

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 and 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-

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

28 INTRODUCTION

29 The UK BIM Government task group has defined BIM as “value creating collaboration
30 through the entire life-cycle of assets, underpinned by the creation, collation and exchange
31 of shared 3D models and intelligent, structured data attached to them” ([UK BIM Taskgroup,
32 2014](#)). In the UK, driven by government targets, BIM adoption has been steadily increas-
33 ing, from 39% in 2013([National BIM Service, 2013](#)) to 48% in 2014 ([National BIM Service,
34 2015](#)).

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

45 A common goal of increasing BIM adoption is the move towards the realisation of a
46 BIM as either a single data model or a series of tightly coupled federated models([Cerovsek,
47 2011; UK Cabinet Office, 2011](#)). This movement towards what is known as “Level 3”
48 BIM([Construction Industry Council, 2013](#)) in the UK, is driven primarily by the desire
49 to reduce the cost of construction projects.

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

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

58 The approach is required as the nature of construction projects mean that stan-
59 dard product life-cycle management tools are not able to be applied(Aram and Eastman,
60 2013). Reasons for this include; the fact that most projects are unique, fragmentation
61 of data across different companies within a project, long life-cycles of buildings, large
62 separation between design and construction activities and multiple possible procurement
63 routes(Rezgui et al., 2013; Aram and Eastman, 2013).

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

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

84 In order to implement this overlay, a particular cloud engine called CometCloud (CometCloud,
85 2014) which enables the implementation of a logical “shared” space that is physically dis-
86 tributed across multiple sites involved in the federation was utilised. It is within this

87 shared space that BIM data is stored and federated.

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

94 **RELATED WORK**

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

97 **BIM Standards**

98 Currently, there is an increasing adoption of standardised approaches to BIM.
99 These include, for the UK, the BS1192 series of British Standards. These stan-
100 dards contain codes of practice for utilising COBie([National BIM Standard US, 2015](#))
101 and BS1192:2007([British Standards Institute, 2008](#)) which is a standard for collabora-
102 tive production of project information. This document provides a naming convention
103 and also models how assets within a project can be modelled through their lifecycle.
104 Another newly emerging standard is PAS (Publicly Accessible Standard) 1192 Part
105 2([National BIM Standard US, 2015](#)). This standard outlines specifications for informa-
106 tion management processes for construction projects using BIM, focusing specifically on
107 the collaborative BIM approaches currently being adopted within the UK construction
108 industry.

109 The area of data standardisation within the construction sector is mainly
110 driven by the IFCs (Industry Foundation Classes), developed by buildingSMART
111 international([International Standards Organisation, 2005](#)). The IFCs specify a rich data
112 model that can be used to organise data within a construction project, the IFCs
113 also define how this model can be communicated between software packages using
114 STEP([International Standards Organisation, 1994](#)), XML([Nisbet and Liebich, 2005](#)) and
115 the newly standardised IFCOwl([Beetz et al., 2009](#)). Other BIM standards related to col-
116 laboration have also been developed, most recently the introduction of the BIM Collabo-
117 ration Format (BCF)([van Berlo et al., 2014](#)). BCF is an xml format based, that enables
118 users to share fragments of BIM data, with attached comments and requests for changes,

119 without the requirement of sharing the entire BIM model. Another related technology
120 to the IFCs is the bimQL query language(Mazairac and Beetz, 2013). This query lan-
121 guage has been created to be an open, platform and implementation independent way of
122 querying, updating and deleting data within IFC models. So far the primary platform
123 that has implemented bimQL is BIM Server(Beetz, 2010).

124 **BIM Technologies**

125 There are a plethora of software packages available to support the adoption of BIM. In
126 fact, the use of BIM authoring environments by stakeholders is becoming more and more
127 common. Well known BIM authoring environments include: Autodesk Revit(Autodesk,
128 2016b) and Bentley Systems AECOSIM(Bentley System, 2016). More critical to the
129 adoption of BIM at a wider scale(Rezgui et al., 2013) is how the data from these authoring
130 applications is coordinated. To solve this problem a number of solutions have been
131 developed, and have become commonly known as “BIM Servers”.

132 Examples of BIM servers include the Onuma system(Onuma, 2015) RevitServer
133 (Autodesk, 2016c), Bentley ProjectWise(Bentley Systems, 2016), Graphisoft BIM
134 Server(Graphisoft, 2016b), BIM Server (Beetz, 2010), Autodesk BIM 360(Autodesk,
135 2016a), Graphisoft BIM Cloud (Graphisoft, 2016a) and 3DRepo(Scully and Timothy,
136 2015). These servers provide a multitude of features but can be broadly classified into
137 two categories based on the way they store data: centralised data repositories, such
138 as Graphisoft Server/BIM Cloud, The Onuma System, 3DRepo and BIM Server, and
139 distributed data repositories, such as RevitServer and ProjectWise.

140 Within a centralised repository, either a cloud based server, or a server deployed within
141 an organisation’s ICT infrastructure is established to provide features such as manage-
142 ment, governance and versioning of BIM data, often bringing significant advantages to
143 their users. However, when adopting such a centralised approach organisations may well
144 face barriers. These include a reluctance to adopt cloud based solutions due to concerns
145 regarding data security and privacy(Redmond and Alan, 2012; Rezgui et al., 2013) and
146 the reluctance of an organisation to relinquish control over data that they are legally liable
147 for being correct. Conversely, deploying such tools on a companies own IT infrastructure
148 limits the possibilities for collaboration, as other organisations are often reluctant to com-
149 mit their own data to a server under the control of another organisation(Rezgui et al.,
150 2013).

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

163 In addition to these commercial offerings, the concept of BIM storage and collabora-
164 tion is also a topic of active research. In their work on SocialBIM, Das et al([Das et al.,](#)
165 [2015](#)) have developed a BIM framework that primarily focuses on modelling the social
166 interactions between stakeholders. The key development is SocialBIM’s ability to al-
167 low users to contribute/download partial BIM models that are then merged/split from a
168 “master” model held in the SocialBIM cloud system. While this ability to work in terms
169 of small “fragments” of BIMs which are then federated is a key development, the fact
170 that the end result is still stored in a centralised way in a cloud system will be of concern
171 to many organisations.

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

183 Other work in this area includes Munkley et al (Munkley et al., 2014), who have de-
184 veloped technologies to synchronize data between Revit Server and an external storage
185 server, enabling external users to see a read only copy of the Revit central model. While
186 this is an interesting way of allowing increased collaboration using RevitServer, it does
187 not adequately provide for the dynamic two way collaboration that is often required in a
188 construction project i.e. the ability to incorporate the results of other discipline's work as
189 background in your own work. Finally, this approach is further limited as it is only able to
190 utilise the Revit proprietary data format. Additionally, Boeykens et al (Boeykens et al.,
191 2015) have developed a layered client/server approach that provides an event based com-
192 munications pool between components embedded into BIM authoring packages. This
193 novel communication approach is a very interesting development and allows the dynamic
194 sharing of data between components. However, all data is still stored on a centralised
195 server that listens to the event based communications and both saves and injects BIM
196 data into the communications pool as needed.

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

210 **OVERVIEW OF A FEDERATED DISTRIBUTED BIM DATA MODEL**

211 A construction project is a complex undertaking dependant on a large number of
212 very different professions and firms. These firms range from SMEs (Small to Medium
213 Enterprises) to large multinational corporations. Each one of these organisations will
214 participate in the construction project for a varying time period and, in that time period,

215 will contribute different quantities and types of data to the project, or even contribute
216 no data. As has been previously described, while interest in cloud based BIM solutions is
217 increasing(Kumar et al., 2010), there are still many obstacles to BIM adoption that must
218 be overcome. These include: (a) lack of clarity as to who owns and is responsible for
219 BIM (b) fragmentation of BIM data across design and engineering teams and then the
220 contractor and FM companies and (c) information is not sustained across the lifecycle
221 and is in continuous danger of being lost due to company mergers or bankruptcy.

222 In response to these obstacles the use of an BIM federation overlay to implement a
223 federated distributed BIM data model within a construction project was proposed. Figure
224 1 describes the overlay and associated data model that has been developed by drawing
225 on technologies from cloud and distributed computing.

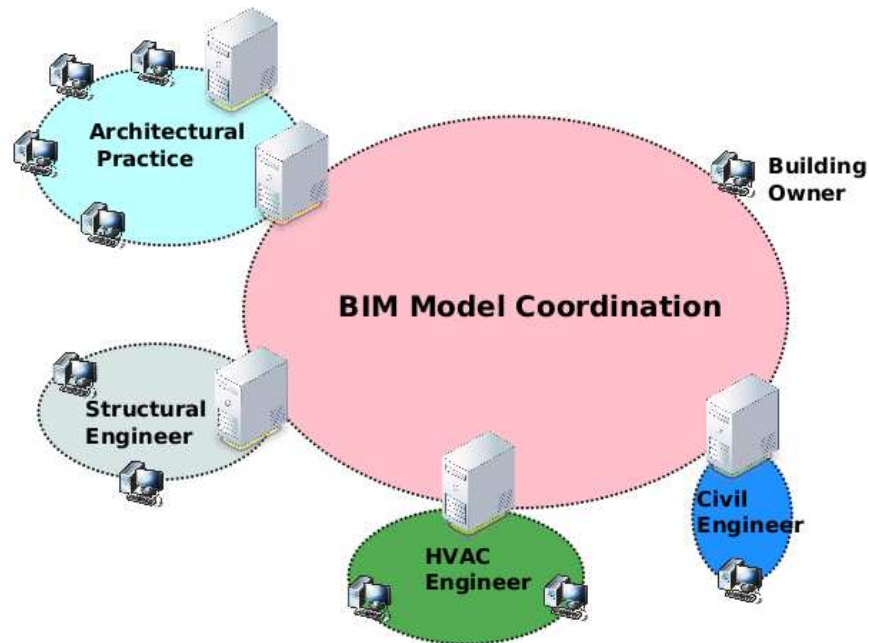


FIG. 1. Overview of a Federated Distributed BIM Data Model

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

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

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

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

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

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

260 **GENERALISING BIM PROCESSES**

261 This section presents the development of a BIM governance and process model to un-
262 derpin the federated BIM overlay. This section determines: *within a federated distributed*
263 *BIM model, how should the process of BIM be structured?* More specifically it tackles
264 three key issues; how is a construction project structured, how is the workflow within

265 each phase of a construction project structured and how is the data that originates from
266 the execution of this workflow structured and stored.

267 **Methodology**

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

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

- 278 • Industry relevant - in that it presents a view of BIM data that adequately repre-
279 sents the view of the construction industry.
- 280 • Sufficiently generalisable - to enable its application to the industry as a whole and
281 not just specific elements of the industry.
- 282 • Requirement led - in that the technology utilised will solve real problems within
283 the industry.

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

292 The focus group sessions took place over 9 months from February 2014 to November
293 2014 and involved the following companies: Building Research Establishment (BRE),
294 Costain , NBS (National BIM Service), AEC3 UK (BIM Consultancy) and Lee Wake-
295 mens(Project Management).

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

299 In addition to a consultation, a review of existing BIM technologies and im-
300 plementations was also conducted. Included in this review were an analysis of
301 the IFCs, which are currently the most widely used open standard for storing
302 BIM([International Standards Organisation, 2005](#)). The IFCs, with its standard set
303 of rules for data storage and data exchange, provides a framework to manage data
304 related to a building throughout its lifecycle([International Standards Organisation,](#)
305 [2005](#); [Nisbet and Liebich, 2005](#)). In addition to the IFCs, Model View Definitions
306 (MVD)([Hietanen, 2006](#)) were also studied. An MVD is used to define a subset of the
307 IFC schema that should be transmitted at any given point of data exchange. Currently,
308 there are many examples of standardised MVDs, these include; the space boundary view,
309 which is used to support the use of BIM in energy and thermal analysis and the quantity
310 take off view, used to support BIM in transmitting base quantities for spatial, building
311 service and structural elements. As part of developing the BIM overlay concepts
312 from both of these technologies have been drawn upon.

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

320 **Structuring a Construction Project**

321 Structuring a construction project into distinct stages or phases is not a new concept
322 within the construction industry. In the UK there has been several sets of defined stan-
323 dards for the way of operating. These include, methodologies such as the RIBA project
324 stages([Royal Institute of British Architects, 2007](#)) a similar process known as Process
325 Protocol ([Aouad et al., 1998](#)) and, most recently, the CIC (Construction Industry Coun-
326 cil) project stages ([Construction Industry Council, 2013](#)). However, in addition to these
327 common methodologies utilised within the construction industry there is also conflicting

328 literature stating that BIM should offer a phaseless workflow(Succar, 2009).

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

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

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

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

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

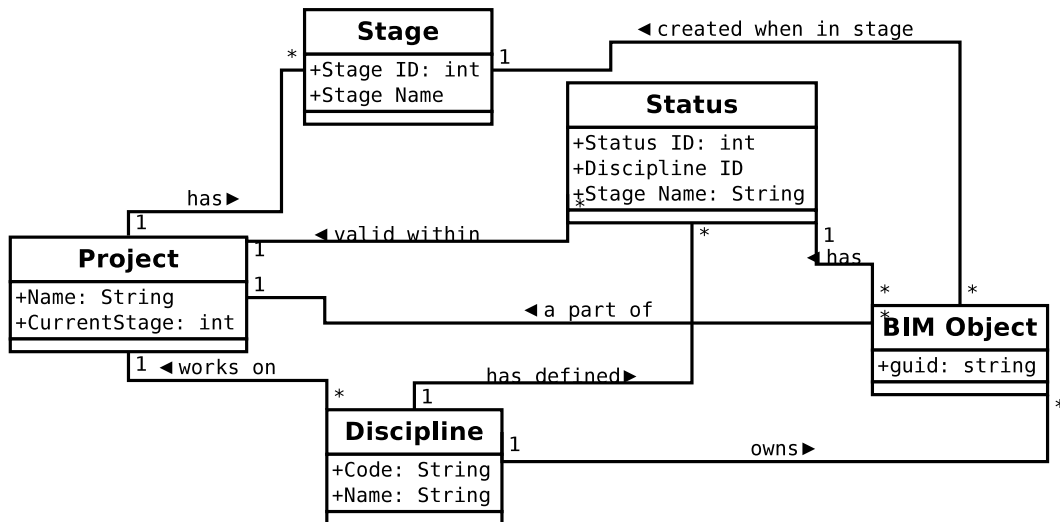


FIG. 2. Structuring data within a Construction Project

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.

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

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

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

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

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

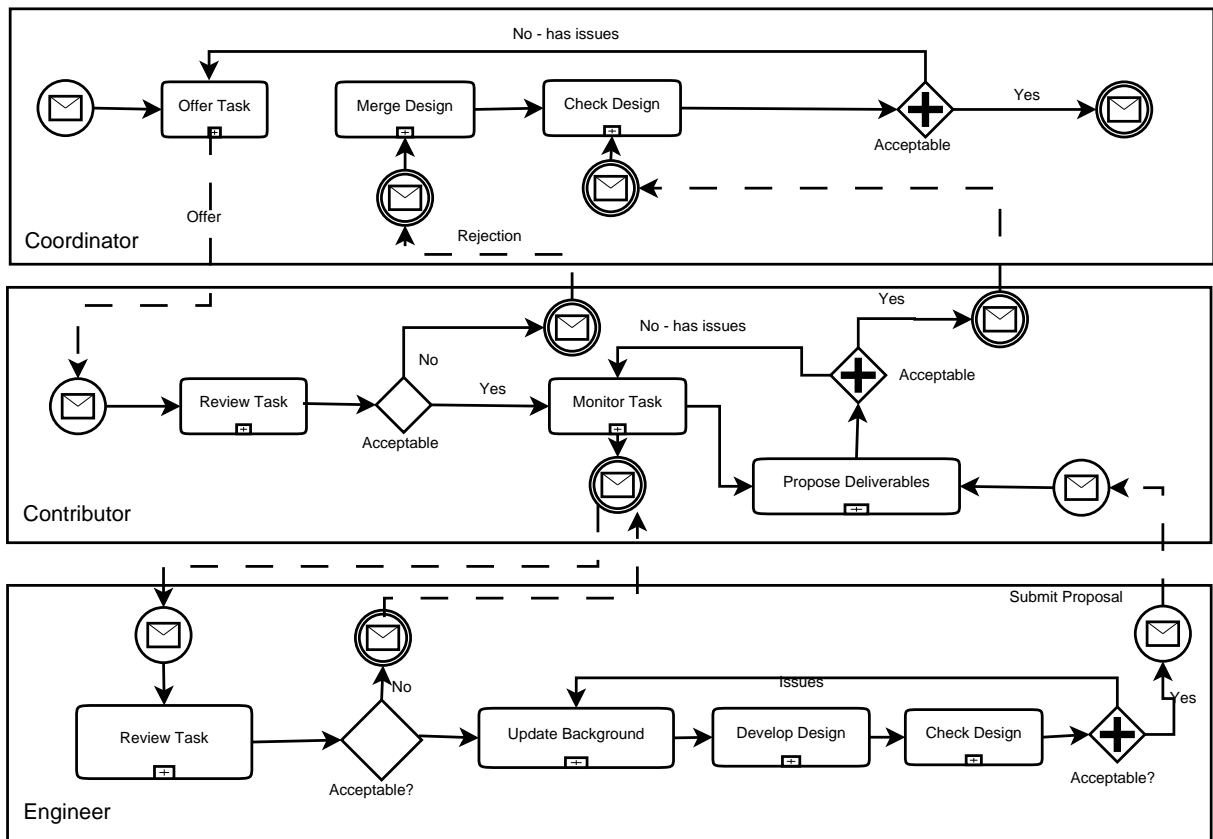


FIG. 3. BIM Process Modelling

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

418 This analysis has verified previous work (Mazairac and Beetz, 2013) that has shown
 419 that there is, in reality, only a few key operations that can be performed when contributing
 420 data to a BIM model. The creation of new objects, updating objects (which is in effect
 421 creation of a new object based on a previous object) and updating the status of an object,
 422 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

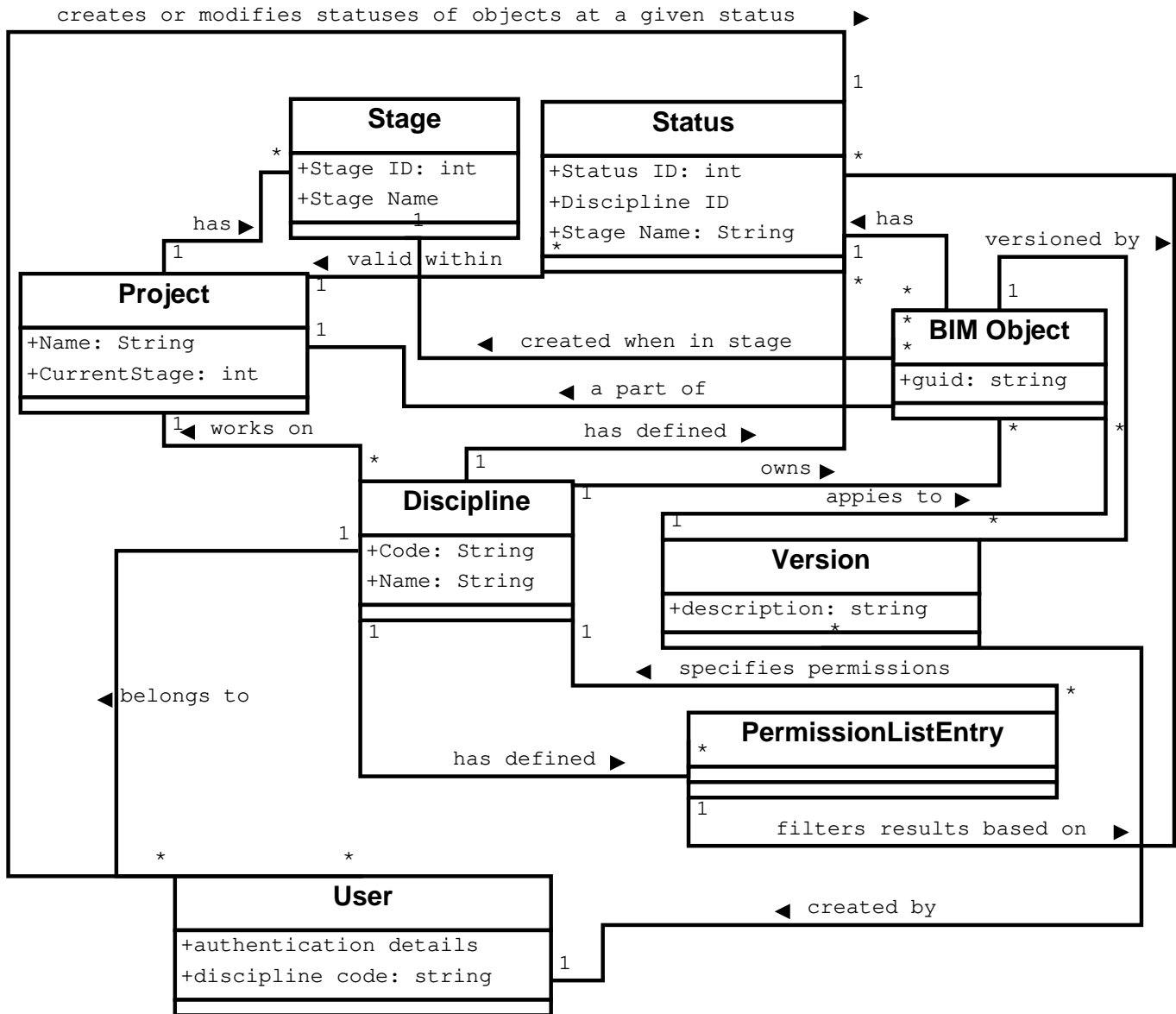


FIG. 4. Governing Data Within a Construction Project

454 being modified outside of the discipline which created it. This approach is very similar
 455 to that adopted as part of the MVD(Model View Definition) definition process(Hietanen,
 456 2006), when the objects required during each exchange of data is specified. Currently,
 457 objects are filtered based on their suitability, but it is equally possible for this to be
 458 specified by on object types. Indeed, it would be completely feasible for the permissions
 459 lists to be automatically generated from existing MVD definitions.

460 Table 1 shows an example permission list. In this figure three disciplines are defined:
 461 K - Client, A - Architect and S - Structural Engineer. This table describes that the
 462 architect discipline allows all other disciplines to utilise it's objects as background as

463 long as they are of status > 6 . This table also specifies that the architect discipline
464 only allows its users to utilise objects from the structural engineering discipline when
465 they are at least status > 5 . This approach is similar in many ways to that of access
466 control lists (Sandhu et al, 1994) the key difference in this case is that the access control
467 is performed on four properties of the object being transmitted; the discipline it is being
468 transmitted to, the discipline that owns it, and the current suitability code of the object.
469 The required values of these properties in order for transmission to be allowed is taken
470 from the governance model.

471 **DEPLOYING A FEDERATED BIM OVERLAY**

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

480 **Implementation of BIM Objects and Federation**

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

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

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

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

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

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

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

556 on the configuration made in the governance and process model.

557 **Integration with IT Systems and BIM Authoring Tools**

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

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

570 **Eliciting Governance Model Data from Users**

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

Visibility of disciplines						
Discipline	Discipline Code	Primary contact	Primary contact email	Visibility of other disciplines' information		
				BRE	Cardiff University	Costain
BRE	B	<input type="text"/>	<input type="text"/>	N/A	✓	✗
Cardiff University	F	<input type="text"/>	<input type="text"/>	✗	N/A	✗
Costain	P	<input type="text"/>	<input type="text"/>	✗	✗	N/A

FIG. 5. Governance Model User Interface

580 **Deployment Hardware**

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

590 **VALIDATION CASE STUDY**

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

- 602 • Contractor - Costain.
- 603 • A cost consultant - Lee Wakemans Ltd.
- 604 • Designer - Capita.

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

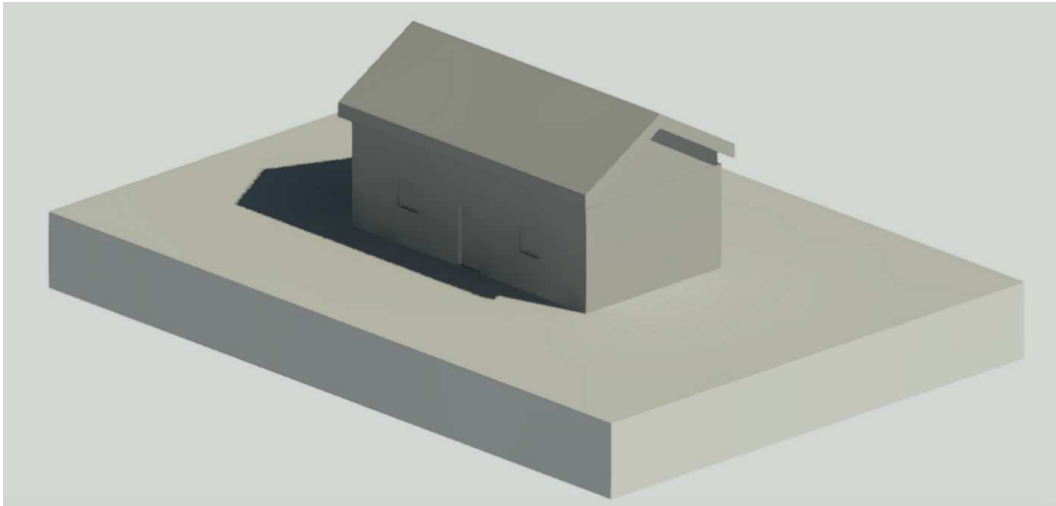


FIG. 6. Preliminary Test Model

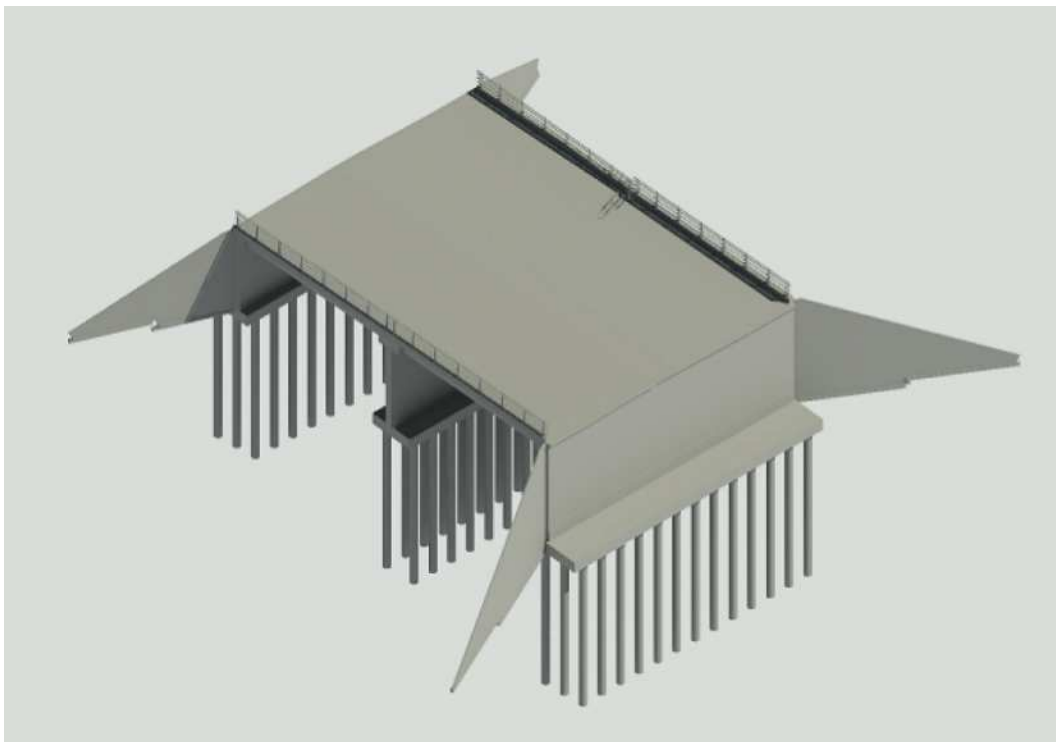


FIG. 7. Our Example Project

611 that the client is also defined as a discipline, except the client discipline (named X in this
612 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
614 workflow were trailed using data from the project. The workflow that was trailed is
615 described in the sequence diagram shown in Figure 8. Note, that for the sake of presen-
616 tation, interactions within a discipline prior to data being shared are not shown. Within

617 the sections of the project's work-flow that are being considered, four sets of objects
 618 were made available via the federated BIM overlay. Finally, once the final design was
 619 produced it was viewed by the client. More detail of each of the stages shown in Figure
 620 8 are described in Table 5

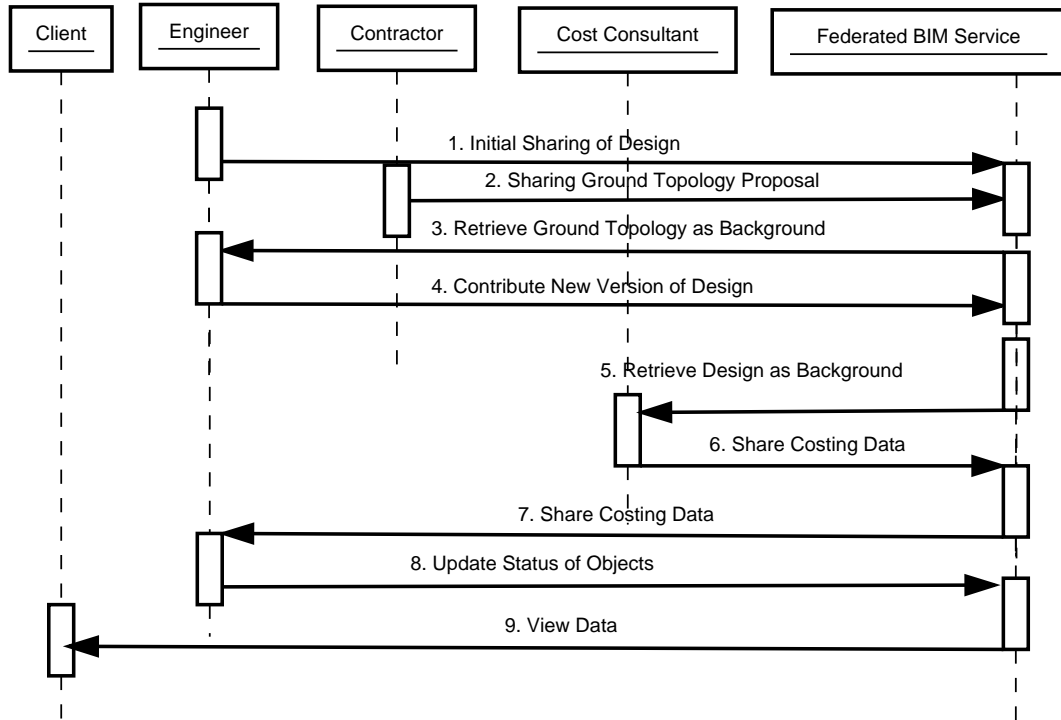


FIG. 8. Project Sequence Diagram

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

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

628 Validating System Functionality

629 The system functionality has been verified through its use on the case study project
 630 that has been previously described, this was conducted using real data from the project
 631 following a duplicate of the process used by the actual project. In setting up the
 632 project, the user interface described previously was utilised by domain users to configure

633 the governance model, and, throughout the course of this verification, the operation of
634 CAD packages was carried out by domain practitioners from appropriate disciplines.

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

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

648 **Acceptance of BIM Process and Governance Model**

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

654 **Evaluation Against BIM Adoption Barriers**

655 Finally, in order to evaluate the possible impact of adopting an automated federated
656 BIM approach within the construction industry, the approach was evaluated against the
657 barriers to BIM adoption described earlier in the paper along with additional more specific
658 obstacles commonly identified in literature (Rezgui et al., 2013; Alreshidi and Rezgui,
659 2015):

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

665 acceptance.

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

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

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

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

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

714 CONCLUSIONS

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

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

725 The federated BIM overlay has been designed, implemented and validated using real
726 construction data. Additionally, when considering this dynamic approach compared
727 to manual approaches for BIM federation, several key advantages are obvious. These

728 include; the automation in the distribution of BIM data across the project's disciplines
729 thus eliminating the need for manual transfers of data, the transparency of the process
730 enabling the often complex process of federation to be hidden from the users and, finally,
731 the ability of the process of federating BIM data to be managed by a project wide and
732 agreed-upon governance model. This final point allows users to be confident that they
733 are only using federated data that is suitable for their use and that their data is only
734 being used by others according to the controls that they have defined.

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

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

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760 terface, and Costain that has provided the construction data utilised.

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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	Discipline	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