate models that are incomplete or have required information that is hidden or absent. Lastly Lu, et al. [43]'s use of gene expression programming provides an interesting solution to the improvement and accuracy of base cost values used within estimates. The developed algorithm uses previous cost data, to provide accurate forecasting of highways construction using design data which is at a conceptual level (bridge lengths, pavement type, number of interchanges, initial earth work volumes etc.).

Along with costs, time is also an important factor. There are many studies dedicated to the automatic, semi-automatic and optimisation of construction schedules and the active collection of construction progress via scanning and predictive technologies, to both analyse productivity and actively adjust the construction schedule in response to the current project state [22]. Schedule generation has been achieved through the use of activity template models [67], genetic algorithms that ensure structural integrity [20], duration forecast tools based on historical datasets [15] and construction sequence generation via spatial reasoning and automated design object linking [66]. The optimisation of construction schedules is also widely explored with simulation methods using spatial clash detection [45], genetic algorithms to minimise interference of workspaces [52] and algorithms for space conflict checking [51]. Lastly construction progress monitoring is a unique topic that has 2 distinct advantages. Firstly, it has the ability to provide accurate up-to-date progress reports and if this is done via scanning technologies can concurrently produce as-built models for the project. Methods explored include the use of photologs and BIM models [24], LiDAR approaches for surveying of a site coupled with 4D BIMs [7] and the use of multiple acquisition methods integrated with a Cost/Schedule model able to monitor progress in terms of tasks and costs incurred [19].

Through each dimension can be taken on its own, it is clear that the integration of multiple dimensions can lead to even more gains for example Kim, et al. [38] has developed a methodology and data model to perform fast highway alignment analysis using the parameters of cost and schedule to fine the most optimal solution. The way in which working durations alter cost values, and allocating more capital to a task can reduce its time to completion, provides an avenue to both interlink the data (changing task durations, adjusts costs), and generate feedback models like that proposed by Liao, et al. [40] to improve initial cost estimates and construction programmes.

Along with the large dimensions of cost and time, health & safety has become an emerging topic demonstrated by the 25 publications found during this study. With the further integration of 3D, 4D and 5D data within building information models it has become possible to quantitatively analyse health and safety aspects of both the static design geometry and the accompanying schedule sequencing and active site layout. Projects such as ToolSHeD a web-based information and decision support tool have been developed to assist designers in integrating the management of Occupational Health & Safety risk into designs, via an expert knowledge base [18]. Other aspects include safety analysis of BIM models for hazard identification [49], use of 4D BIM data to analyse structural safety [33,34], object libraries for planning crane logistics [28] and design decision making assistance via construction safety component libraries. From these examples it is clear that a BIM can provide gains in safety as well as efficiency.

This section illustrates only a few of the implementations and concepts being explored in relation to business processes but some areas are lacking more than others such as quality management and Constructability analysis, these are the identified gaps within this subject.

5.4 Research Gaps identified

As discussed, BIM research for infrastructure and construction has demonstrated the advantages and gains of applying the BIM concept. These benefits include better collaboration between stakeholders, automation of repetitive tasks, advanced analytics and optimisation of construction information and linking of information sets. Nevertheless, four research gaps have been identified by this review and are discussed herein.

(1) *Information integration* – a common data format for Infrastructure: Although there are various different examples of integrating different types of datasets and data formats, no common data format (such as the IFC) has been fully extended to encompass the major types of infrastructure projects such as transport, utilities or environmental projects. This is most probably due to the sheer volume of work that must be completed and further validated to fully extend a common data format for Infrastructure as a whole. In contradiction, a growing use of ontologies, linked data techniques and big data style approaches are reducing the need for stringent, structured data formats, weaving together data using graph based approaches processed via reasoning, rule engines and machine learning. The downsides of this emerging approach is the level of computer science and programming knowledge required to integrate datasets. Therefore, working towards a universally agreed conceptual vocabulary or data structure is an important area of research.

(2) *Data Integration Engine* – for Holistic Information Management: Various studies have focused on technical applications for integrating additional dimensions to the already developed 3D Information model, providing the ability to better analyse and visualise the data on a project. The draw backs of this lie in the need for data to be in specific format or physically integrated into a single file or database. This approach when applied to real world projects and practices provides issues with scalability, data ownership, data responsibility and data conversion. This gap is relevant to both buildings and infrastructure BIM though the solution would require specific components for each particular domain within infrastructure, compared to a possible singular implementation for buildings. Therefore, it is proposed that a virtualized data integration engine be explored to provide both the one point of truth for information that is technology and platform independent while maintaining data segregation, responsibility and ownership.

(3) *Alignment of the Business Process with the BIM Process* – many of the studies described have been able to use the BIM concept to automate and improve various tasks that are carried out during a AECOO project and accompanying methodologies and processes developed to support these solutions. Little consideration has been given to relationship between the BIM Process and the business process of AECOO Stakeholders. The

integration of BIM process elements into an organisations Business process model embedding BIM at an organisation level. Understanding where BIM resides in a business sense approaching from an organisational view point rather than project view point is an area yet to be explored, and would be relevant to both Infrastructure and buildings domain (though the specific solution would vary with regards to domain).

(4) *Framework for Information Governance and defining 'data Usefulness' in Infrastructure*. There are multiple examples of studies which take available data and perform analyses and simulation and look at the connections between different data set. But no substantial work has been conducted to investigate and generate a framework defining the data itself. To properly and efficiently govern the information of a project each particular data component should have specified: (1) Who will produce/edit this information (data responsibility) (2) what process generates this information (data generator) (3) and what process will consume that information (data consumer), if a data item is produced but not consumed then it is inefficient to produce it in the first place. This is applicable to both buildings and infrastructure, but due to the higher value of non-graphical data to infrastructure stakeholders a more defined and information governance strategy, would provide great advantage. This deficit could be addressed by the development of an information Governance framework to assist in the definition and management of Project information.

The underlying factors running through all these identified gaps highlight a theme addressing not the Information itself but the usage and management of that information. The gaps cover 3 key factors or aspects of an Infrastructure BIM concept these are:

1. *Definition of information*- in terms of both the structure and vocabulary of the data itself (gap 1) and defining the related aspects of a single data object, such as generator, consumer, rights and responsibility (gap 4).
2. *Process of Information* – an aligned methodology for the production of construction information providing a view or alignment from an operational/organisational aspect (gap 3) and a project specific production view (gap 4).
3. *Connection of Information* - addressing the requirement to mesh and associate information in a dynamic fashion while maintaining the physical or virtual barriers required to address current legal and security concerns.

5.5 Roadmap for Infrastructure Constructor BIM Development

From the identified research gaps and underlying factors, a corresponding 'Roadmap for infrastructure constructor BIM development' is proposed describing a research strategy to address the topics and factors discussed. The strategy addresses 3 key topics of Information Governance, Information Process & Information Integration which are seen as the main components for moving BIM effectively through the lifecycle and into the infrastructure domain (Figure).

These three topics can be combined together to realize an environment (Figure 15) where information consumers (such as individuals, BIM software or systems) request an information view or snippet from a unified environment representing a single point of truth. This environment then serves the request in a form either native or understandable by the consumer, by aggregating the relevant data from information providers (these being BIM files stored in a DMS, a database, or other web service) to form the dataset. The information itself is distributed between information providers who can manage the storage, release state and approval of their own information, allowing clear segregation of ownership of data while facilitating a virtual common data environment. Within the unified environment, a project governance model specifies the structure, access rights and definition of the Information providers, along with a BIM Entity Linkset describing the relationships between different information entities. This linkset uses a graph based approach to describe the interconnectivity between information objects and sets via unique references, this information coupled with a data aggregation engine to process and convert data provides an environment able to act as centralised project hub, independent of the software and hardware solutions it aggregates.

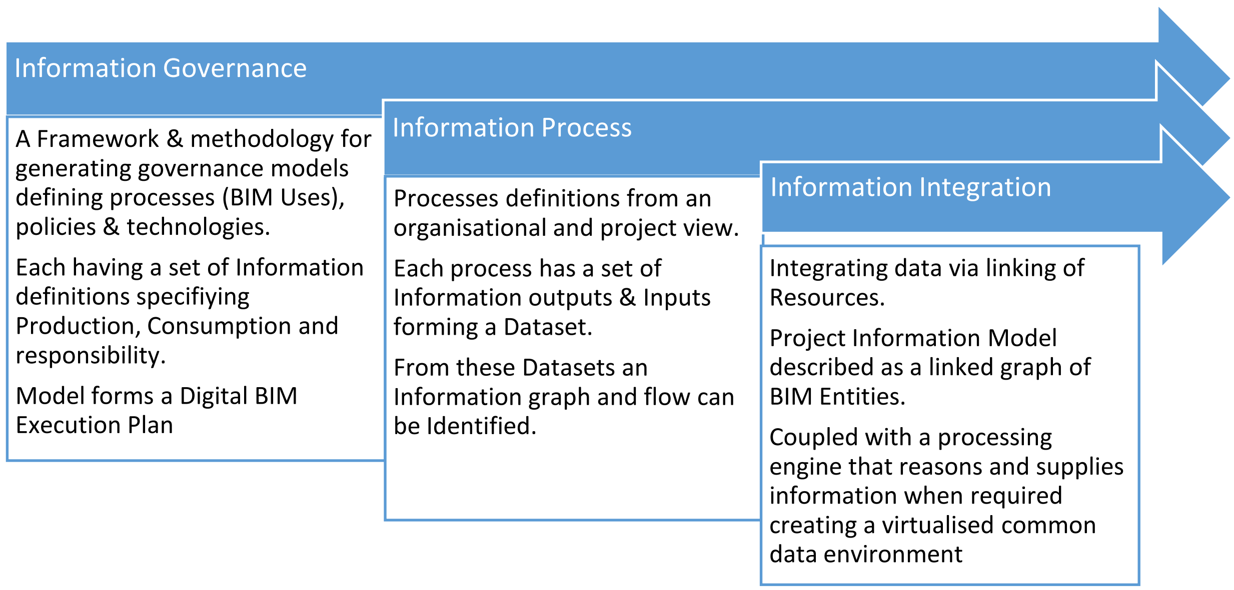

Figure 14 Roadmap for Infrastructure & Constructor BIM Development

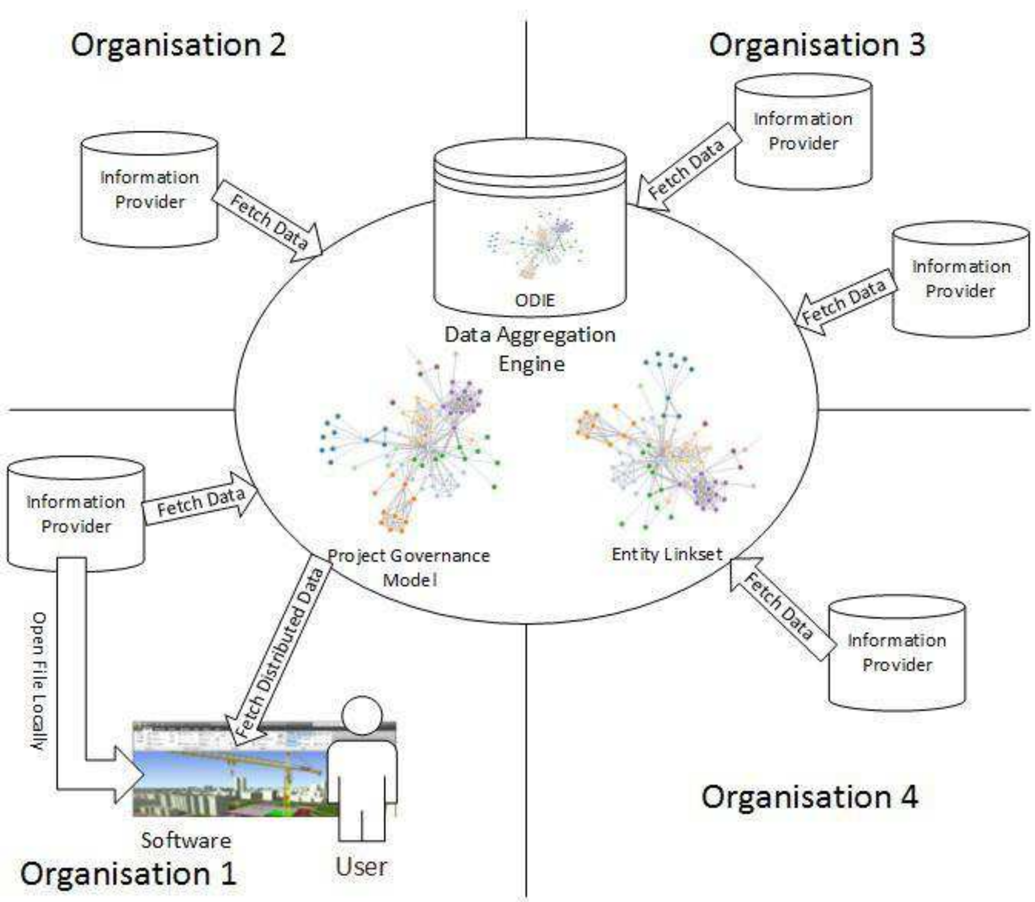

Figure 15 Conceptualization of a distributed common data environment with governance and data aggregation

5.6 Conclusion

This paper aims to conduct a systematic review of BIM Research in the infrastructure sector and construction project phase. A three phase method was used to search, filter and rate the relevant publications to be included in this study. From an Initial volume of 1080 papers, 259 papers were identified for classification and review. An analysis combined qualitative and quantitative was employed, classifying and quantifying the literature volume with regards to the aspects of publications over time, publications by industry sector, publications by country, project phase, organisational level, research them & product and business Dimensions/Processes addressed. From these analyses and the underlying subject of the review 4 main research topics were deduced and the volume qualitatively discussed against the topics of Infrastructure BIM, Data/Process Models and BIM for Constructor business processes/dimensions. From the literature volume four research gaps were discussed and identified: Information integration – a common data format for Infrastructure, Data Integration Engine – for Holistic Information Management, Alignment of the Business Process with the BIM Process and a Framework for Information Governance and defining 'data usefulness' in Infrastructure. In Response to these research gaps a corresponding research strategy was developed focusing on the definition of a governance framework compatible with Infrastructure projects and the development of a unique distributed common data environment utilising a technique to link information artefacts without the need to convert from one format to the other or integrated into a centralised space. The Technologies of RDF, ontologies and linked data mentioned within this study provide a unique process to link resources (data) utilising a graph based and schema independent semantic model rather than the traditional relational models of current file and database structures. This graph based model can facilitate the dynamic Information definition required for proper information governance, while allowing a semantic web based linking of information resources. With the increasing complexity, Information uniqueness and governance requirements of Infrastructure projects graph based technologies and distributed data environments are the way forward in meshing together and leveraging the vast amount of data produced by modern day AECOO Projects.

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Figure

Research Type	Count
System Development	79
Modelling/ Methodology	76
Framework	38
Case Study	23
Subject Analysis	21
Literature Review	13
Proof of Concept	8

Organisational Level	Count
Project	144
Company	44
Industry	41
Sub-Project	27
Public Authority	2

Research Outcomes	Count
System Prototype	90
Study Analysis	61
Data Model/ Modelling Method	41
Tool Prototype	34
Framework	32

Project Phase	Count
Construction	182
Life-Cycle	47
Design	32
Operation & Maintenance	17
Procurement	4
Handover	2

Business Process/Dimension	Count
Cost Management	53
Time Management	53
No Process	47
Project Management	28
Construction Progress Monitoring	28
Health & Safety	25
Resource Management	22
Inspection, Operation & Maintenance	18
Design	18
Quality Management	6
Constructability	6
Quantity Take-off	6
Supply Chain & Procurement	5
Handover	2