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BUILDING INFORMATION MODELLING: PROTOCOLS FOR COLLABORATIVE DESIGN PROCESSES

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SUMMARY: Numerous frameworks and protocols are being developed to facilitate BIM understanding and implementation. A BIM framework is a structured theoretical construct that can assist in organizing BIM domains of knowledge and facilitate the creation of new knowledge. BIM Protocols explain or simplify aspects of the BIM implementation by providing detailed steps or conditions (e.g. workflows, plans, manuals, etc.) to reach a measurable outcome. Currently available BIM protocols lack the level of details and the inclusion of implementation variables and complexities present at project levels. This research aims to propose protocols for BIM collaborative design that can be utilized at project level by an entire supply chain to increase the efficiency and consistency of information flow and BIM deliverables. A grounded theory approach was adopted due to its particular emphasis on providing explicit strategies for defining and studying processes. The proposed protocols consist of flowcharts, diagrams and matrices that guide the processes of BIM implementation for collaborative design among lead architects, engineering consultants, clients and contractors. A top-level model of the protocols, representing the main elements of the protocols, the relations between elements, the underpinning methodology and a gate decision for technology, process and policy approval, is presented as an abstraction of the content of the protocols. The testing of the protocols in two international design competitions, using a mixed quantitative-qualitative, demonstrated their potential in improving the quality and quantity of information delivered to stakeholders involved in the design process. There are primary and secondary contributions that stemmed from this research. The primary contribution is represented by both the methodology for development and testing and the proposed protocols for BIM collaborative design. The secondary contribution derives from the classification and review of BIM frameworks and the demonstration of the influence of the BIM project physical environment on the performance of teams.

KEYWORDS: *Building Information Modelling, framework, grounded theory, protocol.*

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1. INTRODUCTION

All emerging definitions of BIM reflect its transformative capabilities and impact on the Architecture, Engineering and Construction (AEC) industry and very recently on facility management. BIM is an emerging technological and procedural shift within the AEC industry (Succar, 2009); BIM is not just a technology change but also a process change (Eastman et al., 2011); BIM is a disruptive technology (Eastman et al., 2008) and disruptive technologies have upset many other industries and caused them to be totally rethought (Smith and Tardiff, 2009), and BIM is an expansive knowledge domain within the AEC industry (Succar, 2009). As a result, BIM entails greater challenges compared to those witnessed with the introduction of innovations in the AEC industry over the last 30 years (Taylor, 2007). In contrast with localized innovation such as 2D, BIM is classified as "unbounded" innovation (Harty 2005, p. 51) or "systemic" innovations (Taylor and Levitt 2004, p. 84) as it impacts multiple specialist organizations and diffuse more slowly than localized innovations (Taylor, 2007). With such increasing connotation and coverage of BIM, there have been numerous studies investigating BIM adoption and implementation (Gu and London, 2010; Arayici et al., 2011) and BIM value, barriers and drivers (Suermann and Issa, 2009; McGraw-Hill Construction, 2010; Kassem et al. 2012) with the overarching aim of identifying strategies to increase its adoption. While these studies are important to portraying BIM adoption in different project phases and countries and providing data for comparative analysis, the escalating implication of BIM invoke the need for frameworks and protocols that impart knowledge; promote adoption, and increase consistency of implementation.

A BIM framework is a network of taxonomic nodes and relations among the nodes (Succar, 2009) and it assists in organizing domain knowledge, elicits tacit expertise and facilitates the creation of new knowledge (Minsky, 1975). Protocols are steps or conditions to reach a goal or deliver a measureable outcome (Kassem, Succar and Dawood, 2013). These could be in textual or graphical format (e.g. process maps, flowcharts, etc.) in either paper or digital format (Kassem, Iqbal et al., 2013). While BIM framework aims to promote BIM understanding through theoretical constructs that describe and/or prescribe the different domains of BIM knowledge (e.g. technology, process, policy, etc.) and their general requirements, BIM protocols aims to guiding implementation either at industry, enterprise or project level.

Given the revolutionary and radical change associated with BIM phenomenon, as asserted by all emerging definitions, this research argue that there is a need for BIM frameworks, that simplify the domains of knowledge associated with and affected by BIM, to be followed by BIM protocols that guide implementation and drive adoption. Therefore, it is assumed in this research that BIM protocols be based on proven BIM frameworks and must use those frameworks as a starting point.

This research aims to propose protocols for BIM collaborative design that can be used at project-level to increase the efficiency of design processes through enhancing the quality of design information to all stakeholders involved in the project lifecycle. It will review available BIM frameworks (i.e. Taylor and Bernsteain , 2009; Succar , 2009; Jung and Joo, 2010; Singh et al., 2011; Cerovsek, 2011) and select, according to suitable criteria, a BIM framework that will be used a starting point for the development of BIM protocols. The proposed protocols for BIM collaborative design can be used in projects to enhance the consistency of BIM implementation in collaborative design processes and increase the quality of information flow and BIM outcomes to stakeholders involved. The research was undertaken in a two-year research initiative, partially financed by a British research council (i.e. Technology Strategy Board), between academia and members representing an entire supply chain including architects, engineering consultants, contractors and clients.

In the remainder of this paper, we first review currently available BIM frameworks and protocols and present the criteria for selecting a BIM framework which we will utilize as a starting point for the development of the protocols. Then, we illustrate and explain our research methodology which consists of a grounded theory approach, selected for its inherent strategies of defining and studying processes, and combines knowledge elicitation through industrial focus groups and knowledge visualization methods. Finally, we present the testing of the protocols in two international design competitions and we discuss the results and limitations.

1.1 Review of BIM frameworks

A 'framework' is defined, in general, as a network of taxonomic nodes and relations among the nodes (Minsky, 1975). A 'BIM framework' is a theoretical structure explaining or simplifying complex aspects of the BIM domain by identifying meaningful concepts and their relationships (Succar, 2009). This general definition of a 'framework' and the specific definition of a 'BIM framework' are used to identify and categorize current BIM frameworks. Five BIM frameworks were identified in the peer reviewed literature.

The categorization and analysis of the identified BIM frameworks is conducted using two dimensions (Table 1). The first dimension is derived from the variable used in Knowledge Management (KM) to classify frameworks as descriptive frameworks and prescriptive frameworks (Holsapple and Joshi, 1999). Descriptive frameworks characterize an existing complex phenomenon by describing and simplifying its knowledge domains. Prescriptive frameworks prescribe methodologies to follow (Holsapple and Joshi, 1999) and are interpreted as 'anticipated frameworks' providing insights into the future. By transposing these definitions into the BIM domain, a BIM descriptive framework simplifies the domains of knowledge and attributes associated with BIM by characterizing the 'BIM phenomenon' as it is. A BIM prescriptive framework provides 'prescriptions' of how BIM domains and attributes should be in future. The second dimension considers the domains of knowledge addressed by each BIM framework. Due to the broad impact of BIM on the AEC industry, as evidenced earlier, the degree of BIM domain coverage is expected to be different between the available frameworks. The domains of knowledge considered for reviewing existing BIM frameworks include policy, process and technology and their sub-domains as evidenced in table 1. Table 1 reports the mapping of the identified BIM frameworks across the two dimensions. The policy 'domain' includes sub-domains such as the impact of BIM on project lifecycle, the impact of policy on technology and process fields, and contract and regulation. Each framework is briefly discussed in the subsequent sections.

The framework presented by Taylor and Bernstein (2009) aimed at identifying and examining BIM practice paradigms and their evolution from within the firm into the supply chain. Two distinctive paradigms:

- With increasing project experience, firm-level BIM practice paradigms evolve cumulatively along a trajectory from visualization, to coordination, to analysis, and finally to supply chain integration.
- As firms evolve along a BIM practice paradigm trajectory, they are increasingly disposed to share electronic BIM files across the project network and into the supply chain for building materials.

This framework addresses a specific aspect or domain which is the "BIM use" and its paradigm. The importance of this framework derives from providing a prescriptive element capable of demonstrating the paradigms followed by organizations in moving towards greater levels of BIM-based integration. Some of the limitations of this framework are the challenges associated with the inclusion of factors that influence the identified paradigm transition – e.g. inconsistent BIM proficiency and maturity levels of actors in the industry (Giel and Issa, 2012; Succar, 2009) and the different value associated with the inter-organizational uses of BIM (Fox and Hietanen, 2007).

The framework presented by Succar (2009) describes the domains of BIM knowledge and their interrelationships. These domains are 'BIM fields', 'BIM maturity stages' and 'BIM lenses'. BIM fields represent the domain 'players' (i.e. policy, technology and process), their 'deliverables' and interactions. BIM maturity stages describe the maturity level of BIM implementation and BIM lenses provide distinctive layers of analysis that can be applied to both BIM fields and BIM maturity stages to generate specific 'knowledge views' (Succar, 2009). This framework has the most coverage of BIM domains of knowledge as demonstrated in Table 1.

The framework developed by (Jung and Joo, 2010) is intended, according to the authors, to address the issues of practicalities required for real-world projects by identifying and assessing the driving factors for "practical BIM implementation". The framework consisted of three dimensions and six variables. The three dimensions include 'BIM technology', 'BIM perspective' and 'construction business function'. Based on these dimensions, the authors argue that practical BIM implementation incorporates BIM technologies in terms of "property, relation, standards, and utilization" across different construction business functions throughout project, organization, and industry perspectives. There are uncertainties surrounding the prescriptive practical implementation guidelines provided by this framework. For example, the dimensions, categories and variables have been selected based on their relative frequency of discussion in BIM literature instead from an abstraction of the BIM world or a logical analysis of interactions between BIM knowledge domains and concepts.

TABLE 1: Categorization of BIM frameworks (P: Prescriptive, D: Descriptive, D/P: mostly descriptive with minor prescriptive elements.

			D/P	D	D	D	D/P
			Taylor and Bernsteain , 2009	Succar , 2009	Jung and Joo, 2010	Singh et al., 2011	Cerovsek, 2011
Process	BIM use stage	File-based collaboration	●	●	●		
		Model-based collaboration	●	●	●		●
		Network-based integration	●	●	●	●	●
	Interactions between project stakeholders		●	●	●		●
	Impact on project lifecycle phases			●			
Technology	Software			●[1]		●[3]	
	Hardware			●[1]			
	Networking systems			●[1]			
	Technical standards (e.g. interoperability standard)			●[1]	●[2]		●[4]
Policy	Impact on project lifecycle, interaction with technology and process fields			●			
	Contract						

[1] considers the technology domain by mapping a number of technology competency areas that are relevant to the achievement of BIM use stages

[2] identify the need of standard for product and process modelling

[3] assesses and identifies the requirements of BIM servers

[4] identifies requirements and recommendation for BIM schema development

Singh et al. (2011) presented a BIM framework that categorizes the technical requirements for a BIM-server. The framework derived from conducting focus group interviews with representatives from diverse AEC disciplines for capturing industry; a case study using a commercial BIM-server to identify its technical capabilities and limitations, and a critical review and analysis of current collaboration platforms. The BIM server requirements were classified into two main categories covering Operational Technical Requirements (OTR) and Support Technical Requirements (STR). OTRs are features and technical requirements of the BIM-server that directly support a building project (e.g. model organization; Model access and usability, User Interface, etc.) and STRs are features such as BIM-server set-up, implementation and usage assisting requirements. This framework can be classified as a BIM descriptive and technology-specific framework. However, the abstraction level of this framework is limited to a specific BIM technology (i.e. server technology) and domain of knowledge (Table 1).

The framework for BIM technological development, proposed by (Cerovsek, 2011), uses five standpoints – a standpoint is a position from which objects or principles are viewed and according to which they are compared and judged – namely, model, modeling tool, communicative intent, individual project work, and collaborative project work. Both BIM models and BIM schema were analyzed from these five standpoints. This framework can be classified as a BIM descriptive and technology-specific framework with a minor prescriptive element (Table 1). The descriptive element of this framework is about the organization of the areas of interventions, which require technological improvement, in order to enhance project communication and information management with BIM model-based collaboration. The resulting framework is characterized by a high degree of complexity due to the high number of standpoints and their variables which make the understanding of relationships between variables very challenging.

1.2 Selection of a BIM framework

The criteria for the selection of a BIM framework that will be used as the starting point in the development of the protocols are twofold:

- The compliance with the definition of framework and the inclusions of consistent taxonomy that cover the BIM domains of knowledge
- The effectiveness of knowledge visualization and communication methods utilized in the framework.

As to the first criterion, if the reviewed BIM frameworks are compared against the general definition of a framework – as a network of taxonomic nodes and relations among the nodes that assists in organizing domain knowledge (Minky, 1975) – and their capability to provide an abstraction of the BIM domains of knowledge, the framework that includes taxonomic nodes that cover all BIM domains is the framework presented by Succar (2009). In terms of effectiveness of knowledge representation and communication, Succar's framework (2009), is the only framework that utilized concepts maps, considered as the top method for knowledge sharing and visualization with the highest familiarity among practitioners (Bresciani et al., 2008). Given the grounded theory approach adopted, in which field insights of industry experts inductively develop the theory using specialized and focused codes, the selection of a BIM framework that includes a distinct set of taxonomic nodes communicated through an effective visual method is crucial to this research.

1.3 Review of BIM protocols

BIM Protocols provide detailed steps or conditions to reach a goal or deliver a measureable outcome (Kassem, Succar et al., 2013) and are documents or instructions in either textual or graphical format (e.g. process maps, flowcharts, etc.), paper or digital format. Currently available BIM protocols are reviewed in terms of their coverage of the three fields (i.e. policy, technology and process) and their target audience (i.e. industry, project and enterprise) (Table 2). Table 2 shows that there is a proliferation of BIM protocols issued by academic institutions, industry bodies, public authorities and technology providers in several countries. In protocols aimed at industry level (e.g. USACE, BIM Project Execution Plan, ver 1.0), the protocols consists of Level 1 BIM process maps representing the top-level steps required to produce for a specific BIM use (i.e. 4D planning). Protocols aimed at enterprise level (e.g. AIA – E202, New York City Council, The State of Ohio BIM Protocols, etc.) are concerned mostly with ensuring that roles and responsibilities of stakeholders and level of details to be produced in different BIM uses are agreed upon. As a result, Table 2 such protocols lack the level of granularity in the details and the inclusion of implementation variables required at project level to achieve the desired efficiency and effectiveness. In addition, Table 2 shows that none of the available protocols concurrently address all the domains of knowledge (e.g. technology, process and policy) and their subdomains and variables. For example, available protocols do not concurrently consider the enabling technology and the variables affecting its deployment on projects such as interoperability required for different BIM work-streams and the alignment of the BIM work-streams with the country specific policy context (e.g. standard project lifecycle, standards for digital collaboration).

1.4 Policy context: the case of the UK

BIM frameworks and BIM protocols address technology, policy and process fields. When a BIM framework or protocol is proposed, it is important to differentiate between the components that are context-dependent. The available BIM technology is similar between countries and therefore, BIM frameworks and BIM protocols covering the BIM technology field can be transposed from one country to another. However, the process and policy fields vary among countries and require ad-hoc and context-specific protocols. The BIM protocols proposed in this paper are developed in the context of the UK and need to consider the country-specific processes and policies. The process for organizing and managing the design phase of building projects in the UK is specified by The Royal Institute of British Architects (RIBA) and called RIBA 'Oultine Plan of Work' (see FIG. 1). The proposed BIM protocols for the design phase consider this specific context and include processes for aligning elements from the BIM technology field with elements from the BIM policy and process fields.

TABLE 2: Review of a non-exhaustive list of BIM protocols.

Protocol	**Country, Year**	**Domain**			**Target**			**Brief description**
		Technology	**Process**	**Policy**	**Enterprise**	**Project**	**Industry**	
AIA – E202	U.S., 2008			●	●		●	Protocols for level of development (LoD), authorized uses of models and responsibilities for LoDs
AGC - Consensus Docs 301 BIM Addendum	U.S., 2006		●	●			●	Standard contract documents for legal and administration issues associated with using BIM
GSA, 3D-4D-BIM Program Guidelines	U.S., 2010	●	●		●			General guidelines for GSA associates and consultants engaging in BIM practices
USACE, BIM Project Execution Plan, ver 1.0	U.S., 2006		●		●			Protocols for implementing BIM in the U.S. Army Corps of Engineer's civil works and military construction processes with a focus on operation phase
The State of Ohio BIM Protocols	U.S., 2010			●	●			General guidelines for building owners (requests for qualifications, agreements, bidding requirements, contracts)
Penn State University – project execution planning guide, ver 2	U.S., 2010		●				●	Process maps and template resources to assist in the implementation of BIM uses
New York City Council – BIM guidelines	U.S., 2012			●	●			Basic guidelines for use of BIM for municipal agencies
NIST, 2007	U.S., 2007	●					●	Standard definitions for information exchanges
AEC (UK) BIM Protocol	UK, 2012		●				●	guidelines, specific to Revit, Bentley, ArchiCAD and Vectorworks, to inform the creation of BIM elements and facilitate collaboration
BSI / CIC BIM Protocols	UK, 2012		●	●			●	Guides that identify model-based requirements to be produced project team members, permitted uses of models, levels of development and other contractual requirements
RIBA: BIM Overlay to the RIBA Outline	UK, 2012			●			●	An overview of how BIM alter the RIBA work outline plan of work.
CRC-CI national guidelines for digital modeling	AU, 2009		●				●	Guidelines for creation, maintenance, modeling procedures and implementation on large projects
Singapore BIM Guide (ver 1.0)	SG, 2012		●				●	guidelines for mono and multi-disciplinary modeling and collaboration

FIG. 1: RIBA Outline Plan of Work (RIBA, 2007).

2. RESEARCH AIM AND METHODOLOGY

This research aims to propose protocols for BIM collaborative design that can be used at project-level to increase the efficiency of design processes through enhancing the quality of design information to all stakeholders involved in the project lifecycle. This research was undertaken as a collaborative effort between the industry and academia within a Knowledge Transfer Partnership (KTP) scheme. A KTP is a British government-supported scheme, which facilitates the interactions between a company base and an academic base, enabling businesses to use research outputs and skills of academic institutions to address and solve important business challenges. A grounded theory research approach is adopted and it includes five steps (see FIG. 2). This approach will help to analyze the information flow and variables that occur within a process or system and identify the dependencies and interaction among them (Kassem et al., 2011). The delivery of this methodology, the research methods utilized and results obtained are explained in the subsequent sections.

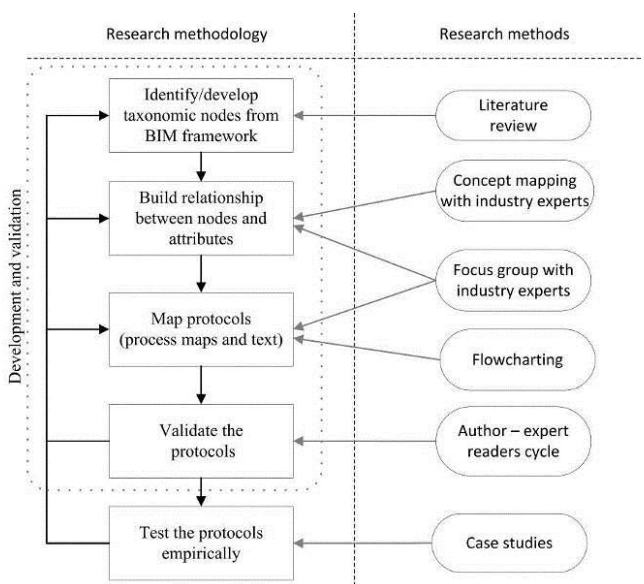

FIG. 2: Research methodology and research method.

3. DEVELOPMENT AND VALIDATION OF THE PROTOCOLS

The development and validation covers the first four phases of the methodology (see Fig. 2). Figure 3 shows an example of the process of delivering the first three phases. In the first phase the domains of knowledge and concepts of the selected BIM framework represented in its taxonomic nodes are utilized and considered as elements and areas that need addressing when developing BIM protocols. A suitable BIM framework – Succar's framework (2009) – was identified in the literature review. In this context, the literature review was employed as a means for providing a comprehensive summary and synthesis of a defined "field of study" and criteria for assessing reviews (Maxwell, 2005). In the second phase (See Fig. 3) the taxonomic nodes from the identified BIM framework are used to elicit knowledge from stakeholders by creating knowledge maps in the form of concept maps that show relationships among nodes and attributes. In the context of this research, concepts maps are therefore utilized as a tool to enabling an inductive approach through which a solution can be predicted or suggested (Saaty, 1998). A concept map is a graph consisting of nodes and labeled lines. The nodes correspond to important terms (standing for concepts) in the domain. The lines denote a relation between two concepts (nodes) and the labels on lines express the relationship between the two concepts (Shavelson, 1993). In specialized studies on comparing different methods of knowledge visualization, generation and sharing, the concept map was proven to be one of top methods for "generating new ideas" and "sharing knowledge" (Bresciani et al., 2008). Hence, it is used in this research as a visual language to capture and represent knowledge. In concept mapping, the starting step is the identification of a set of concept or knowledge terms. The set of concepts are the taxonomic nodes and categorization provided by the identified BIM framework. Additional information can be added to the established categories, as this is an ordinary approach in grounded theory methodology (Crook & Kumar, 1998), in order to establish the completed map (White & Gunstone, 1992, p. 18). The technique utilized in the research to enrich and complete the concept maps is "focus groups" with industry experts representing a whole building project supply chain. A focus group is as in-depth group interview employing relatively homogenous groups to provide information around specific topics (Hughes and DuMont, 1993).

Focus groups permit the collection and observation of a large amount of interactions in a short time (Vaughn et al., 1996 and Greenbaum, 1998). The moderator of the focus groups was the BIM manager of a renowned architectural organization in the UK. The role of the focus group moderator can be classified as "a combination of grasping and transforming experience" (Kolb et al., 1984, p. 2). All the selected participants had a prior working experience in BIM environment and at least five years of working in building projects and were recruited from the supply chain of the lead architects. They represented nine architects and consultants, two major city councils as clients and four large multinational contractors. Four focus groups were conducted to elicit knowledge about BIM-based collaborative design. They started with an open discussion around the identified BIM taxonomic nodes. Table 3 shows a non-exhaustive list of statements given by each group of participants prior to the building of concept maps. Figure 3 shows an example of concept maps and Figure 4 illustrates the exercise of building them at one of the focus group sessions with information being mapped against the RIBA Plan of Work.

This inductive exercise of building the concept maps provided considerable knowledge about BIM collaborative design. However, due to numerous concept maps produced, all participants acknowledged the need for abstracting and structuring the content of the BIM protocols. In particular, there was a need for linked "models" that condense through simplification and abstraction the concept maps while maintaining the relationship between the protocols' elements. Indeed, a model "provides a more condensed representation of what was originally given" and makes "insights more portable between people" (Ritter, 2010, p. 349). These models will represent the core of the BIM protocols. Some of the models produced are **descriptive** (e.g. describing the methodology underpinning the protocols) and others are **instructive** – explaining the sequence of actions to be followed to achieve a pre-defined outcome or BIM deliverable. Figure 5 shows a descriptive model representing the four foundation elements of the methodology underpinning the proposed BIM protocols. It shows the central role of "the BIM coordinator" who leads "the client BIM workshop" which is organized on a project by project basis to provide the client with an overview of BIM concept, BIM work-streams and BIM technologies that are applicable to the project, and more importantly to agree on the BIM services for the project. The project coordinator is responsible for maintaining and communicating the "BIM Execution Plan (BEP)" to the project team and attaining the approval of BEP at "the supply chain BIM approval workshop" attended by BIM coordinators from the project's participating organizations.

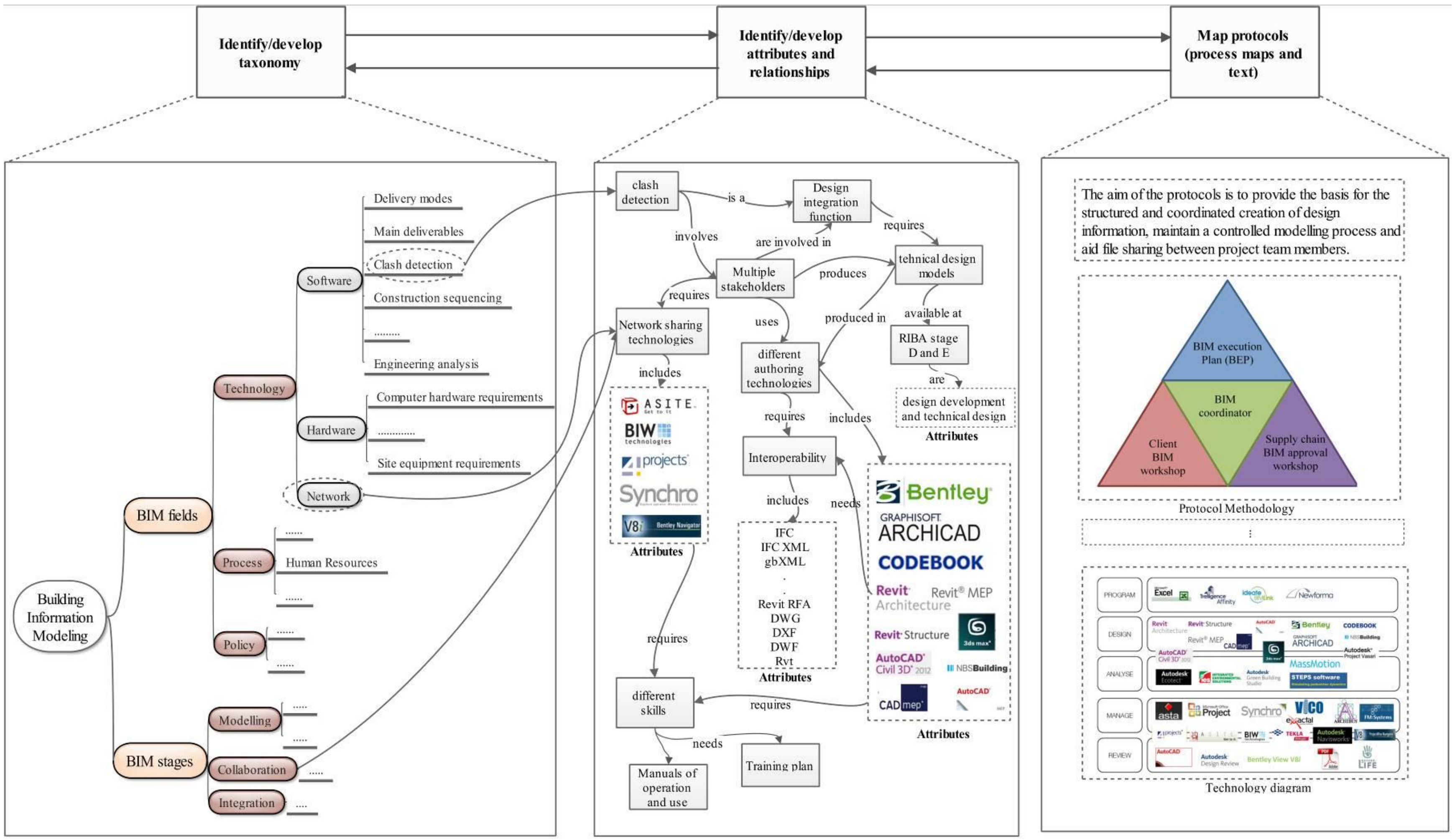

FIG.3: Delivery of the methodology.

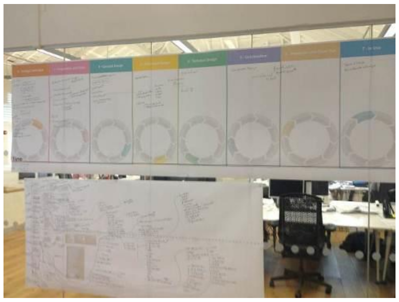

FIG. 4: Building of concept maps for BIM-based collaborative design.

TABLE 3: A non-exhaustive list of participants' statements regarding BIM implementation.

Clients	Contractors	Consultants
Increased awareness across industry of BIM approach and associated benefits	Stakeholders need to adopt integrated practices to support downstream operations in FM stages	The flow, timing and technology associated with communicating information across disciplines needs to be clearly defined
Implementation of mandatory practices for project consultants to implement BIM	FM systems linked with monitoring tools for assessing building need to be exploited performance	Design should be fully completed before the initiation of the construction process
Specification of BIM deliverables prior to project commencement	Standardization of processes across the lifecycle stages i.e. design, construction and operations	Modelling responsibilities for 3D design elements need to be clearly specified
Implementation of sustainable practices to support the design and construction of a facility	High level collaboration between all project stakeholders to support the implementation of BIM	Architect is responsible for design coordination and should provide grid, confirm structural levels, slab edges, stair and core details
Improving the engagement process through visual and interactive technologies	Integration of 3D models with the construction program to visualise build sequences	Need for a clear definition of the services which will be provided to the client through BIM practices
Delivery of BIM Facilities Management solution	Incorporate costs into BIM planning systems to support verification process	Agreed protocols, procedures, and methods of working from project initiation phase
	Users need to be trained internally on BIM technologies i.e. Autodesk Navisworks	MEP model will need to be provided by relevant party at the appropriate work stages
	Requirement for organizations to create standardized libraries that are shared with industry partners	Key requirement is to work with architectural organization which has BIM capabilities
	Organizations need to explore design integration with offsite manufacturing solutions	Identification of how, when and where information is combined / distributed from/to multidisciplinary design teams

Another abstracted model of the protocols is their top level flat view which includes all technology, process and policy fields and their elements (see Fig. 6). Each element of the three fields is systematically described in the BEP and examples from each field are illustrated later in the paper. The three fields (i.e. technology, process and policy) interact with each other in several ways. For example, the assessment of the project team capability (**from process field**) for a specific BIM work-stream is linked to the creation of user manuals (**from technology field**) which refers to the applicable modeling standard - i.e. BS 1192:2007 – (**from policy field**). A key element of the proposed protocols consists of the gate decision phase at which the approval of the technological, process and policy feasibility (See Fig. 6) at the supply chain BIM approval workshop must be obtained before the project is initiated.

Each element in the top level flat representation of the protocols (see Fig. 6) (i.e. technology, process and policy) is systematically explained in the protocols. For example, a technology diagram (**technology field**) for the BIM technologies that can be used to produce the BIM deliverables at different project stages is included in the protocols. The technology diagram (See Fig. 7) consists of a classification of BIM technologies, according to their functions, in programming, design, analysis, management and review technologies. Due to high number of technologies, participants to the focus groups advocated the need for this technology diagram. The mapping of technologies, used by a project's participating organizations on a project by project basis into this diagram, helps linking project BIM deliverables to suitable BIM technologies and interoperability requirements.

The BIM work-streams (**from process field**) that require a contribution from the project's supply chain are structured into a two-dimensional matrix which designates who must be involved in each work-stream (See Table 7). This matrix is then utilized to determine the role and responsibilities of each project's participant involved in the BIM work-streams and to align the BIM work-stream to the country specific design processes (e.g RIBA processes in the UK) - **policy field**. Table 5 shows an example of roles and responsibilities for a number of BIM work-streams and figure 8 illustrates the process for aligning the BIM deliverables to the RIBA processes. These elements of the protocols are examples of the ways the relationships and attributes identified in the concept maps were exploited and extended in the BIM protocols.

The level of details in the developed protocols is incremental. For example, while the roles and responsibilities of each participating organization in each BIM work-streams are shown at a high level - **model level -** in a single diagram (See Tables 4 and 5), a specific diagram for each BIM work-stream clarifies the roles and responsibilities with more details - **at component level** – (See Table 6). For example, for the 3D modelling, the diagram in Table 6 clarifies the roles and responsibilities of each partner for each component. Then, an additional diagram clarifies the level of details for each component at different design stages. A specific user manual for each BIM work-stream is produced and circulated to all organizations involved in the delivery of that BIM work-stream.

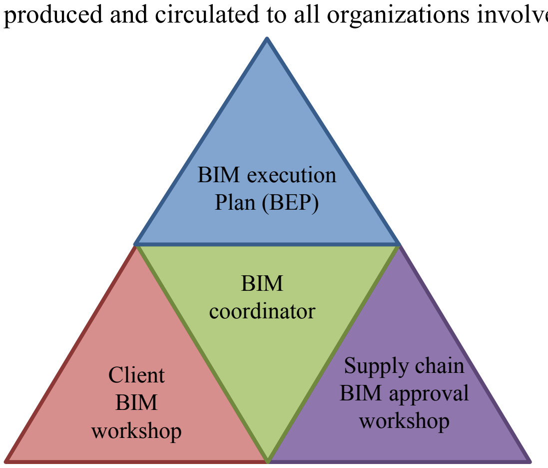

FIG. 5: Core elements of BIM protocols and underpinning methodology.

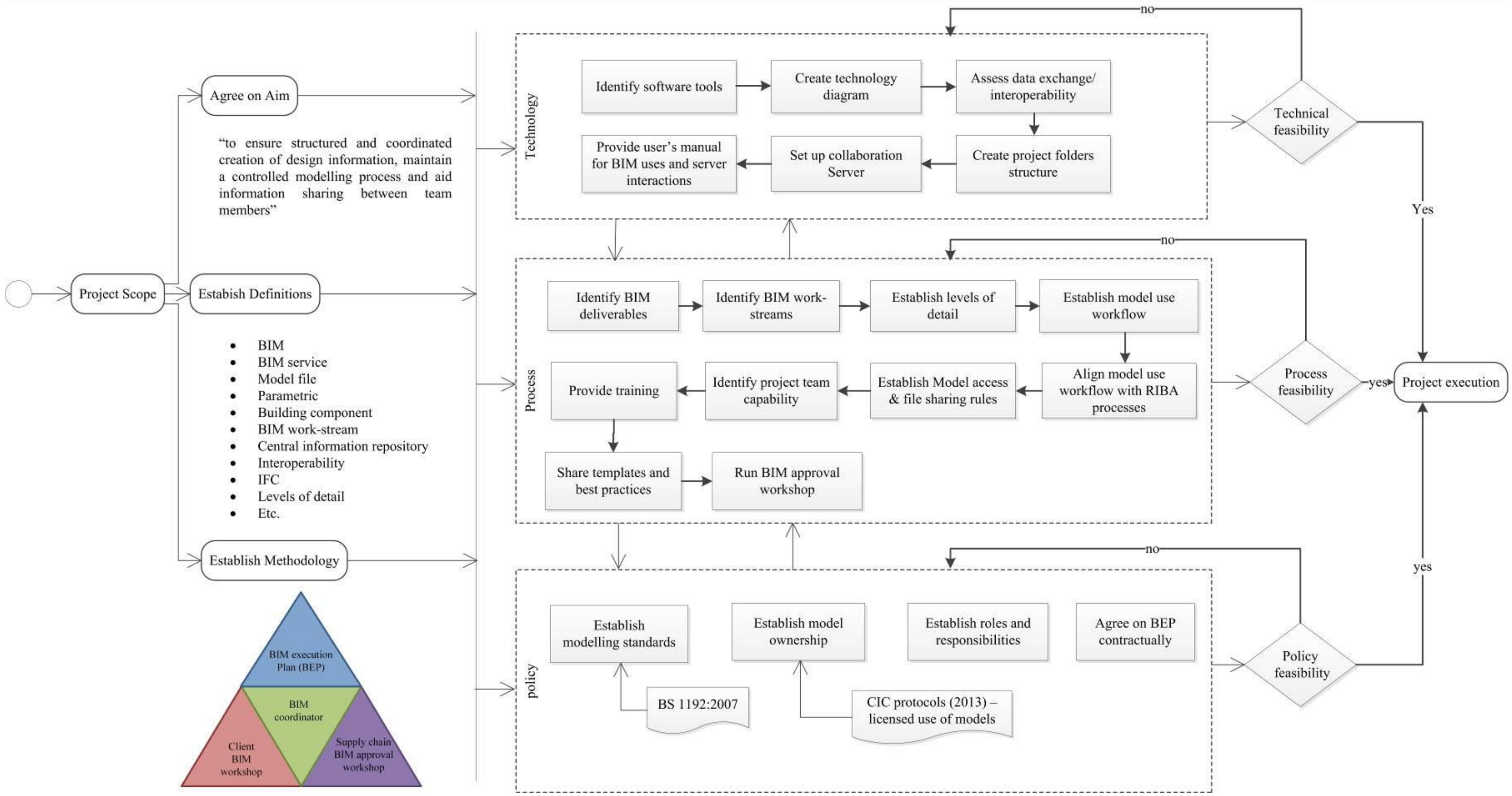

FIG. 6: Flat top- level view of the BIM protocols.

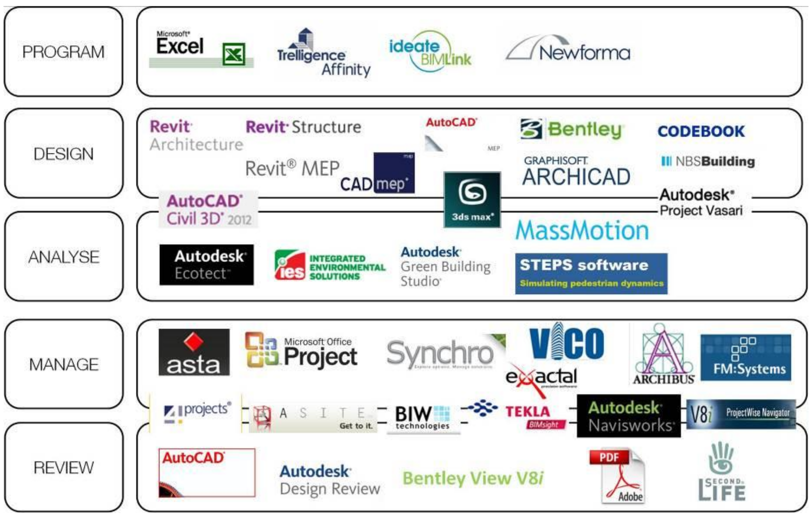

FIG. 7: Technology diagram for BIM protocols.

TABLE 4: BIM workstreams and stakeholder involvement.

	Stakeholders										
BIM use	Client	Contractor	Architect	Building surveyor	Civil/Structural Engineer	MEP Engineer	Facility Manager	Land Surveyor	Interior desin	Quantity Surveyor	Manufacturer and suppliers
Building performance analysis	●	●	●		●	●	●				
Design coordination	●	●	●		●	●			●		
Information	●	●	●	●	●	●	●	●	●	●	●
Laser scanning	●	●	●	●	●	●		●			
Pedestrian analysis	●		●								
Room loading	●	●	●		●	●			●		●
Space programming	●		●		●	●	●				
Prefabrication / offsite manufacturing	●	●	●		●	●					●
3D modelling	●	●	●	●	●	●	●		●	●	●
4D planning	●	●	●		●	●					
5D planning	●	●	●		●	●				●	●
Facility management	●	●	●		●	●	●		●		●

TABLE 5: Responsibilities of project partners in different BIM workstreams
(R:Responsibility, S: Shared responsibility, I: input)

	Architect	Structural consultant	MEP consultant	Contractor	Client	Additional information
3D modelling	S	S	S		I	Discipline specific models
Design coordination	R	I	I	I		
4D planning	I	I	I	R	I	
5D planning	S	I	I	S	I	
Facility management	I	I	I	I	R	Input required from all stakeholders
Environmental analysis	S		S		I	Architect at concept stage MEP at detailed stage
Structural analysis	I	R		I		
Design for prefabrication	S	S	S	I	I	

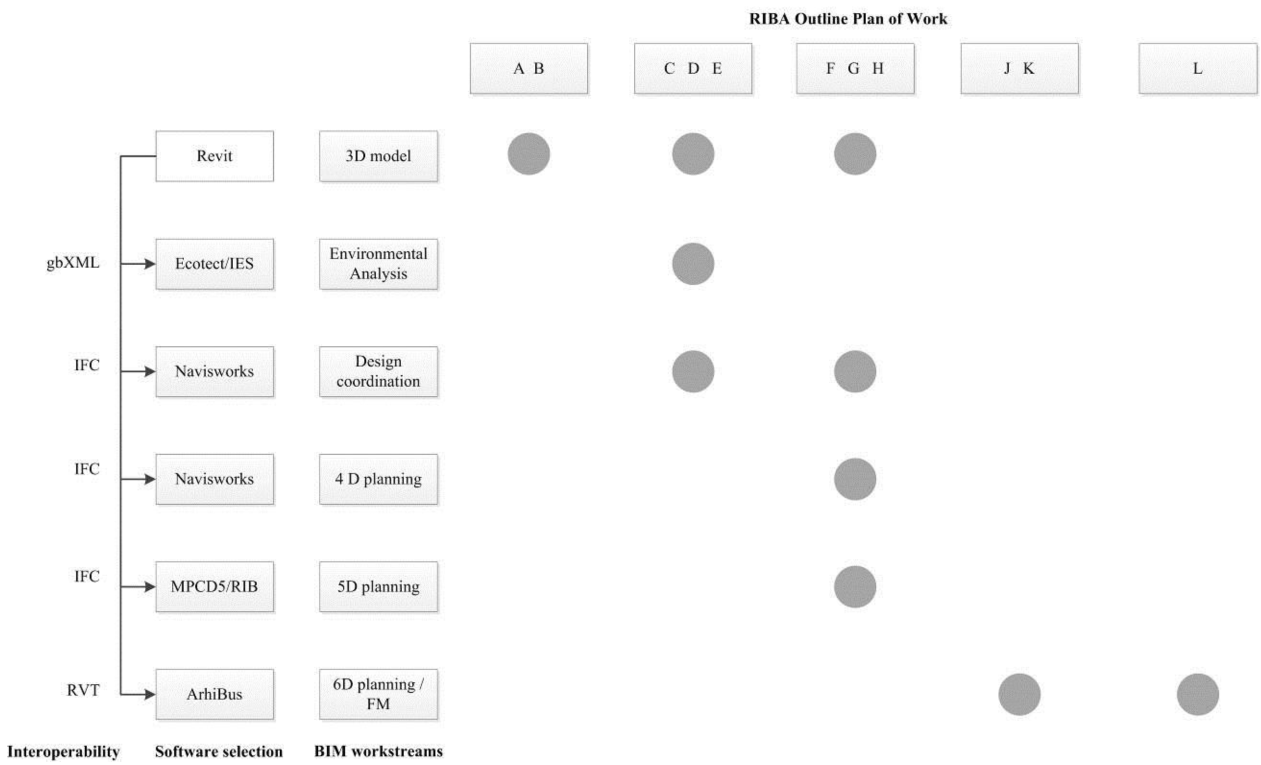

FIG. 8: Interactions between elements of the policy, process and technology fields

TABLE 6: Role and responsibilities at component level in BIM 3D modelling

	Architect	Landscape Architect	Structural consultant	MEP consultant	Additional information
Building layout	R	I	I	I	Including floor level
Building coordinates	R	I	I	-	
Gridlines	S	I	S	I	Including liftshafts
Foundations	I	I	R	I	
Retaining walls	S	I	S	I	Including lift pits
Columns	I	I	R	I	
Beams	I	-	R	I	
Slabs	S	-	S	I	Design team coordination
Bracing	I	-	R	I	
Shear walls	I	-	R	I	
External walls	R	-	I	I	Fabric (Architects) Restraints (structural consultant)
Internal wall	R	-	I	I	
Doors/windows	R	-	I	I	Lintel schedule (structural consultant)
Wall restraints	I	-	R	I	
Roof	R	-	I	I	Fabric (Architects) Restraints (structural consultant)
Stairs and lift	R	-	I	I	Voids in slab included
Voids	S	-	I	S	Ceiling voids/builderswork holes
Mechanical systems	I	-	I	R	Generic zoning and volumes
Electrical systems	I	-	I	R	Generic zoning and volumes
Comms / data	I	-	I	R	Generic zoning and volumes
Public health	I	-	I	R	Generic zoning and volumes

The protocols included also instructive guidelines and shared conventions for the organization, communication and access of design information such as file naming (i.e. fields, abbreviations, sequence, file extensions and exchange formats), archiving (i.e. local folder structure, extranet folder structure for model upload), access rights and the frequency of model update uploads (e.g. weekly) submittal by the project's supply chain.

The validation of the protocols involved the use of the "author-readers" methodology. This method of validation is a standard in collaborative process mapping and modelling such as the IDEF0 (ICAM DEFinition for Function

Modeling, where 'ICAM' stands for Integrated Computer Aided Manufacturing) (IDEF0, 1993) and can be applied for the validation of the proposed protocols. The author-reader method ensures the correctness of a system description through experts or peer review cycles in which the author creates small work packages called “kits” on which expert readers add their comments. Each element of the developed protocols (e.g. diagram, text or flowchart) was sent to the focus group participants using an adapted IDEF0 kit which contained an area for comments about the protocols’ element, subject to validation. The validation between the BIM manager and the focus group participants consisted of an iterative process as illustrated in Figure 9. For most of the protocols’ elements there was a single set of iterations with minor corrections such as correcting the direction of arrows or changing the wording of some sentences. This result was expected due to the collaborative effort in developing the protocols and the process of validation was merely aimed to ensure that the process of grasping and transforming participants’ experience by the BIM manager – the moderator of the focus groups – was accurate.

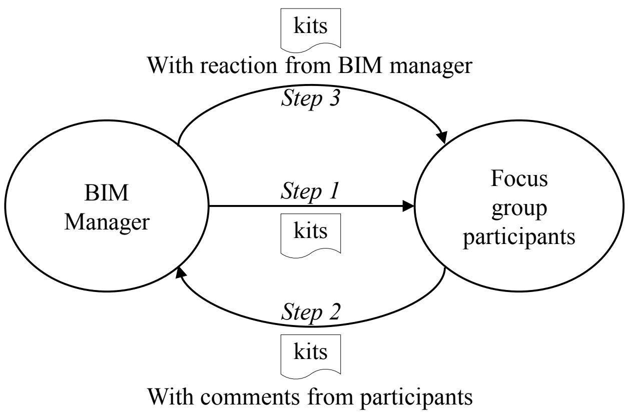

FIG. 9: Methodology for the validation methodology of BIM protocols

4. TESTING RESULTS AND DISCUSSION

The aim of the proposed protocols is to increase the efficiency and consistency of BIM collaborative design and enhance the quality of information delivered to stakeholders involved in a project lifecycle. The testing involved a multi-disciplinary team composed of architects, engineering consultants and contractors in the delivery of two design briefs within two live international design competitions. The evaluation of the results from the testing consisted of a mixed quantitative-qualitative approach. The quantitative measurement was conducted to measure the number of actual BIM deliverables compared to the number of required BIM deliverables. The qualitative assessment was a judgmental evaluation, by an independent committee of experts from the AEC industry, major software vendors and organizations such as The buildingSMART alliance™, on the basis of the following criteria about BIM deliverables: compliance to the brief; design impact and clarity; multi-disciplinary BIM and use of interoperability, and use of BIM for technical assessment. The two international live design competitions were “Build London Live 2009” (BLL) and “Build Qatar Live 2012” (BQL). In these competitions several teams from around the world compete in a 48-hour to deliver a design whose brief is released twelve hours prior to the start of the competition. While the testing in competition projects, judged over limited time, have limitations compared to real life projects, this approach allowed the isolation of some variables such as ‘trust’ considered as an important factor in influencing the collaboration among multidisciplinary teams (Azhar, 2011; Ghassemi and Becerik-Gerber) and ‘legalities and intellectual properties’ considered as key challenges to BIM widespread use (Sebastian, 2010; Kassem et al., 2013). As a result of isolating these variables, the correlation between the performance measures and the proposed BIM protocols is enhanced. Details of the two projects are summarized in Tables 7.

In both competitions, the team using the proposed BIM protocols held the supply chain BIM approval workshop to assess the technology and process feasibility during the 12 hours following the brief release and prior to the competition official start. This workshop ensured that technological and process feasibility are met by tailoring the corresponding elements of protocols to the specific needs of each project and the supply chain. For example, at this workshop the technology diagram that maps the technologies utilized by the multi-disciplinary team (See Fig. 10) and a diagram (See Fig. 11) combining the BIM work-streams for the required BIM deliverables, the roles and responsibilities, the technological compatibility and the model use workflow were produced and agreed by all member of the supply chain.

Once the multi-disciplinary team verified the feasibility of BIM implementation, the project execution started. All the BIM deliverables listed in Table 7 were produced on time in both competitions (20 deliverables in BLL and 40 deliverables in BQL). The produced concept design model of the BLL and BQL are respectively presented in Figure 12. The team adopting the proposed protocols started with the Architect defining the model coordinates, the grid and floor level and communicating them to the structural and MEP (Mechanical Electrical and Plumbing) engineers. The architectural model was then adapted in such a way that areas and spaces are correctly configured to support downstream activities such as environmental analysis, design coordination and 4D planning (See Fig. 13).

TABLE 7: Details of the briefs for the two design competitions

	Build London Live (BLL)	**Build Qatar Live (BQL)**
Site	London, England	Doha, Qatar
Project Name	Mixed use development scheme	Museum of Architecture
Project details	Mixed-use development including a hotel, offices, retail and residential spaces. Site available: 23000m^2 to build - 250 room hotel (at least 100 underground parking spaces) - No less than 50,000 m^2 office (at least 200 underground car parking spaces) - 200 dwellings; 80 x 3 bed apartments, 80 x 2 bed apartments, 40 x 1 bed apartment (1 parking space per dwelling) - 2000 m^2 of retail space - Height restriction of 20 storeys	Mixed-use development including a hotel, offices, retail and residential spaces. Site available: site will be 60,000m^2 on an island (West Bay District) - rail/road terminal - green space - sustainable infrastructure such as a tidal lagoon, solar arrays and other forms of renewable energy - complying to 'Zero Carbon' built environment LEED and the Qatar Sustainability Assessment System (QSAS) - compliance with LEED Gold status
Stage Start Start day / time	RIBA: B (design brief) 1 Mar 2012, 09:00GMT	RIBA: B (design brief) 27 Nov 2012; 09:00GMT
BIM Deliverables	20 deliverables covering: - Disciplinary models in native formats and IFC format - Design intent visualization in JPEG and walkthrough in AVI formats - Energy calculation - Sizing calculation - Design coordination and clash detection - Constructability analysis and 4D planning - 5D/cost analysis - List of software applications utilized - Presentation of the scheme	30 deliverables covering: - Disciplinary models in native formats and IFC format - Design intent visualization in JPEG and walkthrough in AVI formats - Energy calculation - Sizing calculation - Design coordination and clash detection - Constructability analysis and 4D planning - 5D/cost analysis - Facility management information - list of software applications utilized - Presentation of the scheme

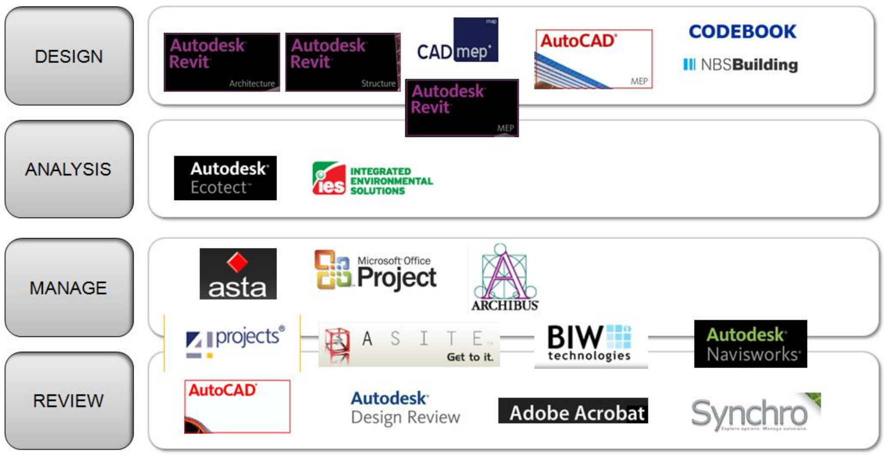

FIG. 10: Technology diagram for BLL

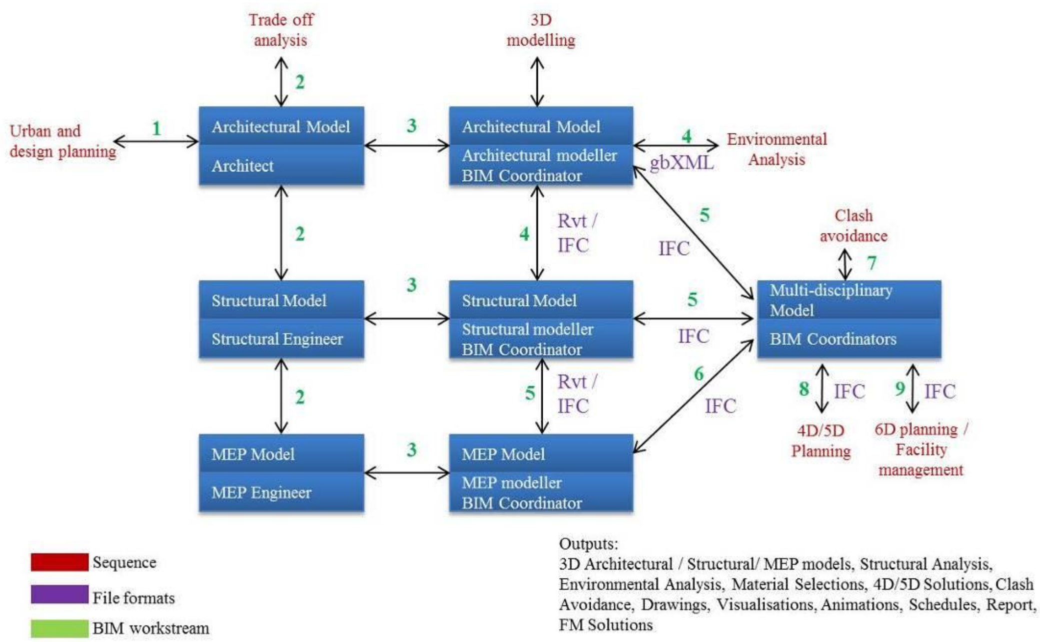

FIG. 11: Model use workflow and technological compatibility for BLL

FIG. 12 : Concept design of London mixed used development (left) and the Muesum Museum of Architecture (right)

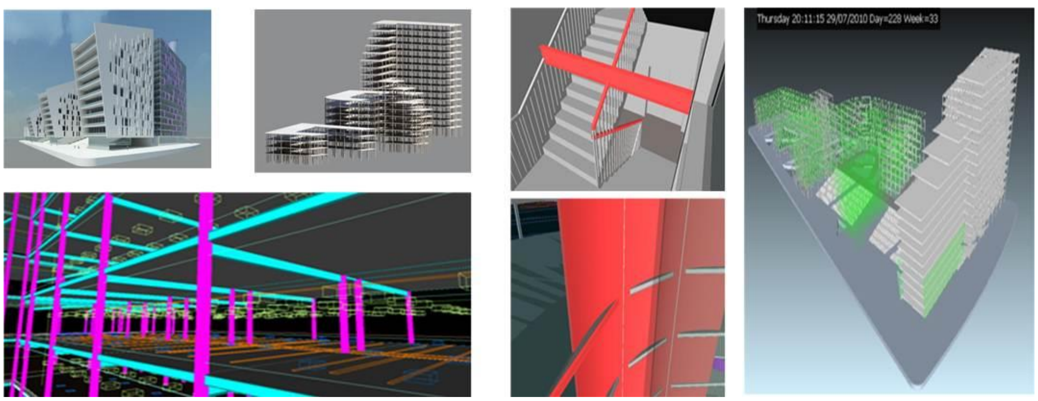

FIG. 13: Architectural, Structural and HVAC Models (left) and Design coordination and 4D planning model (right)

The team, using the proposed protocols, was given the award of best "use of BIM for interoperability" in BLL and was the overall winner for the best BIM effort in BQL. In BQL the team produced 19 additional deliverables (e.g. pedestrian analysis, landscape details, lifecycle cost, carbon footprint, several design viewpoints and virtual reality presentations, etc.) which were not required by the project brief. Indeed, the team has spare time toward the end of the competition to produce these additional BIM deliverables. The justification of this lies in the differences of the physical environments used in the two competitions (See Fig. 14). This was an unexpected finding to an important research issue highlighted in previous studies. Some previous studies advocate that the characteristics of the project physical environment and technical characteristics of data sharing in projects affect the performance of teams and identify these areas as future areas for investigation (Smith et al., 2011). Also Succar's theoretical "BIM stages – modelling, collaboration and integration" (2009) indicate that as the use of BIM move from the stage of modelling through collaboration to integration, fast tracking and overlap start occurring between the project phases. In the competitions undertaken, the collaboration and integration use stages were emulated respectively in BLL and BQL. In BLL, the multi-disciplinary teams were working in separate locations, using extranet (i.e. Asite) and emails as the primary communication methods used. Therefore, the design development stages could not be overlapped in the same way as in BQL where design teams were collocated in the same environment allowing the overlap of design phases by increasing informal face to face communication and ad-hoc input from all disciplines throughout the design process. This is an empirical demonstration of the relationship between the project physical environment and the performance of design phase. The difference in the project physical environments influenced also the type of iteration among participants, classified by Costa and Sobek (2006) in in behavioral iterations (negative iterations) and design interactions (positive as allows design to be tested and improved). Participants observed that repetition and behavioral iterations were nearly absent in BQL while some were encountered in BLL. These factors explains the difference in the performance on the two projects and suggest that higher level of integration in the physical project environment (or enabling BIM technology) improve the efficiencies of projects if protocols are adopted for the creation of a shared vision, the setting of roles and responsibilities and the verification of the feasibility of processes. Other benefits, observed by the project participants, and directly associated with the use of the protocols were the creation of a shared vision about the implementation of BIM processes, the facilitation of communication between project teams and the enhancement of the quality of information to all stakeholders involved in the collaborative design process. This help avoiding di-synchronization in the design team effort considered in previous studies as the result of design team members not agreeing on a standard design process to follow (Austin et al., 2001).

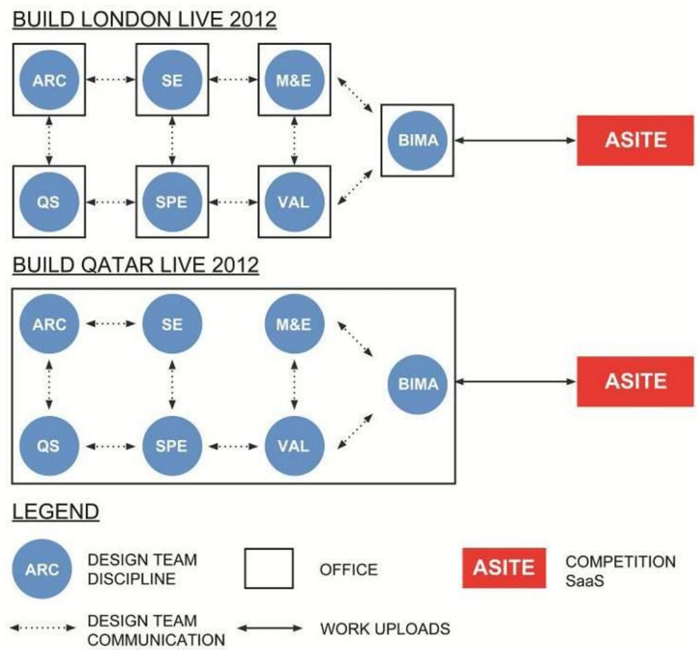

FIG. 14: Physical environment and communication methods used in the two competitions

5. CONCLUSIONS

The implementation of BIM on projects require the adoption of protocols that create a shared vision of project delivery processes and increase the consistency of processes and quality of BIM information and deliverables to involved stakeholders. The review of existing studies and initiatives in this domain revealed that BIM protocols are often proposed at industry-wide level and require substantial adaptation in order to be applied at project level. However, there are a number of studies presenting frameworks describing and/or prescribing the BIM domains of knowledge. The methodology adopted in this research argues that the development of BIM protocols be based on BIM frameworks that provide a thorough description of the BIM domains of knowledge (i.e. technology, process and policy). A grounded research approach, where field insights collected from focus groups conducted with industry experts, was utilized to build protocols for BIM collaborative design. The taxonomic nodes of a selected BIM framework covering process, technology and process fields were used to elicit knowledge about BIM implementation by enriching the nodes with relationships and attributes using collaborative concept mapping. The concepts maps were then abstracted into the protocols consisting of: a- top level models showing the underpinning methodology; the interactions between technology, process and policy fields, and key feasibility decision points b- flowcharts and diagrams with increasing level of details (project, model and component levels). The testing of the protocols conducted in two international design competitions, allowing the isolation variables such as trust, legalities and intellectual properties, and in two different project physical environments, enhanced the correlation between the performance of the teams in the competitions and the value of the protocols. The challenge of completing the brief objectives within the constrained time of the competitions is as an indication of the facilitating role of BIM protocols in creating a shared vision about collaborative design processes, facilitating the communication between project teams, and enhancing the quality and quantity of information produced by and delivered to all stakeholders involved.

The key contributions and implications of this research to the body-of-knowledge of BIM derive from: 1- the methodology utilized to develop the protocols for BIM collaborative design. The methodology can be used by project networks and supply chains to develop their own protocols for design phase and/or other project lifecycle phases 2- the protocols for BIM collaborative design including a top-level abstracted view of protocols content and gate decision phase requiring the assessment of the technological, process and policy feasibility prior to project execution, 3- the empirical investigation of the link between BIM project performance and the project physical and environment 4- a review of BIM frameworks and 5- the definition of BIM protocols.

The key limitations in the testing of the protocols are the isolation of trust and legalities (e.g. Intellectual Property - IP) variables. However, these were deliberately used as part of the experiment design to enhance the correlation between the testing outputs and the proposed protocols. In real world projects, the current trend to address legalities is to include the BIM protocols in one of the usual documents within the various construction contracts (e.g. Employers requirements in a JCT contract). Regarding the IP, the ConsensusDocs (e.g. Consensus Docs 301 BIM Addendum – AGCA, 2006) globally addresses legal and administration issues associated with the use of BIM. Also the UK CIC protocols (CIC, 2013) also includes several intellectual property rights' clauses clarifying permitted uses of models, levels of development and other contractual requirements. These documents can complement the proposed protocols with regards to legality issues.

Finally, despite the effort made in designing the experiments, the testing environments were competition projects judged over limited design stages and hence there are still limitations. Further research is required to develop key performance indicators for assessing the efficiency increase of design processes in the project's supply chain and the role of the protocols in homogenizing the different levels of BIM capability of project participants currently considered as one of the barriers to BIM widespread use on projects.

6. REFERENCES

AGCA - The Associated General Contractor of America (2007). *The Contractors' Guide to BIM*, Publication No. 2926, edition one, p. 3

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C. and O'Reilly, K. (2011). BIM adoption and implementation for architectural practices, *Structural Survey*, 29 (1), 7-25.

Austin, S., Steele, J., Macmillan, S., Kirby, P. and Spence, R. (2001). Mapping the conceptual design activity of interdisciplinary teams, *Design Studies*, 22 (3), 211-232.

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry, *Leadership and Management in Engineering*, 11(3), 241–252.

BCA - Building and Construction Authority (2012). *Singapore BIM Guide*, http://www.corenet.gov.sg [accessed November 2013].

Bresciani, S., Blackwell, E.F. and Eppler, M. (2008). A Collaborative Dimensions Framework: Understanding the Mediating Role of Conceptual Visualizations in Collaborative Knowledge Work, *Proceedings of the 41st Hawaii International Conference on System Science*, 7-10 January 2008, Waikoloa, Big Island, HI, USA.

BSI - Department of Business Skills and Innovation (2012). PAS 1192-2:2012 *Building Information Management – Information requirements for the capital delivery phase of construction projects*, http://www.cic.org.uk [accessed June 2013].

Cerovsek, T. (2011). A review and outlook for a 'Building Information Model' (BIM): A multi-standpoint framework for technological development, *Advanced Engineering Informatics* 25, 224-244.

Costa, R. and Sobek, D.K. (2006). Iteration in engineering design: inherent and unavoidable or product of choices made?, *Proceedings of Design Engineering Technical Conferences and Computers and Information in Engineering Conference Chicago*, Illinois USA, September 2-6, 2003.

Crook, C.W., and Kumar, R.L. (1998). Electronic data interchange: a multi-industry investigation using grounded theory, *Information & Management*, 34(2), 75-89.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2008). Managing BIM Technology in the Building Industry, AECbytes, Feb 12, 2008.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, 2nd Ed., John Wiley & Sons, Inc., New Jersey.

Fox, S., and Hietanen, J. 1 (2007). Interorganizational use of building information models: Potential for automational, informational and transformational effects. Construction Management and Economics, 25 (3), 289-296.

General Services Administration (2008). *3D-4D Building Information Modelling, Series 04 - 4D Phasing*, Washington DC, U.S.

Ghassemi, R. and Becerik-Gerber, B. (2011). Transitioning to Integrated Project Delivery: Potential Barriers and Lessons Learned, *Lean Construction Journal*, 2011, 32-52.

Giel, B. & Issa, R.A. (2012). Quality and maturity of BIM implementation within the AECO industry, In: *Proceeding of 14th International Conference on Computing in Civil and Building Engineering* (14th ICCCBE), Moscow, June 27-29.

Greenbaum, T. (1998). *The handbook for focus group research*, second edition. Thousand Oaks: Sage Publications.

Gu, N. and London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry, *Automation in Construction*, 19 (8), 988-999.

Harty, C. (2005). Innovation in construction: a sociology of technology approach, *Building Research and Information*, 33(6), 512-522.

Holsapple, C. W. and Joshi, K. D. (1999). Description and Analysis of Existing Knowledge Management Frameworks." *Proceedings of the Thirty-Second Annual Hawaii International Conference on System Sciences*, 1, 1072-1086.

Hughes, D., and DuMont, K. (1993). Using focus groups to facilitate culturally anchored research. *American Journal of Community Psychology*, 21(6), 747-773.

IDEF (1993). IDEF0 Function Modeling Method. http://www.idef.com/idef0.html, [accessed Nov 2013].

Jung, Y. and Joo, M. (2011). Building information modelling (BIM) framework for practical implementation, *Automation in Construction*, 20(2), 126-133.

Kassem, M., Dawood, N. and Mitchell, D. (2011). A Structured Methodology for Enterprise Modeling: a Case Study for Modeling the Operation of a British Organization, *Journal of Information Technology in Construction*, Vol 16, pp. 677-690.

Kassem, M., Brogden, T. and Dawood, N. (2012). BIM and 4D planning: a holistic study of the barriers and drivers to widespread adoption, KICEM Journal of Construction Engineering and Project Management, 2 (4), 1-10.

Kassem, M., Iqbal, N. and Dawood, N. (2013). A practice oriented BIM framework and workflows, *ASCE International Workshop on Computing in Civil Engineering*, 524 – 532.

Kassem, M., Succar, B., & Dawood, N. (2013). A proposed approach to comparing the BIM maturity of countries, *CIB W78 2013 - 30th International Conference on the Applications of IT in the AEC Industry, Beijing, China*.

Kassem, M., Succar, B., & Dawood, N. (2014). Building Information Modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy, In R. Issa & S. Olbina (Eds.), *Building Information Modeling: applications and practices in the AEC industry*, ASCE Technical Council on Computing and IT, University of Florida.

Kolb DA (1984). *Experiential learning: experience as a source of learning and development*. Prentice Hall, USA.

Maxwell, J.A. (2005). *Qualitative research design: An interactive approach (2nd ed.).* Thousand Oaks, CA: Sage Publications.

McGraw-Hill Construction (2010). *The business value of BIM in Europe, H.M. Bernstein* (Eds), McGraw-Hill Construction, Bedford: MA.

Minsky, M. (1975). A Framework for Representing Knowledge. Reprinted in *The Psychology of Computer Visio*n, P. Winston (Eds.), McGraw-Hill, 1975.

New York City Department of Design & Construction (2012). *BIM Guidelines*, Long Island City, NY

NIST - National Institute of Building Sciences (2007). *National Building Information Modeling Standard – part 1: Overview, Principles and Methodologies*, Washington, DC, U.S.

Penn State (2010). *BIM Project Execution Planning Guide and Templates – Version 2.0 BIM Project Execution Planning*, CIC Research Group, Department of Architectural Engineering, The Pennsylvania State University.

RIBA - Royal Institute of British Architects (2007). *Outline Plan of Work 2007*, RIBA Publishing, London.

RIBA - Royal Institute of British Architects (2012). *BIM Overlay to the RIBA Outline*, RIBA Publishing, London.

Ritter, H. (2010). *Models as Tools to Aid Thinking: Towards a Theory of Thinking*. In B. Glatzeder, V. Goel & A. Müller (Eds.), 347-374, Springer Berlin Heidelberg.

Rogers, E. (1962). *Diffusion of innovations*. Glencoe: Free Press.

Saaty, T. L. (1998). Reflections and Projections on Creativity in Operations Research and Management Science: A Pressing Need for a Shift in Paradigm, *Operations Research*, 46(1), 9-16.

Shavelson, R.J et al. (1993). On Concept Maps as Potential Authentic Assessments in Science. *Indirect Approaches to Knowledge Representation of High School Science*, National Center for Research on Evaluation, Standards, and Student Testing, Los Angeles, CA.

Singh, V., Gu, N., and Wang, X. (2011). A Theoretical Framework of a BIM-based Multi-disciplinary Collaboration Platform. *Automation in Construction*, 20 (2), 134-144.

Smith and Tardiff (2009). *Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Manager*: John Wiley and Sons: New Jersey.

Smith, R.E., Mossman, A. and Emmitt, S. (2011). Editorial: Lean and Integrated Project Delivery Special Issue, *Lean Construction Journal*, 1-16.

Succar, B. (2009). *Building information modeling framework: a research and delivery foundation for industry stakeholders*, *Automation in Construction*, 18 (3), pp. 357-375.

Suermann P, Issa R (2009). Evaluating industry perceptions of building information modelling (BIM) impact on construction, *Journal of Information Technology in Construction*, 14, 574-594.

Taylor, J. (2007). The antecedents of successful 3D CAD implementation in design and construction networks." *Journal of Construction Engineering and Project Management,* 133 (12), 993‑1002.

Taylor, J. and Levitt, R. (2004). A New Model for Systemic Innovation Diffusion in Project-based Industries, *Project Management Institute International Research Conference*, London, UK.

Taylor, J.E. and Bernstein, P.G. (2009) Paradigm trajectories of building information modelling practice in project networks, *Journal of Management in Engineering*, 25 (2), 69-76.

USACE - U.S. Army Corps of Engineers (2010). *USACE BIM Project Execution Plan*, Version 1.0, Washington DC, U.S.

Vaughn, S., Schumm, J. S., & Sinagub, J. (1996). *Focus group interviews in education and psychology,* Thousand Oaks, Sage.

White, R., and Gunstone, R. (1992). *Probing understanding*, London: The Falmer Press.