Management of Collaborative BIM data by Federating Distributed BIM Models

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ABSTRACT

The Architecture Engineering and Construction sector is currently undergoing a significant period of change and modernisation. In the United Kingdom (UK) in particular this is driven by the government's objective of reducing the cost of construction projects. This is to be achieved by requiring all publicly funded projects to utilise fully collaborative Building Information Modelling by 2016. A common goal in increasing the Building Information Model (BIM) adoption of the industry is the movement towards the realisation of a BIM as either a single data model or a series of tightly coupled federated models. However, there are key obstacles to be overcome including; uncertainty over data ownership, concerns relating the security/privacy of data and reluctance of companies to "outsource" their data storage. This paper proposes a framework that is able to provide a solution for managing collaboration in the Architecture Engineering an Construction (AEC) sector. The solution presented in this paper provides an overlay that automatically federates and governs distributed BIM data. The use of this overlay provides an integrated BIM model that is physically distributed across the stakeholders within a construction project. The key research question addressed by this paper is whether such an overlay can, by providing dynamic federation and governance of BIM data, overcome some key obstacles to BIM adoption including questions over data ownership, the security/privacy of data and reluctance of companies to share data.

More specifically, this paper provides the following contributions: (i) presentation of a vi-

sion for the implementation and governance of a federated distributed BIM data model, (ii) description of the BIM process and governance model that underpins the approach and (iii) provision of a validation case study using real construction data from a UK highways project, demonstrating that both the federated BIM overlay and the process and governance model are fit for purpose.

INTRODUCTION

The UK BIM Government task group has defined BIM as "value creating collaboration through the entire life-cycle of assets, underpinned by the creation, collation and exchange of shared 3D models and intelligent, structured data attached to them"(UK BIM Taskgroup, 2014). In the UK, driven by government targets, BIM adoption has been steadily increasing, from 39% in 2013(National BIM Service, 2013) to 48% in 2014 (National BIM Service, 2015).

Successful delivery of a construction project is a highly complex process; requiring collaboration between employers, designers, suppliers and facilities managers through a range of design and construction tasks. This complexity is a key motivation for the use of BIM, with financial and time savings offered by its adoption(Bryde et al., 2013). Other motivating factors for BIM adoption include (a) project failure caused by lack of effective project team integration across supply chains (Latham, 1994; Egan, 1998) (b) emergence of challenging new forms of procurement i.e. Private Finance Initiative, Public-Private Partnership and the design-build-operate (Barrett and Sexton, 2006; Dainty et al., 2006) and (c) decreasing the whole life cost of a building through the adoption of BIM in facilities management(Becerik-Gerber and Calis, 2012).

A common goal of increasing BIM adoption is the move towards the realisation of a BIM as either a single data model or a series of tightly coupled federated models(Cerovsek, 2011; UK Cabinet Office, 2011). This movement towards what is known as "Level 3" BIM(Construction Industry Council, 2013) in the UK, is driven primarily by the desire to reduce the cost of construction projects.

However, before "Level 3" BIM can truly achieve widespread adopted there are key obstacles to be overcome. These include(Rezgui et al., 2013; Alreshidi and Rezgui, 2015): (a) lack of clarity as to who owns and is responsible for BIM (b) fragmentation of BIM data across design and engineering teams and then the contractor and FM companies and (c) information not being sustained across the lifecycle of a building.

This paper, proposes that the use of a BIM federation overlay to automatically federate distributed BIM data models, in a consistent and managed way provides a viable route to overcoming obstacles in adopting an integrated approach to BIM.

The approach is required as the nature of construction projects mean that standard product life-cycle management tools are not able to be applied(Aram and Eastman, 2013). Reasons for this include; the fact that most projects are unique, fragmentation of data across different companies within a project, long life-cycles of buildings, large separation between design and construction activities and multiple possible procurement routes(Rezgui et al., 2013; Aram and Eastman, 2013).

The research question is: Does the use of a BIM federation overlay to automatically federate BIM data that is physically distributed across stakeholders and supply chains provide advantages of standard model merging technologies by overcoming key obstacles to BIM adoption. These obstacles include questions over data ownership, the security, privacy and sustainability of data, and reluctance of companies to share data.

To answer this research question, this paper will describe the overlay, its implementation and the BIM process and governance model that underpins its functionality. This paper shows how it can provide automatic federation and governance of BIM models, distributed across stakeholders within a construction project, but still federated across these stakeholders in such as way that this distribution is transparent to the users of the model. This paper also describes the validation that has been conducted by analysing this approach against a case study using real construction data drawn from a UK highways project. Finally, this paper shows how this approach provides key advantages in terms of the management, governance (i.e. the implementation of access control, control of modifications to data and managing how BIM data can be used across the project) and user acceptance of the integrated use of BIM across project stakeholders. Demonstrating that a federated distributed BIM data model can meet the requirements of BIM workflows and provide advantages over existing approaches, while offering key advantages over other common BIM server implementations including, increased dynamism and a lack of centralised data sources.

In order to implement this overlay, a particular cloud engine called CometCloud (CometCloud, 2014) which enables the implementation of a logical "shared" space that is physically distributed across multiple sites involved in the federation was utilised. It is within this shared space that BIM data is stored and federated.

The remainder of this paper is structured as follows; a survey of related literature will first be presented followed by an overview of the shared distributed BIM data model. Then the next section outlines how the BIM process and governance model that underpins the federated BIM overlay was developed, along with documenting the implementation of the federated BIM overlay. Finally, a validation using real construction data and conclusions are presented.

RELATED WORK

This section will outline key related works in the two main areas relevant to this paper; BIM Standards and BIM Technologies.

BIM Standards

Currently, there is an increasing adoption of standardised approaches to BIM. These include, for the UK, the BS1192 series of British Standards. These standards contain codes of practice for utilising COBie(National BIM Standard US, 2015) and BS1192:2007(British Standards Institute, 2008) which is a standard for collaborative production of project information. This document provides a naming convention and also models how assets within a project can be modelled through their lifecycle. Another newly emerging standard is PAS (Publicly Accessible Standard) 1192 Part 2(National BIM Standard US, 2015). This standard outlines specifications for information management processes for construction projects using BIM, focusing specifically on the collaborative BIM approaches currently being adopted within the UK construction industry.

The area of data standardisation within the construction sector is mainly driven by the IFCs (Industry Foundation Classes), developed by buildingSMART international(International Standards Organisation, 2005). The IFCs specify a rich data model that can be used to organise data within a construction project, the IFCs also define how this model can be communicated between software packages using STEP(International Standards Organisation, 1994), XML(Nisbet and Liebich, 2005) and the newly standardised IFCOwl(Beetz et al., 2009). Other BIM standards related to collaboration have also been developed, most recently the introduction of the BIM Collaboration Format (BCF)(van Berlo et al., 2014). BCF is an xml format based, that enables users to share fragments of BIM data, with attached comments and requests for changes, without the requirement of sharing the entire BIM model. Another related technology to the IFCs is the bimQL query language(Mazairac and Beetz, 2013). This query language has been created to be an open, platform and implementation independent way of querying, updating and deleting data within IFC models. So far the primary platform that has implemented bimQL is BIM Server(Beetz, 2010).

BIM Technologies

There are a plethora of software packages available to support the adoption of BIM. In fact, the use of BIM authoring environments by stakeholders is becoming more and more common. Well known BIM authoring environments include: Autodesk Revit(Autodesk, 2016b) and Bentley Systems AECOSIM(Bentley System, 2016). More critical to the adoption of BIM at a wider scale(Rezgui et al., 2013) is how the data from these authoring applications is coordinated. To solve this problem a number of solutions have been developed, and have become commonly known as "BIM Servers".

Examples of BIM servers include the Onuma system(Onuma, 2015) RevitServer (Autodesk, 2016c), Bentley ProjectWise(Bentley Systems, 2016), Graphisoft BIM Server(Graphisoft, 2016b), BIM Server (Beetz, 2010), Autodesk BIM 360(Autodesk, 2016a), Graphisoft BIM Cloud (Graphisoft, 2016a) and 3DRepo(Scully and Timothy, 2015). These servers provide a multitude of features but can be broadly classified into two categories based on the way they store data: centralised data repositories, such as Graphisoft Server/BIM Cloud, The Onuma System, 3DRepo and BIM Server, and distributed data repositories, such as RevitServer and ProjectWise.

Within a centralised repository, either a cloud based server, or a server deployed within an organisation's ICT infrastructure is established to provide features such as management, governance and versioning of BIM data, often bringing significant advantages to their users. However, when adopting such a centralised approach organisations may well face barriers. These include a reluctance to adopt cloud based solutions due to concerns regarding data security and privacy(Redmond and Alan, 2012; Rezgui et al., 2013) and the reluctance of an organisation to relinquish control over data that they are legally liable for being correct. Conversely, deploying such tools on a companies own IT infrastructure limits the possibilities for collaboration, as other organisations are often reluctant to commit their own data to a server under the control of another organisation(Rezgui et al., 2013).

Recently, the concept of decentralised repositories, where data is stored across multiple servers, has also originated. This type of service is currently provided by both Revit Server and Bentley System's ProjectWise. In these systems, data is spread between multiple servers (termed integration and caching servers in the case of Bentley, and hosts and accelerators for Revit Server). However, current implementations of this concept still do not remove the barriers that have been described previously. This is due to the fact that, despite both Revit and Bentley allowing the distribution of BIM data across multiple servers, there still remains one authoritative (or master) copy on the data, hosted in a centralised way on a given server. This latent centralisation presents organisations with many of the same concerns as for centralised BIM server approaches i.e. ownership of data if it is placed onto another organisations server, and concerns regarding data security and their liability for this data.

In addition to these commercial offerings, the concept of BIM storage and collaboration is also a topic of active research. In their work on SocialBIM, Das et al(Das et al., 2015) have developed a BIM framework that primarily focuses on modelling the social interactions between stakeholders. The key development is SocialBIM's ability to allow users to contribute/download partial BIM models that are then merged/split from a "master" model held in the SocialBIM cloud system. While this ability to work in terms of small "fragments" of BIMs which are then federated is a key development, the fact that the end result is still stored in a centralised way in a cloud system will be of concern to many organisations.

vanBerlo et. al (van Berlo et al., 2016) have proposed the "BIM Bots" distributed framework using the concept of bots (automated expert systems) to inform when a change of the design takes place. The authors approach shares commonalities with "BIM Bots" framework in terms of the decentralised method it adopts and its approach to the distribution of events representing activities that may occur with a project. The main differentiation factor focuses on the extent to which the author's system is distributed. More specifically, BIM bots provides a workflow to logically distribute BIM processing such as simulation/analysis, directed by a centralised BIM Server instance. The authors work, however, physically distributes BIM data across disciplines located at different network locations in a true peer-to-peer sense, with no centralised storage of data in any form.

Other work in this area includes Munkley et al(Munkley et al., 2014), who have developed technologies to synchronize data between Revit Server and an external storage server, enabling external users to see a read only copy of the Revit central model. While this is an interesting way of allowing increased collaboration using RevitServer, it does not adequately provide for the dynamic two way collaboration that is often required in a construction project i.e. the ability to incorporate the results of other discipline's work as background in your own work. Finally, this approach is further limited as it is only able to utilise the Revit proprietary data format. Additionally, Boeykens et al (Boeykens et al., 2015) have developed a layered client/server approach that provides an event based communications pool between components embedded into BIM authoring packages. This novel communication approach is a very interesting development and allows the dynamic sharing of data between components. However, all data is still stored on a centralised server that listens to the event based communications and both saves and injects BIM data into the communications pool as needed.

This section has reviewed existing related works in the field. From this, it is clear that the concept of federating BIM models is not a new one(Solihin et al., 2016) with a large amount of work being conducted in the area of federating BIMs within BIM authoring packages or on model servers(Solihin et al., 2016). The key differentiating factor of this work is the distributed nature of the approach, where the authoritative copy of data is always stored within a discipline's own servers and is only federated with other disciplines when required and in accordance to the governance model that is controlling access to the data. Another key differentiating factor is the increased level of dynamic communication that is possible between multiple disciplines using this approach, i.e. when a single discipline makes updates that are visible to other disciplines, these updates are automatically propagated to the relevant disciplines, without a need for the other disciplines to query if any updates have been made. The fact that this communication and federation is also transparent to the user is key.

OVERVIEW OF A FEDERATED DISTRIBUTED BIM DATA MODEL

A construction project is a complex undertaking dependant on a large number of very different professions and firms. These firms range from SMEs (Small to Medium Enterprises) to large multinational corporations. Each one of these organisations will participate in the construction project for a varying time period and, in that time period, will contribute different quantities and types of data to the project, or even contribute no data. As has been previously described, while interest in cloud based BIM solutions is increasing(Kumar et al., 2010), there are still many obstacles to BIM adoption that must be overcome. These include: (a) lack of clarity as to who owns and is responsible for BIM (b) fragmentation of BIM data across design and engineering teams and then the contractor and FM companies and (c) information is not sustained across the lifecycle and is in continuous danger of being lost due to company mergers or bankruptcy.

In response to these obstacles the use of an BIM federation overlay to implement a federated distributed BIM data model within a construction project was proposed. Figure 1 describes the overlay and associated data model that has been developed by drawing on technologies from cloud and distributed computing.

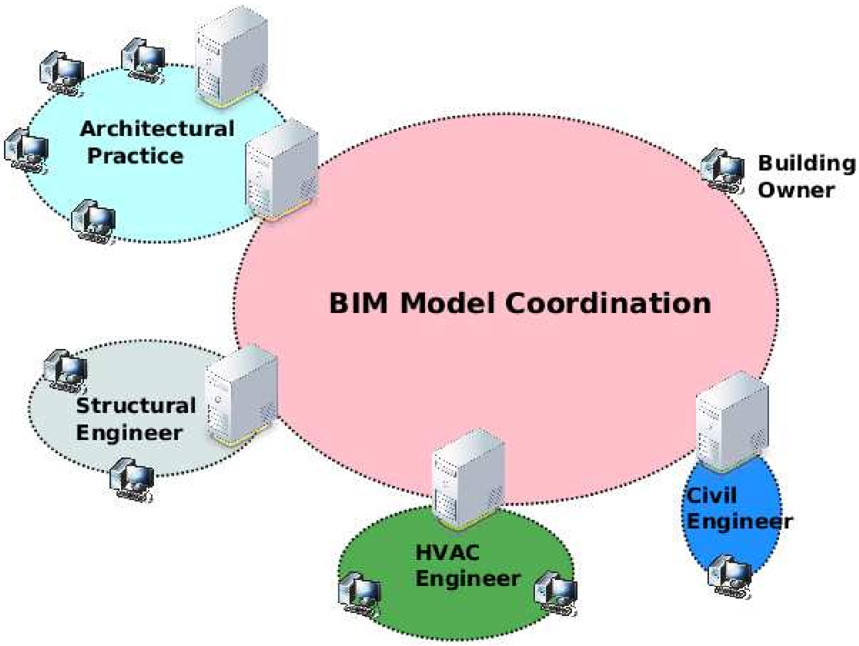

FIG. 1. Overview of a Federated Distributed BIM Data Model

Figure 1 shows that within the proposed architecture the team of individuals working on a construction project will be sub-divided in some way. In this case, they have been subdivided into their respective disciplines. This has been done, in this case, for ease of presentation, and because, in many cases, each discipline possesses their own IT infrastructure and will be phsyically co-located. However, the sub-division of the project is completely definable.

Once the project has been sub-divided each division (discipline in this example) i.e.

the Architectural Practice, will continue to work with their own elements of the BIM model stored initially on their own systems. At the project level, a BIM model federation overlay is present to coordinate and federate the data between the participating disciplines. It is also important to note that the building owner is included in Figure 1 to represent how a user could access the complete BIM model without directly contributing data. It should be noted that the disciplines presented in Figure 1 are examples of possible disciplines that could be involved in a construction project, this approach is completely customizable in the number and the identity of the disciplines that are involved.

The computing infrastructure of each discipline is used to store and also to perform various operations on the BIM models. These disciplines also contribute their computing capability towards the creation of the shared coordination space where BIM model synchronisation takes place.

This architecture imposes that the ownership of data remains with the discipline that created that data and that the use of the BIM federation overlay allows users of the BIM model to transparently view it as a single model. The sharing of BIM data between disciplines and what data is visible to external users, is managed automatically by the system based on a configurable process and governance model that has been developed. Finally, information is duplicated across the discipline sites, providing a cache of read only BIM objects across the overlay. This provides sustainability for BIM data, i.e. preventing loss of data following failure of discipline computing resources, to allow for data to be preserved should a discipline leave the system and to improve performance and reduce the network load. It should be stressed however, with the exception of these circumstances, that the authoritative copy always remains with the authoring discipline.

The deployment of the federated distributed BIM model is further described in Section 5. The following sections will now describe the methodology for developing the process, governance and management model that ensures the secure sharing of data between disciplines when utilising the BIM federation overlay.

GENERALISING BIM PROCESSES

This section presents the development of a BIM governance and process model to underpin the federated BIM overlay. This section determines: *within a federated distributed BIM model, how should the process of BIM be structured?* More specifically it tackles three key issues; how is a construction project structured, how is the workflow within each phase of a construction project structured and how is the data that originates from the execution of this workflow structured and stored.

Methodology

This section describes the methodology employed in the development of the process and governance model. As a starting point, this sections describes a clear vision that the system will operate on the basis of being distributed across the stakeholders within a construction project and integrated across these stakeholder in such a way that this distribution is transparent to the users of the model. However, it is critical that the data within this model is managed and governed correctly. To this end a detailed consultative approach will be undertaken to develop the governance and process model for collaborative BIM data.

Important considerations when defining the approach are to ensure that the final developed solution is:

- Industry relevant - in that it presents a view of BIM data that adequately represents the view of the construction industry.
- Sufficiently generalisable - to enable its application to the industry as a whole and not just specific elements of the industry.
- Requirement led - in that the technology utilised will solve real problems within the industry.

To meet these requirements a qualitative approach has been adopted, utilising two key inputs; focus groups - consisting of companies currently using, or involved with BIM implementation and literature (both industrial and academic). Utilising this mixed approach enabled the research to be based on industry requirements from focus groups and draw industry requirements from industrial literature to ensure the developed system is not specific to the companies involved in the focus group. These are coupled with a process of drawing in the state-of the art ideas that may not yet have been applied in practice from academic literature.

The focus group sessions took place over 9 months from February 2014 to November 2014 and involved the following companies: Building Research Establishment (BRE), Costain , NBS (National BIM Service), AEC3 UK (BIM Consultancy) and Lee Wakemens(Project Management).

The initial consultation methodology took an iterative approach and sought to determine the following: How is a construction project structured, how can BIM data be managed across its lifecycle, and how should access to this data be governed.

In addition to a consultation, a review of existing BIM technologies and implementations was also conducted. Included in this review were an analysis of the IFCs, which are currently the most widely used open standard for storing BIM(International Standards Organisation, 2005). The IFCs, with its standard set of rules for data storage and data exchange, provides a framework to manage data related to a building throughout its lifecycle(International Standards Organisation, 2005; Nisbet and Liebich, 2005). In addition to the IFCs, Model View Definitions (MVD)(Hietanen, 2006) were also studied. An MVD is used to define a subset of the IFC schema that should be transmitted at any given point of data exchange. Currently, there are many examples of standardised MVDs, these include; the space boundary view, which is used to support the use of BIM in energy and thermal analysis and the quantity take off view, used to support BIM in transmitting base quantities for spatial, building service and and structural elements. As part of developing the BIM overlay concepts from both of these technologies have been drawn upon.

Following this consultation and review, the results were formulated into a generalised model of BIM processes. The documented BIM processes model will then be extended with a governance model for a shared, integrated and collaborative BIM. This governance model and the overall system implementation will subsequently be validated by utilising a previously unseen industrial case study, that was selected after the consultation phase of the research. This case study will involve the documentation of specific processes, drawn from real construction projects from the consultation team's expertise.

Structuring a Construction Project

Structuring a construction project into distinct stages or phases is not a new concept within the construction industry. In the UK there has been several sets of defined standards for the way of operating. These include, methodologies such as the RIBA project stages(Royal Institute of British Architects, 2007) a similar process known as Process Protocol (Aouad et al., 1998) and, most recently, the CIC (Construction Industry Council) project stages (Construction Industry Council, 2013). However, in addition to these common methodologies utilised within the construction industry there is also conflicting literature stating that BIM should offer a phaseless workflow(Succar, 2009).

The key output of the consultation was the need for flexibility in the ability of project managers and domain users to specify how they wish to share and subsequently use shared information. Furthermore, it became apparent from meetings that no one model of governance could adequately represent the complexity of the construction sector. Thus, the approach was taken to a develop high level, simple but flexible model. However, a few more detailed agreements were reached: that the implementation of a project process such as the RIBA or CIC model is currently essential to achieve construction industry adoption, the names of the project stages themselves often vary between projects and project teams and the implementation of the project stages within a construction project is not an exact science and it is impossible to impose a rigid rules on what each project phase means to a project.

These results have drawn the following conclusions; that the implementation of the set of project stages is essential, that the structuring of these stages should be flexible enough to model all currently available standards (such as the RIBA or CIC models) or even project specific implementations, and that the use of project phases is at the project management level, and should enforce no requirements when it comes to data within the BIM.

Figure 2 shows the defined model for structuring a construction project. Three key concepts have been introduced:

- project - which represents the high level construction project,
- stage - which represents that a project can have one or more stages within it - but these stages can be freely defined,
- disciplines - show the relationship described previously between disciplines and the BIM objects they define,
- the fact that the project is made up of BIM objects (which will be discussed in more detail in the next section).

It is important to note that the BIM objects are largely decoupled from the project stages - the only link between them is stage they were first created in.

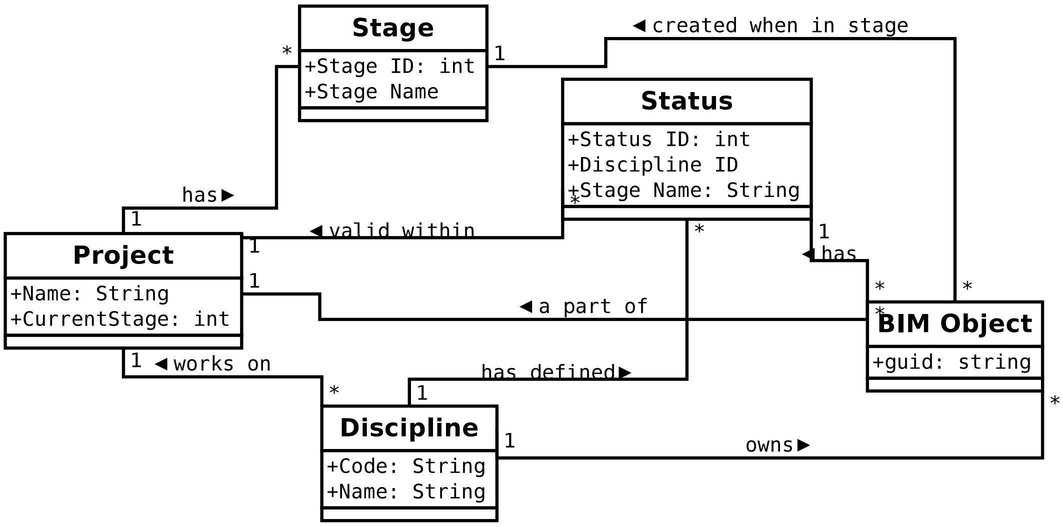

FIG. 2. Structuring data within a Construction Project

Managing BIM Data Across its Life-cycle

The second important aspect of managing BIM data is understanding the data itself, and the life-cycle of this data within the overall BIM model. In order to build this understanding, this section defines an abstract process that integrates the results of the consultations. This process has abstracted the approaches defined in BS1192a(British Standards Institute, 2008) and, by integrating and abstracting the variety of processes described by participants during workshops, has defined the typical structure of a construction project using BPMN (Business Process Modelling Language).

This approach also provides a time based evidence of the changes that an IFC object may go through over time by implementing a BIM data access/provenance tracking service. This enables this paper's approach to take a more consistent view of the model and clearly determine the operations that have been applied to IFC objects and to the IFC model itself. This provenance model stores information about the disciplines, timestamps, the IFC objects and the project stage when a particular update has been applied. The analysis has identified three distinct suitabilities of use that data goes through as part of its life-cycle. These three suitabilities are termed; portfolio - representing finalized data available to the client, this suitability maps to the "Published" concept in BS1192, and Project - representing data available to be shared with other disciplines within the project, this maps to the "Shared" concept in BS1192 and (c) Discipline - which represents data that is not yet ready to be shared within the project, this maps to the "Work in Progress" concept from BS1192.

Further consultation within the focus groups revealed that while these three levels of suitability provide a high level of abstraction; in many larger organisations more sub-levels are required in order to separate data within each of the high level suitabilities. To cater for these scenarios it is defined that a each suitability will define a series of sub-levels, termed statuses.

Figure 2 shows how each status is then assigned to a BIM object, modelling that object's position through it's lifecycle. The maturity and suitability for use of this object will increase as its status increases through the of the Discipline, Project and Portfolio suitabilities. This approach is made even more flexible by the fact that each discipline within the construction project is free to define the number of statuses they wish to utilise, along with how they want each status identified. This feature was a key output from the consultation, as it was found that small companies will require very few statuses, reflecting the relative simplicity of their organisations, whereas large companies will often require a far larger number of statuses.

This is a simple but flexible approach providing a powerful enough abstraction to model the lifecycle of data within a construction project. However, another important concern is to understand the workflow by which each item of BIM data moves through its lifecycle. The initial analysis, and review in focus groups, has identified three key classes of actors within a construction project: (a) Coordinator (b) Contributor and (c) Engineers. To this end, the processes associated with this three classes of actors been modelled using BPMN. Figure 3 shows the overall workflow that has been documented and validated. More specifically the BPMN models describe that: (a) the coordinator is responsible for offering tasks and then merging and checking the solution to the task, (b) the contributor reviews tasks that have been assigned by a coordinator, delegates the task and then awaits the submission and (c) the engineer accepts a task, checks the background information available and then develops a solution to the task.

It should be noted, is that this model allows (but it cannot be shown in the Figure) that there may be multiple layers of contributors between an engineer and the coordinator.

Figure 3 shows that, at an abstract level, the operation of a construction project can actually be generalised into a series of relatively simple repeating tasks. With the multiple layers of contributors essentially modelling the lifecycle of each item of data through multiple levels of approval and thus increasing suitability.

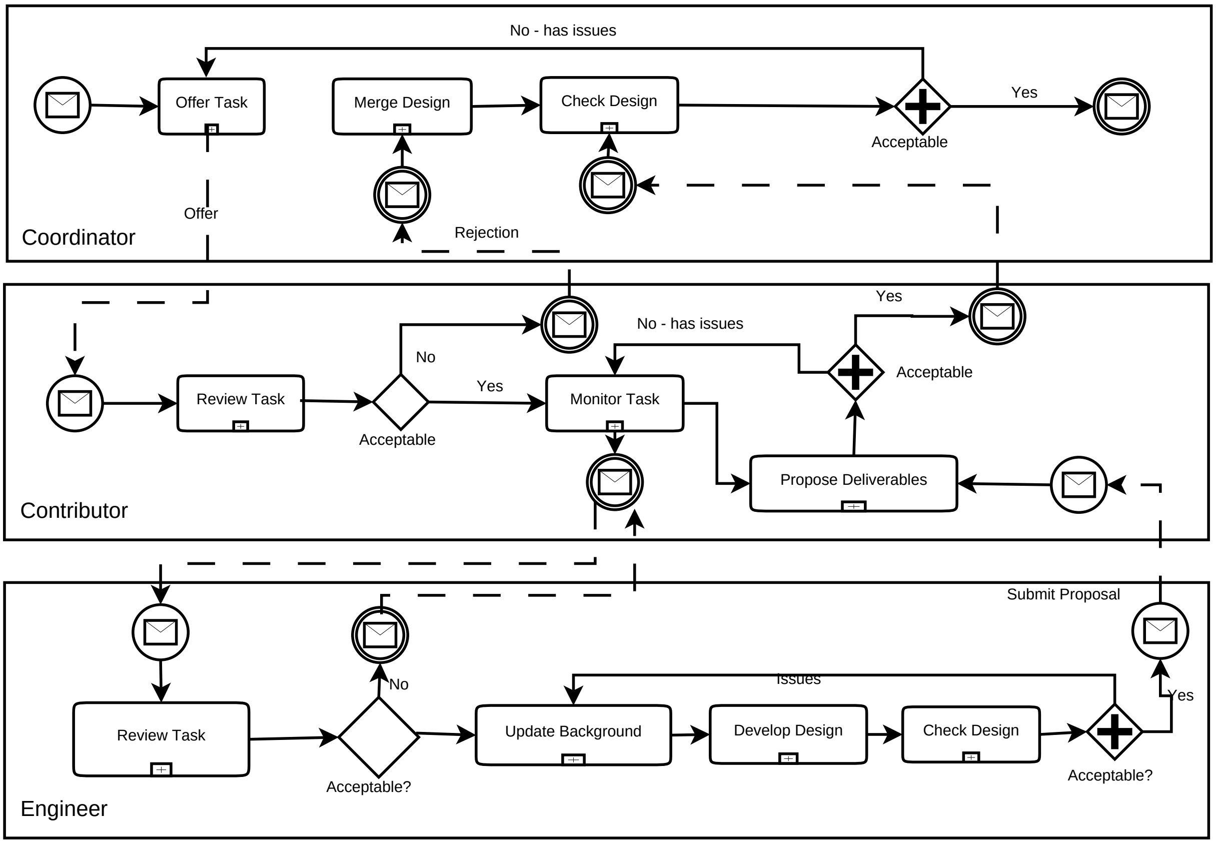

FIG. 3. BIM Process Modelling

This process model enabled several key conclusions to be drawn about how data should be managed; only the engineer role of actors actually contribute content directly to the BIM model and contributor and coordinator roles coordinate work for the levels above them issuing tasks and managing the process merging design. Finally, it should be noted that the process of merging new elements into the overall building design can be related to the previously defined concept of *statuses* such that essentially merging new objects into the wider model is in fact increasing their status within the project i.e. moving from Discipline to Project suitabilities.

This analysis has verified previous work(Mazairac and Beetz, 2013) that has shown that there is, in reality, only a few key operations that can be performed when contributing data to a BIM model. The creation of new objects, updating objects (which is in effect creation of a new object based on a previous object) and updating the status of an object, either increasing or decreasing its suitability for use.

A Governance Model for Shared, Integrated and Collaborative BIM Data

In the previous sections the process model that is utilised to organise the data within a distributed shared BIM model has been described. Another important aspect that must be considered, however, is that this data is governed. To this end a simple, but powerful governance model for BIM data has been developed and iteratively reviewed with focus groups. This model takes the concepts of disciplines, levels, and the classes of actors within a building project and integrates it with a set of explicit governance rules.

The explicit governance rules that form the model are:

- Only users within a discipline may modify that discipline's data,.
- The engineer actors within a discipline may modify data within their own discipline.
- The supervisor actors may modify the status of BIM a object within their discipline within a pre-set range of levels as defined by the the governance model in operation.
- Each discipline can select at which status another disciplines may utilise their BIM objects as background to their work.
- Each discipline can also select the statuses at which BIM objects from other disciplines may be utilised as background.

These key rules define the governance approach that is being utilised with the federated distributed BIM model. However, this model is further realised by the meta data structures that support the BIM data by capturing the overall process and objects/artefacts that are stored within the model. This is shown in Figure 4.

Figure 4 documents two key points: the introduction of a permission list, defining what disciplines objects each discipline can see and the two types of permission entries one defined by a discipline to determine which of its objects it allows another discipline to see and one defined by a discipline to define which objects of another discipline it allows its engineer's to see. A sample permission list is Shown in Table 1.

This flexible approach of defining permission lists on a per discipline level allows the definition of what are essentially lenses(Succar, 2009) that are applied to all users within a discipline to filter how they view the BIM data within the model that they will be using as background. It should be stressed that this only applies to reading data and that the governance approach that has been taken specifically restricts BIM data from

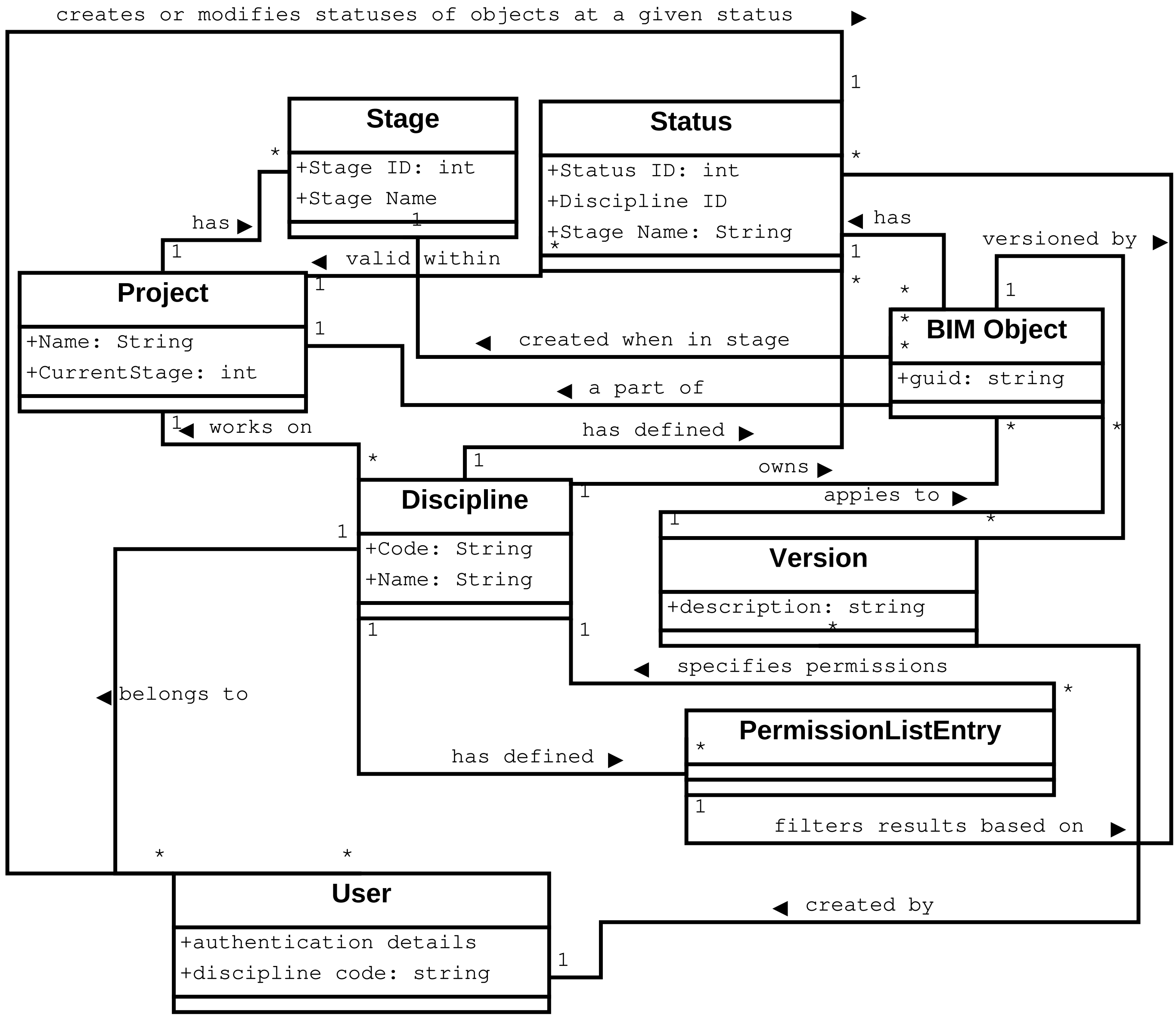

FIG. 4. Governing Data Within a Construction Project

being modified outside of the discipline which created it. This approach is very similar to that adopted as part of the MVD(Model View Definition) definition process(Hietanen, 2006), when the objects required during each exchange of data is specified. Currently, objects are filtered based on their suitability, but it is equally possible for this to be specified by on object types. Indeed, it would be completely feasible for the permissions lists to be automatically generated from existing MVD definitions.

Table 1 shows an example permission list. In this figure three disciplines are defined: K - Client, A - Architect and S - Structural Engineer. This table describes that the architect discipline allows all other disciplines to utilise it's objects as background as long as they are of status > 6. This table also specifies that the architect discipline only allows its users to utilise objects from the structural engineering discipline when they are at least status > 5. This approach is similar in many ways to that of access control lists (Sandhu et al, 1994) the key difference in this case is that the access control is performed on four properties of the object being transmitted; the discipline it is being transmitted to, the discipline that owns it, and the current suitability code of the object. The required values of these properties in order for transmission to be allows is taken from the governance model.

DEPLOYING A FEDERATED BIM OVERLAY

This section will describe the implementation of the federated BIM overlay, focusing on the actual implementation of the process and governance model that has been previously described, showing the main stages in its development. These stages include; (a) how the concrete storage of BIM data has been implemented, (b) how existing cloud computing technologies have been leveraged to provide a sound technological foundation for the work, (c) the BIM API (Application Programming Interface) that has been developed to allow BIM software tools to interact with the BIM overlay and (d) the physical computing infrastructure required to operate the overlay.

Implementation of BIM Objects and Federation

The concept of a "BIM object" was introduced in the previous section. While this, at an abstract level, is sufficient for the purposes of describing the governance and process model, this section will now define how this translates into an implementation.

As mentioned previously, the IFCs are currently the most widely used open standard for storing BIM. It is for this reason that the IFCs have been selected as the author's chosen BIM standard for this work. To this end the following definition has been applied: *A single BIM object is each object from the IFC model that is categorised by the IFC specification as an entity. Also included in the BIM object is any supporting IFC objects attached to this entity that are not categorised as entities.* This essentially enables a BIM object to represent the minimum amount of IFC objects that must be transmitted in order to convey the data behind single entity within an IFC model. Adopting this type of abstraction is not new, and has often been utilised in previous work and as part of the MVD definition process(Hietanen, 2006).

This implementation of conceptual BIM objects has allowed for the adoption of a two phased approach to federating data. In this approach data is federated in two ways - intra-discipline and inter-discipline.

Intra-Discipline: Intra-discipline federation consists of firstly producing the most up to date version of the IFC model held on a given discipline as viewable by another discipline. This stage consists of iterating through every BIM object on a given discipline and selecting the most up to date version that is viewable by the discipline requesting the data (if any). These selected objects are then exported into an IFC model and transmitted to the discipline requesting the data.

Inter-Discipline: The inter-discipline federation consists of federating the models produced from each discipline. This process simply consists of combining all of the models that have been received.

By adopting this two level approach, where the latest version of a given discipline's IFC data is assembled within the discipline that created it and then subsequently federated, allows the system to provide data consistency. This is achieved because there is only ever an one authoritative copy of an object, residing on the discipline that created it and any merging of multiple versions of this object takes placed before any data is communicated from that discipline. This is verified by the verification of the functionality of the system as part of the validation case study, which is described later in the paper.

A key issue when performing this type of federation is ensuring that consistency is maintained. This is an issue that has also been tackled by a variety of other works in the field of truth maintenance. In these works a truth maintenance engine is utilised in order to; maintain consistency of CAD data by providing a distinct context for each for each user collaborating over that data (Tang and Frazer, 2001) and generating new design options(Zha, 2000). This paper's approach takes a similar approach, except for the utilisation of the explicit version structure of each disciplines objects to ensure consistency in intra-disciplines federation and, due to the enforced distribution of objects between disciplines and the fact that each object within the model is owned by only one discipline, the inter-discipline merging approach can produce consistent models, the only consistency checking that is needed in this case is to ensure that any duplicated objects are removed.

Leveraging Existing Cloud Computing Technologies

On the computing side, in order to develop the federated BIM overlay, an existing federation model based on the CometCloud (CometCloud, 2014; Petri et al., 2014; Villegas et al., 2012; Kim et al., 2009) coordination "spaces" as utilised. In comparison to other BIM servers, the CometCloud distributed framework enables the creation of coordination spaces as an abstraction, based on the availability of a distributed shared memory that all users(disciplines) of the spaces can access and observe, enabling information sharing by publishing requests/offers to/for information to this shared memory. These coordination spaces are used by the federated BIM overlay to exchange messages, to discover available data/resources, announcing changes or routing users' requests for data. More specifically the adoption of the CometCloud coordination spaces allows the overlay to: (a) exchange messages between disciplines, informing them when new data is available, (b) request data - without necessarily knowing what discipline it resides on, (c) ensure duplication of data across disciplines, (d) keep governance data is in sync across all disciplines, (e) log messages to ensure all actions on BIM data are logged.

A Distributed BIM data access API

To enable proprietary software packages such as Revit to connect to the developed coordination framework a Java BIM API has been implemented. A set of methods for enabling the distributed manipulation of IFC objects where various disciplines associated with a project can work on the same IFC model have also been developed. This API consists of two parts; (a) a metadata API that allows the fetching and setting of values and (b) the BIM API that allows the retrieving and managing of BIM data. The BIM API is shown in Table 2

In the BIM API presented bellow, "metadata" refers to a set of data about an IFC objects and the project itself, this includes the ability to manipulate the governance model and permission lists. The key methods that have been implemented as part of the API are:(1) updateModel() and (2) getCurrentModel().

updateModel – enables the user to make the federated layer aware of new IFC objects that have been authored, along with their intended status codes. The parameters for this method are a set of objects that have been updated and their status codes.

getCurrentModel – enables the client to fetch the latest version of the model as background from the other collaborative disciplines. The data that will be returned is based on the configuration made in the governance and process model.

Integration with IT Systems and BIM Authoring Tools

One of the key strengths of this approach is that it can integrate with existing IT systems within the organisation. The federated BIM overlay can be installed on machines within a companies existing ICT systems, allowing the BIM data already stored on these systems to be federated (subject to configuration of the overlay when deployed). Additionally, by leveraging the functionality of CometCloud the federated BIM overlay is also able to support a master worker approach, allowing integration with companies that run their own internal private cloud systems, or outsource their data storage to public cloud systems.

On the client side, a Revit plug-in was developed to assist engineers with adding status/suitability codes to IFC objects and to view the status codes of objects that are retrieved as part of the federated BIM model. This Revit plug-in fetches and retrieves data from the federated BIM overlay using the API described previously.

Eliciting Governance Model Data from Users

In addition to the overlay itself and the integration with BIM authoring tools, a user interface was also developed to allow data for the governance model to be captured from users. This is shown in Figure 5. This interface allows end users to specify which disciplines they wish to share and utilise objects from. It also allows the specification, in an intuitive way, of the suitability rules that govern the sharing of objects. This means that each discipline can specify what other disciplines can use their objects, and at what level of maturity these objects can be shared. Secondly, a discipline can also select what objects from other disciplines they wish to use and at what level of maturity these can be used (subject to the other discipline sharing these objects).

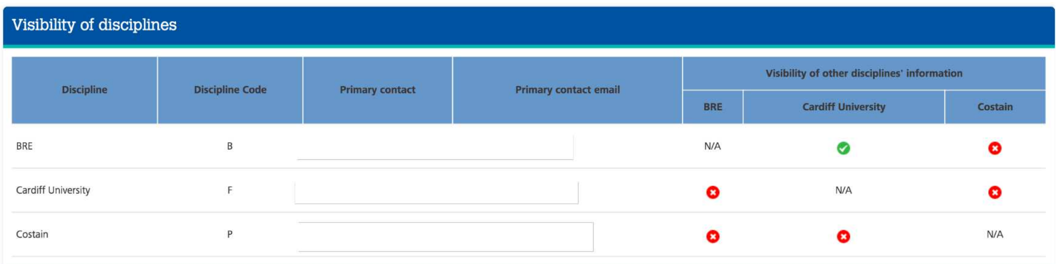

FIG. 5. Governance Model User Interface

Deployment Hardware

To conduct the test deployments of the C4C system, multiple local computing resources plus IBM Softlayer virtualized cluster-based infrastructure hosted at IBM's Amsterdam Data Centre, utilising dedicated virtual servers was utilised. A total of four sets of virtualised servers to simulate a construction project with four different disciplines were used to carry out this task. Two of these sets of virtual servers were hosted in different physical local locations (simulating organisations with standard IT infrastructure), with a further two hosted in IBM Softlayer (simulating organisations utilising a cloud based data storage infrastructure), allowing the simulation a life-like scenario where disciplines within a construction project will utilise multiple IT systems, hosted in differing locations.

VALIDATION CASE STUDY

In order to validate the system, a trial was conducted using the data and processes from a real construction project provided by the project partner Costain. To demonstrate the scalability of the solution an initial verification where the model used is a simple house (please refer to Figure 6) was utilised. This was followed by a larger project trial identifying the Highways England construction of a new bridge on the A556, this is shown in Figure 7. This trial was conducted using this deployment hardware described previously. Within the trial a series of domain users from the various disciplines within the project utilised the system either using a Revit plug in or a simplified client that utilises the API described in this paper to directly produce/consume IFC files from other domain software tools. The disciplines involved, were set up to duplicate the reality of the project and each of these is listed below:

- Contractor - Costain.
- A cost consultant - Lee Wakemans Ltd.
- Designer - Capita.

In order to ensure the verification is able to duplicate the processes of a real project, the process and governance model for the federated BIM overlay was configured in-line with the processes conducted within the project. This is shown in Table 3, which shows the disciplines involved, and what status codes have been defined for each discipline. This table also shows, in brackets, the shorthand codes assigned to each discipline and suitability code. Table 4 shows the permissions list for each discipline. It should be noted

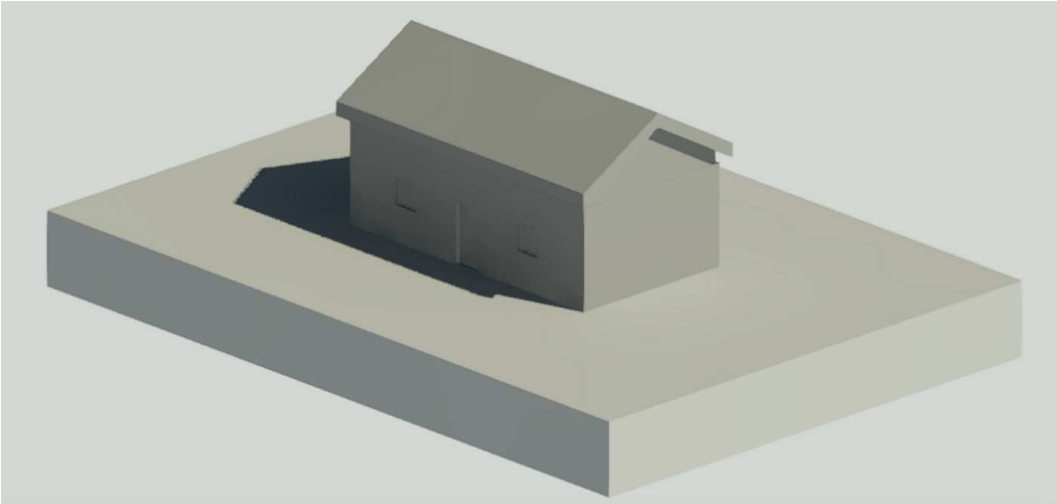

FIG. 6. Preliminary Test Model

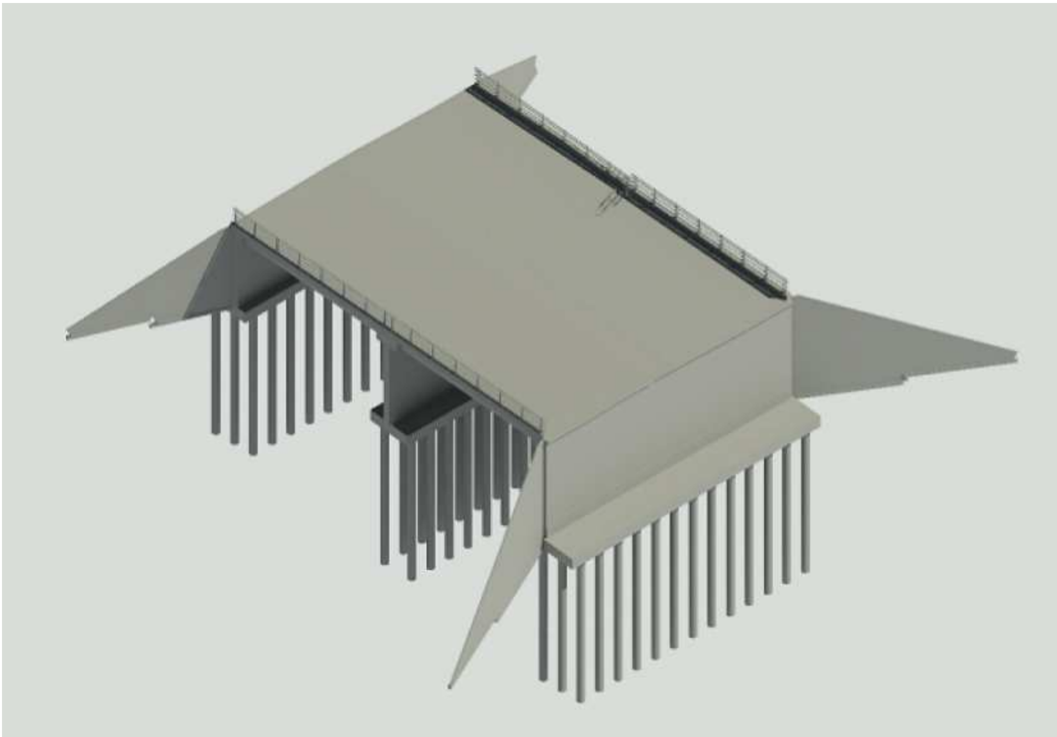

FIG. 7. Our Example Project

611 that the client is also defined as a discipline, except the client discipline (named X in this case) does not define status codes as they do not contribute data to the model.

613 Once the permissions of the project have been established, elements of the project's workflow were trailed using data from the project. The workflow that was trailed is described in the sequence diagram shown in Figure 8. Note, that for the sake of presentation, interactions within a discipline prior to data being shared are not shown. Within

the sections of the project's work-flow that are being considered, four sets of objects were made available via the federated BIM overlay. Finally, once the final design was produced it was viewed by the client. More detail of each of the stages shown in Figure 8 are described in Table 5

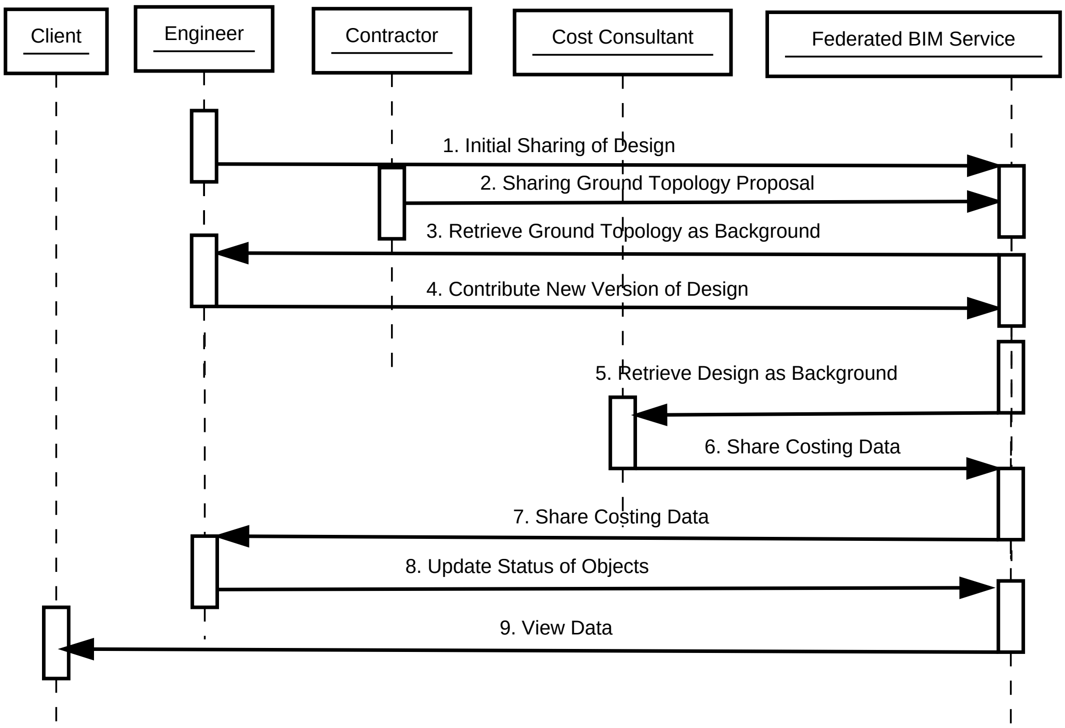

FIG. 8. Project Sequence Diagram

As has been described previously, the key goal of this paper is to determine whether the federated BIM overlay is fit for purpose and able to overcome key obstacles to BIM adoption. This section will discuss the results of the validation case study (described in the previous section) in the context of the goals of this paper.

This validation that been performed has focused on three areas; the verification of the functionality of the system, the acceptance of the BIM process and governance approach and the impact of the approach on the common barriers to BIM adoption.

Validating System Functionality

The system functionality has been verified through its use on the case study project that has been previously described, this was conducted using real data from the project following a duplicate of the process used by the actual project. In setting up the project, the user interface described previously was utilised by domain users to configure the governance model, and, throughout the course of this verification, the operation of CAD packages was carried out by domain practitioners from appropriate disciplines.

At every stage of this verification, the output data was checked to ensure it is correct, consistent and only the appropriate objects were visible. Finally, this entire workflow was presented to the construction partners involved to ensure that the aspects of the workflow that have been considered were correctly modelled. The tests that were performed have been documented in Table 6 in more detail.

Throughout this verification the system proved to be fully functional. However, one challenge that was faced was that of performance. It was found that that there are significant overheads encountered by transmitting and parsing IFC files. This is especially true when combined with the requirement for versioning and federating BIM. The key reason for this IFC performance issue relates to the continual requirement to convert to/from the STEP file format for communication to various software packages. Additionally, this means, that in order to produce a valid STEP file for use by a authoring package many additional objects must be transferred, rather than that small amount that have changed.

Acceptance of BIM Process and Governance Model

The more theoretical aspect of whether or not the BIM process and governance model that has been developed as part of this work is fit for purpose has been validated in two ways. Firstly it was tested to ensure that it can correctly model the structure of the case study construction project. Secondly, it was further validated by means of a focus group discussion session with construction partners involved.

Evaluation Against BIM Adoption Barriers

Finally, in order to evaluate the possible impact of adopting an automated federated BIM approach within the construction industry, the approach was evaluated against the barriers to BIM adoption described earlier in the paper along with additional more specific obstacles commonly identified in literature (Rezgui et al., 2013; Alreshidi and Rezgui, 2015):

Lack of clarity as to who owns and is responsible for BIM - Adoption of the governance approach defined in this paper provides key clarifications on this issue, in that it is stipulated that: (a) the authoritative copy of data is stored on the discipline's own infrastructure (b) that the discipline that created the data is responsible for its accuracy and correctness. In focus groups sessions with industrial partners, this received broad acceptance.

Fragmentation of BIM data across design and engineering teams and then the contractor and FM companies: - The fragmentation of BIM data is a key problem. The key contribution of this work is in providing a BIM coordination framework that allows the representation of the fragmented nature of BIM data as a single distributed data model in a way that is transparent to the user. However, overcoming this barrier not only requires the deployment of new technologies to aid collaboration, but also the reduction of other barriers that prevent organisations within construction projects for engaging in BIM in the first place. In order to test the successes in this area the approach has been compared to several other barriers found in literature.

- The limited process and technical maturity and capability among SMEs - This approach, while not completely overcoming this obstacle does move someway towards this objective by allowing both more and less technically capable SMEs participating and using BIM data from the distributed BIM data model without necessarily needing the infrastructure to host or manage BIM data. This has been evidenced in this case study with the participation of a quantity surveyor that is a small SME consultancy
- Uncertainties over costs involved with a BIM approach - While this obstacles covers a scope far wider than the area considered in this paper, this has demonstrated that the use of a single distributed BIM model can reassure companies of the data storage costs within the timeframe of their participation of the project. This is due to the fact that it is envisaged that the deployment of the distributed BIM coordination layer on top of companies existing data storage infrastructure. In the case study example, the deployment was tested on multiple cloud systems along with a deployment on a standard server.
- The reliance on frozen paper-based documents - This is a key socio-technical issue for BIM adoption and while a technological solution can never completely overcome this for all elements of the construction sector. However, this approach of making BIM objects immutable allows this approach to ensure that users of BIM data can access a "frozen" version of the model at a given time. This has been proved as part of the technical verification of the system's performance.
- BIM servers carry no legal or contractual obligations - This concern is is often

cited when suggestions are raised for outsourcing BIM data to external service providers of BIM data services. A key difference in this approach is that the the federated BIM overlay can be installed on either cloud based systems or on ICT architectures owned an operated by the organisation, thus under their own control. This flexibility provides a much higher level of reassurance if an organisation requires it.

- The belief that BIM data is not secure even when stored on BIM servers - While this paper does not tackle the security of data directly, the federated approach adopted in this paper allows each company to retain control over their data, securing it as they wish.

Information is not sustained across the lifecycle - This barrier refers to the risk of data loss due to the dynamic nature of construction projects. Problems that can occur in this area include; when companies enter/leave a project in the course of its life-cycle, when organisations cease trading while part of a project or a catastrophic data loss is suffered due to an IT of other fault. The system's approach tackles this issue by providing a long term cache of BIM objects on each discipline, allowing a copy of a discipline's data to be sustained should that discipline leave the project or suffer a loss of data.

CONCLUSIONS

This paper has described a BIM overlay that allows the *automatic federation of distributed BIM data in a consistent and managed way.* This paper has also described a distributed federated approach to BIM that tackles several key barriers to the adoption of BIM within the construction industry. The authors tackle these barriers by; transparently federating data stored on individual discipline's IT infrastructure so that concerns over ownership of data and concerns over exposing the data to unauthorised changes can be eased, as no-one outside of the authoring discipline is permitted to change data.

This approach allows BIM data sharing across different disciplines by use of a virtual integrated BIM model that is actually distributed physically across the stakeholders within a construction project but still federated transparently across these stakeholders.

The federated BIM overlay has been designed, implemented and validated using real construction data. Additionally, when considering this dynamic approach compared to manual approaches for BIM federation, several key advantages are obvious. These include; the automation in the distribution of BIM data across the project's disciplines thus eliminating the need for manual transfers of data, the transparency of the process enabling the often complex process of federation to be hidden from the users and, finally, the ability of the process of federating BIM data to be managed by a project wide and agreed-upon governance model. This final point allows users to be confident that they are only using federated data that is suitable for their use and that their data is only being used by others according to the controls that they have defined.

The validation that has been conducted so far and is documented in this paper represents an initial validation on real construction data, with real domain users. However, there is further validation that needs to be conducted in order to fully ensure this approach is fully mature. Future planned validation exercises include; presentation of the governance approach, along with necessary refinements to a wider range of construction industry stakeholders, and a further detailed technical validation with a larger construction project, featuring an increased number of disciplines involved.

At a global level, the key research question of this paper was: *Does the use of a BIM federation overlay to automatically federate BIM data that is physically distributed across stakeholders and supply chains provide advantages of standard model merging technologies by overcoming key obstacles to BIM adoption? These obstacles include questions over data ownership, the security, privacy and sustainability of data, and reluctance of companies to share data.*. So far, with the current validation that has been undertaken, the initial results have been positive. With the validation showing that, not only does the developed system work, but the overall approach that has been developed, is acceptable to the construction users the authors worked with. Thus, analysing the progress against a series of common obstacles to BIM adoption, it can be seen that it does indeed move towards enabling several key obstacles to BIM adoption to be overcome. Furthermore, by considering the approach against manual methods of BIM federation definite advantages can be provided by this dynamic approach.

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REFERENCES

Alreshidi, Eissa, M. M. and Rezgui, Y. (2015). "Cloud-based BIM governance platform requirements and specifications: Software engineering approach using BPMN and UML.." *Journal of Computing in Civil Engineering*.

Aouad, G., Hinks, J., Cooper, R., Sheath, D. M., and Kagioglou, M. (1998). "An IT map for a generic design and construction process protocol." *Journal of Construction Procurement*, 4, 132–151.

Aram, S. and Eastman, C. (2013). "Integration of PLM solutions and BIM systems for the AEC industry.." *Proceedings of 30th International Symposium of Automation and Robotics in Construction and Mining*.

RIBA. (2007). "Outline Plan of Work".

Autodesk (2016a). "AudtoDesk BIM360." *[Online] available at: http://www.autodesk.com/products/bim-360/overview*.

Autodesk (2016b). "Autodesk Revit." *[Online] available at: http://www.autodesk.co.uk/products/revit-family/overview*.

Autodesk (2016c). "Autodesk Revit Server." *[Online] available at: https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2015/ENU/Revit-Server/files/GUID-4DE9A327-583E-40DA-81EB-1150D60E6887-htm.html*.

Barrett, P. and Sexton, M. (2006). "Innovation in small, project-based construction firms." *British Journal of Management*, 17, 331–346.

Becerik-Gerber, B., J. F. L. N. and Calis, G. (2012). "Application Areas and Data Requirements for BIM-Enabled Facilities Management." *Journal of Construction Engineering Management*, 138(3), 431–442.

Beetz, Jakob, e. a. (2010). "Towards an open building information model server." *Proc. of the 10th International Conference on Design & Decision Support Systems in Architecture and Urban Planning*.

Beetz, J., Leeuwen, J. V., and Vries, B. D. (2009). "IfcOWL: A case of transforming EXPRESS schemas into ontologies." *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 23(1), 89–101.

Bentley Systems (2016). "Projectwise Server." *[Online] available at: https://www.bentley.com/en/products/brands/projectwise*.

Boeykens, Stefan, and Nys., K. (2015). "Interactive bi-directional BIM model and application linking." *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015*.

British Standards Institute (2008). "British Standard 1192:2007 – Collaborative production of architectural, engineering and construction information, Code of practice".

Bryde, D., Broquetas, M., and Volm, J. M. (2013). "The project benefits of Building Information Modelling (BIM)." *International Journal of Project Management*, 31(7), 971 – 980.

Cerovsek, T. (2011). "A review and outlook for a "Building Information Model"(BIM): A multi-standpoint framework for technological development." *Advanced Engineering Informatics*, 25(2), 224–244.

CometCloud (2014). "CometCloud Web site - available at: http://nsfcac.rutgers.edu/CometCloud/".

Construction Industry Council (2013). "BIM Protocol".

Dainty, A., Moore, D., and Murray, M. (2006). "Communication in Construction: Theory and Practice." *Taylor & Francis*.

Das, Moumita, Cheng, J. C., and Kumar, S. S. (2015). "Social BIMCloud: a distributed cloud-based BIM platform for object-based lifecycle information exchange.." *Visualization in Engineering*, 3(1), 1–20.

Egan, J. (1998). "Rethinking construction." *Department of the Environment, Transport and Regions*.

Graphisoft (2016a). "GraphiSoft BIM Cloud." *[Online] available at: http://www.graphisoft.com/bimcloud/overview/*.

Graphisoft (2016b). “Graphisoft BIM Server.” *[Online] available at: http://www.graphisoft.com/bim-server/.*

Hietanen, J. (2006). “IFC model view definition format..” *International Alliance for Interoperability*, 1 – 29.

International Standards Organisation (1994). “Industrial automation systems and integration – Product data representation and exchange – Part 1: Overview and fundamental principles.” *ISO 10303-1:1994*.

International Standards Organisation (2005). “ISO/PAS 16739:2005 - IFC.”

Kim, H., el Khamra, Y., Jha, S., and Parashar, M. (2009). “An Autonomic Approach to Integrated HPC Grid and Cloud Usage.” *5th IEEE International Conference on e-Science*.

Kumar, Bimal, Cheng, J. C., and McGibbney, L. (2010). “Cloud computing and its implications for construction IT.” *Proceedings of the International Conference Computing in Civil and Building Engineering.*”, 30.

Latham, M. (1994). “Constructing the Team: Final Report of the Government/Industry Review of Procurement and Contractual Arrangements in the UK Construction Industry.”

Mazairac, W. and Beetz, J. (2013). “BIMQLAn open query language for building information models.” *Advanced Engineering Informatics*, 27, 444 – 456.

Munkley, J., M. K., and Dawood, N. (2014). “Synchronous Building Information Model-Based Collaboration in the Cloud: A Proposed Low Cost IT Platform and a Case Study.” *Computing in Civil and Building Engineering*.

National BIM Service (2013). “National BIM Report”.

National BIM Service (2015). “National BIM Report”.

National BIM Standard US (2015). “Construction Operation Building Information Exchange (COBie).” *[Online] available at:* $https://www.nationalbimstandard.org/files/NBIMS-US_V 3_4.2_C OBie.pdf$.

Nisbet, N. and Liebich, T. (2005). "ifcXML Implementation guide." *International Alliance for Interoperability*.

Onuma (2015). "Onuma Planning System." *[Online] available at: http:// onuma.com/products/BimDataApi.php*.

Petri, I., Beach, T., Zou, M., Diaz-Montes, J., Rana, O., and Parashar, M. (2014). "Exploring Models and Mechanisms for Exchanging Resources in a Federated Cloud." *Int. Conf. on Cloud Engineering (IC2E)*.

Redmond and Alan, e. a. (2012). "Exploring how information exchanges can be enhanced through Cloud BIM." *Automation in Construction*, 24, 175–183.

Rezgui, Y., Beach, T., and Rana, O. (2013). "A governance approach for BIM management across lifecycle and supply chains using mixed-modes of information delivery." *Journal of Civil Engineering and Management*.

Sandhu, Ravi S, and Pierangela Samarati. (1994). "Access control: principle and practice." *IEEE communications magazine 32.9: 40-48*.

Solihin W, Eastman C, and Lee Y.C. (2016). "A framework for fully integrated building information models in a federated environment." *Advanced Engineering Informatics* 30(2) 168-189.

Scully and Timothy, e. a. (2015). "3drepo. io: building the next generation Web3D repository with AngularJS and X3DOM." *Proceedings of the 20th International Conference on 3D Web Technology*.

Succar, B. (2009). "Building information modelling framework: A research and delivery foundation for industry stakeholders." *Automation in Construction*, 18, 357 – 375.

Systems, B. (2016). "AECOSIM." *[Online] available at: https://www.bentley.com/en/products/brands/aecosim*.

Tang, Ming Xi, and John Frazer. (2001). "A representation of context for computer supported collaborative design.." *Automation in Construction 10.6 715-729*.

UK BIM Taskgroup (2014). "UK BIM Taskgroup." *[Online] http://www.bimtaskgroup.org/*.

UK Cabinet Office (2011). "Government Construction Strategy".

van Berlo, Lcon, and Krijnen, T. (2014). "Using the BIM Collaboration Format in a Server Based Workflow." *rocedia Environmental Sciences*, 22, 325–332.

van Berlo, L., Bektas, E., and Vullings, H. (2016). "Using Multi Criteria Analyses and BIM to evaluate design solutions of complex buildings, A case study in automated KPI checking in the early desing phase." *DDSS*.

Villegas, D., Bobroff, N., Rodero, I., and Delgado, J. (2012). "Cloud federation in a layered service model." *Journal of Computer Systems Science*, 78(5), 1330–1344.

Zha, Xuan F. (2000). "An object-oriented knowledge based Petri net approach to intelligent integration of design and assembly planning." *Artificial Intelligence in Engineering 14.1 83-112*.

TABLE 1. A Sample Permission List

Inbound/Outbound	To Domain	From Domain	Status List
In	K	*	*
Out	*	K	5
In	A	*	6
Out	S	A	5
In	S	*	4
Out	A	S	3

TABLE 2. BIM Data Access API

Method	Description
getCurrentModel	Fetches a current version of the BIM Model.
updateModel	Updates the current model with new objects
getObject	Returns an IFC Object with GUID
setObjectStatus	Sets the status on an object
getObjectStatus	Return the status of an object
getObjectMetaData	Return the metadata of an object
setObjectMetaData	Sets the metadata of an object

TABLE 3. Project Disciplines and Statuses

Suitability	Engineer(E)	Contractor(C)	Quantity Surveyor(Q)
Discipline	Work In Progress(ES1)	Work In Progress(CS1)	Work In Progress(QS1)
Discipline	Internal Shared(ES2)		
Project	Shared(ES3)	Shared(CS2)	Shared(S2)
Portfolio	For Construction(ES4)	For Construction(CS3)	For Construction(QS3)

TABLE 4. Validation Permissions List

Inbound/Outbound	Domain	From Domain	Status List
IN	X	E	ES4
IN	X	C,Q	CS3,QS3
IN	Q	E	ES3
IN	Q	C	CS2
OUT	Q	E	ES2
OUT	X	E	ES3
IN	C	E	ES3
OUT	C	E,Q	CS2
OUT	C	X	CS3
IN	E	C,Q	ES2
OUT	E	C,Q	ES3
OUT	E	X	ES4

TABLE 5. API Interactions

No	Discipine	Action	Status Codes Utilised	Number of Objects Updated
1	E	Share Outline Design	S3	933
2	C	Share Ground Topology	S3	341523
3	E	Retrieving Ground Topology	C:S3	NA
4	E	Sharing of Updated Design	S3	440818
5	Q	Retrieving Design	E:S3,C:S3	NA
6	Q	Sharing Cost Data	S3	198
7	E	Retrieving Cost Data	Q:S3	NA
8	E	Updating Status of Objects	S4	NA
9	X	Viewing Data	E:S4, C:S3, Q:S3	NA

TABLE 6. Summary of Test Results

Verification Test Performed	Result
Indexing of IFC data correctly performed	Achieved
Multiple Versions of IFC objects correctly merged intra-discipline	Achieved
IFC models from multiple disciplines successfully merged	Achieved
Verifying the update correctly propagate across disciplines	Achieved
Verifying the permissions lists are correctly applied	Achieved
Validating that a frozen version of the BIM mode can be generated	Achieved
Updating meta-data on IFC objects correctly performed	Achieved
Downloading of model data successfully performed	Achieved
Deployment on a variety of cloud / server platforms	Achieved