A Framework for the Integration of Information Requirements Within Infrastructure Digital Construction

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Summary

It can be anticipated that the adoption of digital construction/BIM processes on projects will enhance the efficiency of the management of an asset over its lifecycle. Several initiatives have been taken to foster the implementation of Standard Methods and Procedures (SMP) related to BIM, such as the UK government's mandate for them to be adopted on all centrally procured public sector projects. However, this research identifies that there are still many barriers hindering the adoption of BIM.

To help break down these barriers the initial stage of this research involved the implementation and analysis of BIM SMP on a highway infrastructure project in the UK. This entailed adopting the relevant procedures during construction of the project in order to better understand the challenges faced when adopting BIM, barriers to adoption and the type of information generated over the course of an infrastructure project. The analysis highlighted that there was still a need to align SMP with existing construction processes as this was considered to be one of the greatest barriers to adoption. Further, it was observed that over 90% of the information handed over on completion was in flat file formats, therefore losing the benefits of data that can be readily queried and updated.

Based on the findings of the initial stage, the research explores the process and digital construction domains in order to analyse how project specific requirements can be identified. The research then explores which of these processes can be automated in order to enhance the reliability of the information that is collected.

The thesis finally presents a framework that has been developed to help engineers identify the project specific information requirements and processes that are required to assure the successful implementation of a digital construction approach. The framework that was developed was then trialled on an airport infrastructure project and identified processes that would have enhanced the implementation and delivery of the digital construction model.

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Contents

List of Figures

List of Tables

List of Abbreviations

AIM	Asset Information Model
AIR	Asset Information Requirements
AMP	Asset Management Plan
API	Application Programming Interface
BASIR	Built Asset Security Information Requirements (BASIR)
BEP	BIM Execution Plan
BIM	Building Information (Modelling/ Model/ Management)
BPM	Business Process Management
BPMN	Business Process Model and Notation
BPMS	Business Process Management System
CAFM	Computer Aided Facilities Management
CDE	Common Data Environment
CMMN	Case Management Model and Notation
COBie	Construction Operation Building information exchange
CPIc	Construction Project Information Committee
CPIx	Construction Production Information Exchange
CRFI	Client Request For Information
CSI	Construction Specifications Institute
CSV	Comma Separated Value
DMN	Decision Model and Notation
DMRB	Design Manual for Roads and Bridges
DPoW	Digital Plan of Works
EDMS	Electronic Document Management Systems
EIR	Employers Information Requirements
FEEL	Friendly Enough Expression Language
FM	Facilities Management
GIS	Geographic Information Systems
GUID	Globally Unique Identifier
IAN	Interim Advice Notes
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
ISO	International Stnadards Organisation
JCT	Joint Contracts Tribunal
LOD	Level of model Detail
LOI	Level of Information
MCHW	Manual of Contract Documents for Highways Works
MIDP	Master Information Delivery Plan
MPDT	Model Production Delivery Table
MVD	Model View Definition
NBIMS-US	National BIM Standards – United States

NBS	National Building Specification
NCR	Non-Conformance Report
NEC	New Engineering Contracts
NWC	Navisworks Cache File
NWD	Navisworks Document File
NWF	Navisworks File Format
O&M	Operations and Maintenance
OIR	Organizational Information Requirements
OMG	Object Management Group
PAS	Publicly Available Standards
PCF	Project Control Framework
PDT	Product Data Template
PIM	Project Information Model
PLQ	Plain Language Questions
QA	Quality Assurance
RFI	Request For Information
RIBA	Royal Institute of British Architects
RPA	Robotic Process Automation
SGAR	Stage Gate Assessment Review
SMP	Standard Methods and Procedure
TIDP	Task Information Delivery Plan
TQ	Technical Query
UUID	Universally Unique Identifier
VDC	Virtual Design and Construction

Chapter 1 Introduction

The construction industry is making a shift towards the digitization of data produced by it in order to better manage and analyse an asset's performance. In order to make this transformation, Building Information Management (BIM) or Virtual Design and Construction (VDC) processes are used. This chapter will outline the core challenges that are faced during the adoption of VDC on projects. It will then define the research hypothesis, the relevant research questions that were asked as a result of this hypothesis, and the main contributions resulting from this research.

1.1 Problem statement

The digital construction domain has developed significantly over the last few decades and has evolved into various sub-domains varying from the structuring and standardising of digital construction information, the manipulation of such structured information for energy analysis, design decisions, and the visualisation of assets using technologies such as virtual reality and augmented reality.

While significant steps have been taken in order to adopt this new technology, industry surveys such as those carried out by the National Building Specification (NBS) have shown that there are a number of challenges that are faced that hinder adoption and/or can lead to negative outcomes on a project. A significant level of research has been carried out in applying VDC to energy modelling and cost domains. Further, a large volume of research has been carried out on projects which have a finite footprint such as with buildings. In order to encourage adoption of VDC on projects, mandates such as those set by the UK government (HM Government, 2012) have been placed.

Following the UK mandate on adopting VDC on centrally procured construction projects, there has been an increase in adoption and awareness within organisations. However, an observation was made that many organisations are not seeing the full benefits of making this digital transformation. Many practitioners have observed that the manner in which the standards are interpreted, and the tools that are used can vary between organisations which can be problematic when attempting to collaborate.

1.2 Research stages and motivation

This section will outline the main motivation for this thesis and the work carried out in order to address the challenges defined in the problem statement. The research was broken down into three main phases as shown in Figure 1-1.

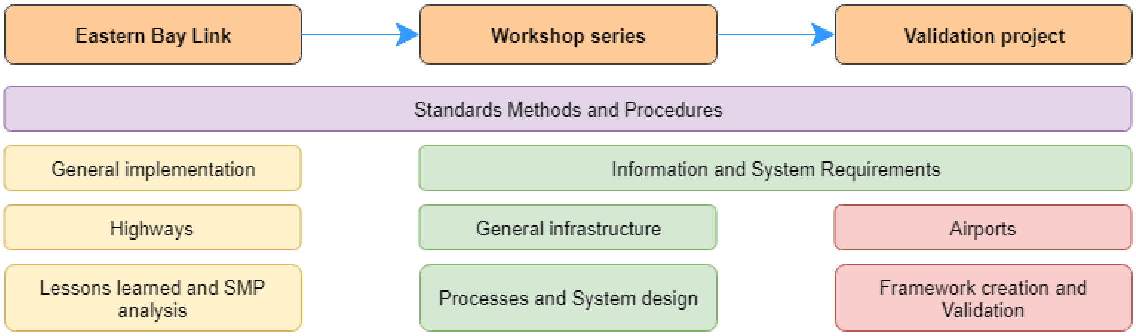


Figure 1-1 Projects and sources of data and validation

1.2.1 Construction and handover

Implementing VDC on projects can lead to the production large volumes of construction information which will then be used to manage the asset. As was highlighted in the problem statement, there are several challenges that are faced when implementing VDC on construction projects. As a result, the first stage involved implementing VDC on projects and attempting to understand the challenges that are currently faced during implementation.

Figure 1-2 The Eastern Bay Link (EBL) viaduct (Image taken from Google Maps)

This first stage therefore involved the implementation of VDC on the Eastern Bay Link (EBL) project which is a 1.2 km long dual carriageway consisting of a 700m long viaduct which comprised both steel and concrete structures in Cardiff, UK. The processes were implemented in accordance to the industry Standard Methods and Procedure (SMP) in order to understand the challenges that are faced during implementation. This stage was essential for understanding what volume and type of information is produced on projects such as the EBL.

1.2.2 Gathering of system and information requirements

The lack of a procedure for the transition from current processes to those described by the SMPs was evident during the first stage of the research. In order to ensure that information is delivered as required, processes and information exchange requirements need to be recorded. The assumption was that this can also be beneficial for understanding and changing existing processes as needed. This stage of the research focused on first understanding how processes and information requirements can be recorded in a machine-readable format. Then an analysis of these processes and requirements were carried out in order to develop a system which has the capability of parsing and automating them.

In order to understand how the SMP's are interpreted and implemented currently a series of workshops were attended. The aim was to understand the current barriers to adoption and to record existing processes and information requirements. Based on the findings made over the course of the workshop series, a prototype system was created in order to execute processes and exchange information with other systems as required.

1.2.3 Developing a framework based on findings

Based on the information gathered from the first two stages of the research, a conclusion was made that there was a need for projects to have a procedure in order to identify system and information requirements in order to implement VDC on projects. Therefore, a framework was presented in order to identify both process and information requirements as well as system requirements.

Once the framework was created, it was trialled on an airport project as it was useful to understand whether it is feasible to implement the framework on any type of infrastructure project.

1.3 Hypothesis and Aims

Following the definition of the problem statement as well as the stages and motivations for the research, the aim was to create a framework which allows users to gather system and information requirements and implement them. The framework had to take the current SMP's as well as existing processes into account in order to ensure that it complies with existing protocols and contractual frameworks. Therefore, the overarching hypothesis to be tested was:

"Implementing Virtual Design and Construction processes on infrastructure projects is advantageous. Aligning these processes with existing asset and organisational information requirements will help achieve greater benefits over the lifecycle of an asset."

To evaluate this hypothesis, the following research questions were formulated:

1. How is BIM/VDC implemented on linear infrastructure projects and what kind of information is generated during this process?
2. What are the main challenges that are faced when implementing BIM/VDC on this type of linear infrastructure project?
3. Upon identification of the main causes that hinder the adoption of BIM/VDC and affect the development of the Asset Information Model (AIM), how can current construction processes be redefined to alleviate these issues?
4. Can processes and information requirements that have been defined be automated, and what type of system can execute and govern these requirements?
5. Can the defined processes and system be adapted on an infrastructure project and what steps need to be taken to do so?

1.4 Structure of the thesis

The thesis has been broken down into 8 chapters including an Introduction and Conclusions. Figure 1-3 shows the structure of the thesis and the way each of the sections and subsections are linked to each other. This chapter aimed to outline the wider context of the thesis, the main stages of the research, and the decomposition of the hypothesis into five research questions.

Chapter 2 is a literature review, which contains an assessment of digital construction processes, the industry standards, and a critical review of the current state of the art. As the research focuses on the management of the flow of information throughout the lifecycle of an asset, the various components that will make up the proposed solution will be reviewed in depth.

Chapter 3 will provide the overarching methodology that was then followed over the course of the research. This chapter breaks down the methodology in detail in order to clarify the approach taken and the resources used in order to answer the research questions.

Chapter 4 analyses the work carried out when implementing BIM on a real-life project, the Eastern Bay Link (EBL). This section analyses the SMP implemented and then explores the lessons learned over the course of the project. The chapter then focusses on the challenge of collecting and using large volumes of data. It then discusses the outcomes of the project in order to identify the potential factors that hinder adoption and the type of information that is created over the course of a project such as this.

Chapter 5 then focuses on a series of workshops which helped identify various scenarios that occur over the course of a project which can lead to issues during the handover of construction information. Then based on the methodologies, strategic and operational process maps will be created in order to record general processes that are carried out over the course of a project.

Chapter 6 builds on the findings made in Chapters 4 and 5 in order to create a prototype tool which will be able to parse processes and information requirements in order to exchange construction with a BIM server. This section effectively implements the methodology stated in Chapter 3 and then presents the prototype system.

Chapter 7 analyses the outcomes of the previous three chapters and presents a framework based on these findings. The framework has the potential to help users identify system requirements in conjunction with processes and information requirements in order to govern the flow of information over the course of a project. In order to validate this framework, it was then trialled on an airport infrastructure project.

Chapter 8 concludes this thesis by critically appraising the proposed system, identifying its limitations and highlighting the significant findings of the research. It reports the overall conclusions of the study and recommends the further work that can be carried out.

1.5 Research contribution

The work carried out during this research contributed to the wider body of knowledge by:

1. Highlighting that a large volume of construction information is produced and shared in flat file formats which can reduce the value of the information produced. Therefore, a system which exchanges information on an object level was created and analysed. The protype system and its architecture has been discussed in this thesis.
2. Mapping and analysing processes in order to understand the flow of information. A strategy in which these processes and information can be recorded has been presented in this thesis. This will be useful for BIM managers when identifying project specific requirements and processes.
3. Providing a framework which enables engineers to identify system and information requirements in order to streamline the flow of information. The framework was created in order to ensure that the relevant Standard Methods and Procedures (SMP) are adhered to, and information requirements are described and executed as needed.

The main contribution is the framework that was formulated based on the first two points and will help those implementing it on infrastructure projects define system, information and process requirements in order to effectively implement BIM on their projects.

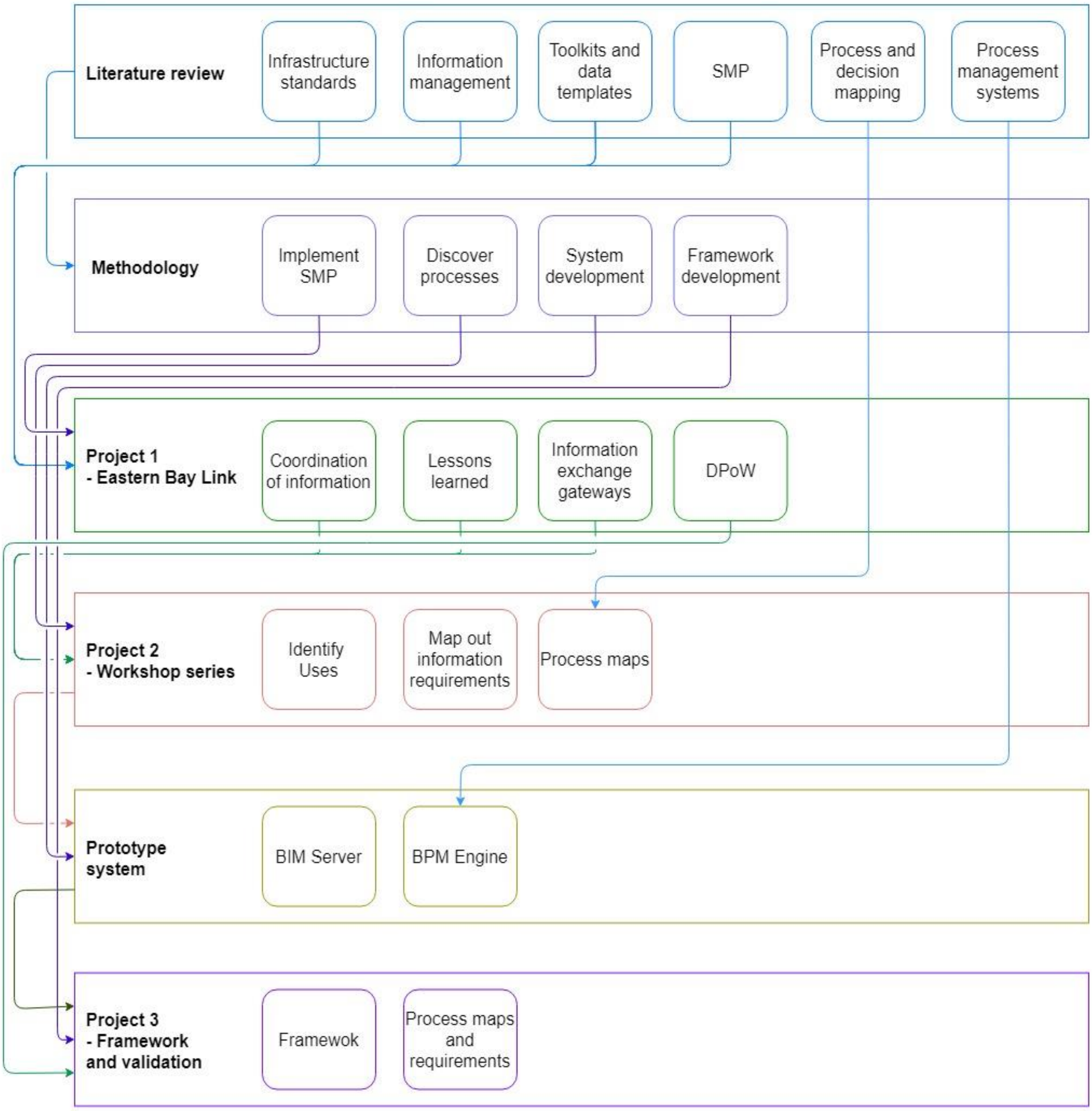


Figure 1-3 The structure of the research

Chapter 2 Literature Review

This chapter summarises the work carried out to understand the state of the art and analyse the challenges that are faced in the domain of digital construction. This chapter begins with the strategy that was used to find the relevant literature. The three sections after that will cover the digital construction and process domains before finally introducing the research gaps that were identified.

There were two comprehensive reviews that were made in relation to the implementation of BIM for infrastructure. Bradley et al. (2016) analysed literature regarding BIM within the infrastructure domain. This review highlighted that there were research gaps related to the generation of information, the need to align processes and the need for the effective governance of construction information. Costin et al. (2018) produced a review that focused on BIM for transport infrastructure. This review had a list of limitations and challenges including process-related challenges where the alignment of BIM standards with existing transportation industry processes was not occurring effectively.

Following a broad initial review of literature, a focus was made on the VDC/BIM and infrastructure domain as well as the processes domain. As was initially identified by both Bradley et al. (2016) and Costin et al. (2018), this chapter reaffirms that there is a need to align BIM processes with existing construction workflows and then identifies the gaps in the research that need to be addressed in the next few chapters.

2.1 Search methodology

To ensure that a thorough review of the research was conducted, various search methodologies were explored, and a decision was made to follow an approach similar to that prescribed by Booth et al. (2012). They suggest identifying the fundamental elements of the research question; the ‘Who?’, ‘What?’, and ‘When?’. A framework similar to that proposed by Petticrew (2006) was then used in combination with this. The techniques were initially used in the field of medicine but have since been adapted in other domains. In the case of this research a framework known as PICOC (Population, Intervention, Comparison, Outcome, and Context) which was proposed by Petticrew and Roberts (2006) was used to create a set of keywords to search for (Table 2-1).

Population	What is the question about, the exact problem area and the related technical terms (e.g. BIM, Asset Management, Value, Process etc.)
Intervention	In what way can we intervene in this situation (e.g. Contracts, BPMN, DMN, Governance models etc.)
Comparison	Comparison of other methods (Was considered to be optional given the context)
Outcome	How can it be measured, and the expected outcome (e.g. as-built information, structured data, view definitions etc.)
Context	As there were varying standards globally, keywords from this field were used to when reviewing the industry standards

Table 2-1 PICOC framework used for literature search

The databases that the search was carried out in were, Scopus, Google Scholar, IEEE, Science Direct, ICONDA, ASCE Library and the Web of Science. Along with the above-mentioned databases, industry publications such as the Construction Information Service (CIS), Construction Manager, Global Construction Review, BIM+, Smart Highways, Transport Network, the New Civil Engineer, the Institution of Structural Engineers magazines and Institution of Civil Engineers publications were reviewed over the course of the research.

BuildingSMART International (2018) initiated the ‘BIM Guide project’ which is a database of BIM documents globally. As of 2018 it had listed 126 BIM Guides, and 754 documents listed in its reference compendium. Reviews such as those done by Cheng and Lu (2015), and Sacks et al. (2016a) were also essential references for finding and reviewing the industry standards.

The benefits of using BIM can be truly realised by the state of the art in industry, as it centres around the coordination between various disciplines and parties. The application of digital construction processes in linear infrastructure has been relatively recent in comparison to that of buildings. A recent review by Costin et al. (2018) confirmed that a significantly increasing frequency of publications were being released from 2011 onwards in relation to this area.

There is a debate both in academia as well as in industry on exactly what term should be used to when referring to the digital construction domain. For bridges, authors such as Chipman et al. (2016) and Shirole et al. (2009) referred to it as Bridge Information Management (BrIM). The acronym CIM is used when discussing the implementation digital construction processes in civil engineering projects. Sankaran et al. (2016) referred to it as Civil Integrated Management and Guo et al. (2014) referred it as Civil Information Modeling. Koch et al. (2017) for example used the term Infrastructure Information Modelling (IIM) (also mentioned by Bradley et al. (2014)), as well as Tunnel Information Modelling (TIM) for tunnels.

A much broader term used for this topic of interest is Virtual Design and Construction (VDC) as defined by the Center for Integrated Facility Engineering (CIFE) (2015) and Alarcon et al. (2010). Upon reviewing literature, VDC can be described as a verb in comparison to BIM being a noun. Therefore, VDC is more related to processes and the virtual construction of an asset with the aid of an information model.

An observation was made that the acronyms BrIM, TIM, CIM and IIM, to name a few, can be considered to follow similar modelling standards and generally fall under the most commonly used acronym for this domain; BIM. It was also observed that VDC is a very broad definition of actions that make use of the Building Information Modelling concept.

When conducting the literature search, combining the acronyms and words, and then filtering out the information was important. Due to the scope of the research, one of the initial criteria was that there was a focus on infrastructure projects. During the initial, broad search of literature in relation to 'BIM', there was a significant proportion of the literature focused on the use of BIM and energy modelling. Once an overall understanding of the state of the art was analysed, the focus then shifted to implementation of VDC/BIM on large infrastructure projects.

The search criteria were then narrowed down based on the findings of this broader analysis of the domain, as well as the findings made by implementing the standards on the Eastern Bay Link project (discussed in Chapter 3).

The research focused heavily on the digital transformation in the construction industry and therefore it was important to identify the progress made in various countries in the adoption of digital construction processes. Countries such as the USA tended to have a different approach to enforcing the implementation of BIM to that of the UK. In the case of the USA, various government departments and organisations have created their own specifications, while in the UK a set of specific standards (the BS 1192 suite) were recognised throughout the country. At the time of carrying out the review a set of international standards (ISO 19650) were expected to be released with the aim of eventually superseding standards such as the BS 1192.

Towards the latter stages of the research, the ISO 19650 (Part 1 and 2) were released which superseded the BS 1192:2007+A2:2016 and PAS 1192-2:2013 in the UK. However, an observation was made that these new international standards followed the British standards closely and apart from certain terminology, they covered similar concepts. As a result, the standards that have been reviewed for this research was up to date even though most of the research that was undertaken was when the BS 1192 series was the recognised standard.

This chapter will consist of three major sections and the above search methodology and relevant databases were used for each of them. The three main sections will be:

1. Infrastructure and Digital Construction/BIM standards
2. Process and related modelling and notation standards
3. Combination of construction and process domains, and an analysis of the gaps in the research

Each of these three sections will consist of a separate introduction, followed by a critical analysis and conclusion.

2.2 Infrastructure and Digital Construction review

The primary aim of this research was to bridge the gap between the construction and IT domains. It has been widely acknowledged that, if implemented effectively, the introduction of IT based collaboration into construction has the potential to increase efficiency, save time and money, and can have positive knock-on effects on areas such as sustainability and health and safety.

Upon review, it has been evident that there are major challenges that are being faced when attempting to integrate the above two domains. This section will approach the problem initially by reviewing and critically analysing the relevant developments in the infrastructure domain, the 'BIM' domain and then concluding with an analysis of the combination of the two.

2.2.1 Review on the infrastructure domain

The research focused on the implementation of Virtual Design and Construction (VDC) in infrastructure. Therefore, the various stages of a project and the processes and information exchange gateways had to be identified first. As will be discussed in Chapter 3, certain steps will need to be taken to transform existing construction processes in order to adopt the new Standard Methods and Procedures (SMP). As a result, the existing stages and gateways of linear infrastructure projects were discussed following the analysis of current standards. This section of the review is aimed to:

1. Establish a generic set of stages for linear infrastructure projects
2. Establish the type of information that is exchanged at each of the defined information exchange gateways
3. Identify for what purpose the information is used for

A decision was taken to consider the UK standards as well as some guidelines produced by the U.S. Department of Transport (U.S. Department of Transportation Federal Highway Administration, 2017a). In their reference guide to the Project Control Framework (PCF), Highways England (2017) states that the PCF is a means of providing a process for the management and delivery of schemes. This framework will coincide with the Design Manual for Roads and Bridges (DMRB) (DMRB, 2017), Manual of Contract Documents for Highways Works (MCHW) (Highways Agency, 2008) , Interim Advice Notes (IAN) and WebTAG (Department for Transport, 2014).

All major projects can be split into three major phases, which are the options, development and construction phases (Highways Agency, 2013). The option phase identifies which solution is the best for the problem, which is then taken through the necessary statutory processes and design during the development phase, right up to the decision to commit to invest. Then the construction phase is when the proposed solution is built, operated, and finally closed down.

The PCF is in place to ensure that there is consistency and continuity between various projects and teams. Similarly to the RIBA stages there are 8 key stages in a projects lifecycle according to the PCF and the framework ensures that the information exchanged is of a certain standard and therefore provides reassurance to the Senior Responsible Owner (SRO). This framework focuses on the exchange of products throughout the above-mentioned lifecycle stages. These products refer to any deliverable, whether it is a report or a project management plan. Each of these stages will have a Stage Gate Assessment Review (SGAR) which progress to the next stage is assessed based on legal requirements, standards and best practice. For single option projects, which are projects within a highway boundary with routes that have already been fixed. The phases have been redefined for single option projects, with it starting from preliminary design (4th Stage, Figure 2-1).

When analysing the example of hand over documentation on highways projects, the PCF documentation was referred to (Highways Agency, 2013):

1. As-built information (drawings/documentation)
2. Operational (Traffic Management (TM)/ Regional Control Centre (RCC)) documentation and certificates
3. Updated H&S file (from stage 2)
4. Handover schedule template
5. Civils maintenance (Managing Agent Contractors (MAC) /Asset Support Contracts (ASC)) handover certificate
6. Technology maintenance (Tech MAC / Regional Technological Maintenance Contracts (RMTC)) documents and certificates
7. Technology commissioning plan
8. Updated permit to connect from stage 5 of the PCF

Establishing gateways and assessment reviews were important, and the documentation from the Highways Agency (2013a) was referred to understand the gateway process. Figure 2-2 shows the gateways and the stages of a project they occur. The gateways reviews are in place to ensure that protocols are being followed at a particular stage. The SGAR focuses on the quality assurance of a project that ensures that products installed have been signed off as fit for purpose.

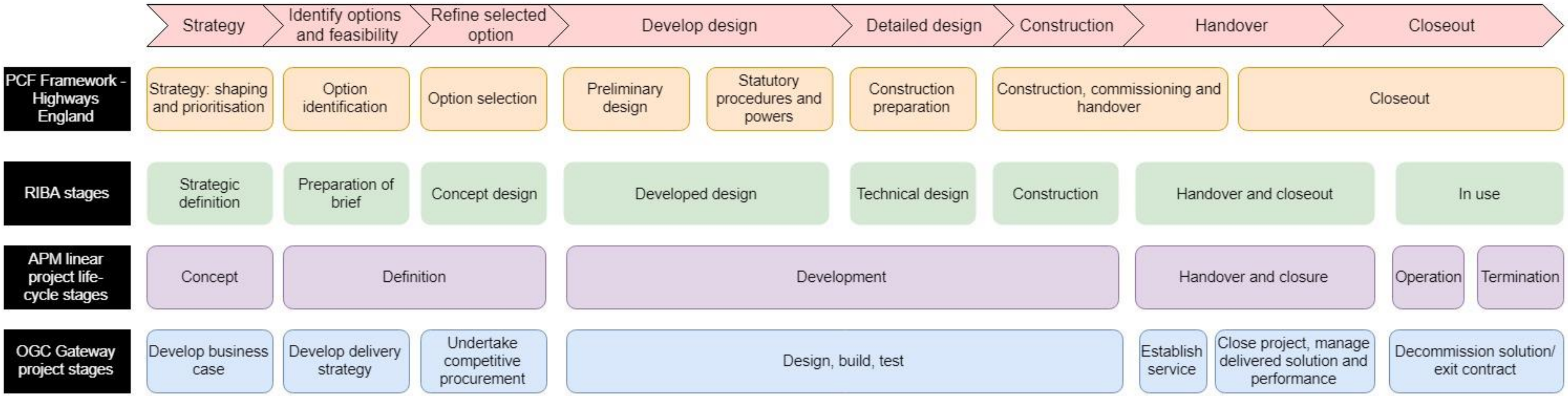


Figure 2-1 Comparison of lifecycle stages as defined by various organisations (stages defined during the research in red)

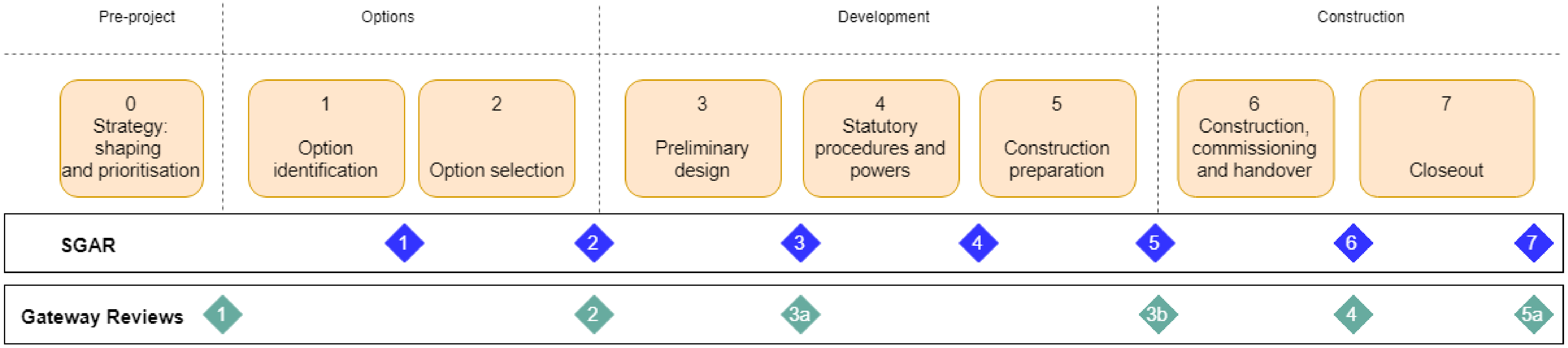


Figure 2-2 Stages in which SGAR and Gateway Reviews are made (Highways Agency, 2013)

Establishing these types of gateways and ensuring that they are integrated into BIM Execution Plans (BEP) is important to ensure that the relevant information is delivered at each gateway. Chapter 3 will discuss the information exchange process and the type of data that is handed over when implementing BIM on a highways project. Understanding the type of information that is used based on the type of maintenance process is important when defining information requirements for a project. Walsh et al. (2011) defined 3 types of maintenance:

- Reactive maintenance – Occurs when responding to complaints, emergencies or during inspection
- Routine/Cyclic maintenance – Has a regular schedule where lamp replacement, cleaning and landscape maintenance etc. occur
- Planned/Programmed maintenance – It is a flexible scheme for reconditioning and renewal

Establishing the type of asset attributes that are needed for each of these types of information will be valuable for formulating basic information requirements. The UK Roads Liaison Group (2016) highlight how new technology and processes are expected to be implemented by organisations. They state that BIM will be a fundamental enabler of the government strategies in attempting to reduce cost, delivery time and emissions. It covers the various stages of an asset's lifecycle and highlights the impact poor information management has on an asset. The documentation highlights that maintenance planning resorts to traditional methods (e.g. time-based/ scheduled maintenance). The documentation also states that by being able to support a risk-based maintenance planning scheme, unnecessary maintenance activity can be avoided and in other situations maintenance activities can take place in anticipation of an issue propagating. In order to move away from the traditional methods, having accurate and updated machine-readable asset information is important.

In conclusion, this stage of the review:

1. Established 8 generic stages for the lifecycle of an asset and an example of review gateways added within these stages
2. Helped understand what type of information will be exchanged at handover

3. Established the main types of maintenance and highlighted the need for accurate machine readable as-built information

2.2.2 Review of the digital construction information management domain

This section of the review is aimed at understanding the state of the art in digital construction with the aim exploring:

- What is the rate of adoption of VDC/BIM?
- What is hindering adoption of VDC on projects?
- What are the perceived benefits of adopting the related standards and technology?
- What are the differences between various standards?
- Which standards will be used over the course of the research?
- What are the requirements that have been set within the selected standards?

Once the most relevant Standards, Methods, and Procedures (SMP) have been identified and the 6 questions have been answered, a detailed analysis was carried out to anticipate which measures have to be taken to successfully implement them on infrastructure projects. These sub-sections will cover the topics of:

- Roles/functions that have been defined by the standards
- Information management
- Structuring and classification of information
- Digital Plans of Work (DPoW) and Product Data Templates (PDT)
- Security and protocols
- International standards

2.2.2.1 What is the rate of adoption of VDC/BIM?

Gilligan and Kunz (2007) conducted a survey in 2006 and 2007 on the use of VDC and BIM technologies in the AEC industry. They observed that there was resistance to this digital transformation and even though the value of adoption was recognised, organizations were not likely to require its use during projects. Reports such as that by Ravenscroft (2017) and Boutle (2017) 10 years after this survey, show that experts still believe that the rate of adoption given the benefits are still low. Ravenscroft (2017) had conducted a discussion with industry experts which included representatives for

Autodesk, and the HS2 in the United Kingdom. One of the interviewee's noticed that figures such as 20% saving in capital expenditure has been highlighted when driving the mandate. However, the survey indicates that asset owners and operators cannot see how these savings can be made as details have not been provided on where the savings can potentially be made from. This in turn leads to a lack of confidence for the various parties who might benefit from adopting these processes as the benefits have not been fully proven.

However, there is a growing awareness and the rate of adoption has generally increased over the past few years in the UK. The National Building Specification (NBS) has carried surveys on the adoption and views of adopting BIM in the UK since 2011. The rate of adoption amongst participants had grown yearly at 31% (2011), 41% (2012), 43% (2013) and 54% (2014) according to the results NBS surveys. Following a dip in 2015, the rate of adoption has grown to 69% amongst participants in the National Building Specification as of 2019. However, there is concern among experts that there are challenges faced by organisations that hinder adoption that may slow down this growth.

2.2.2.2 What is hindering adoption?

In their review of various standards globally, Sacks et al. (2016) confirmed that each of the standards reviewed had disparate requirements leading to confusion among those using them. Gurevich et al. (2017) who reviewed the adoption of BIM in 5 large UK government agencies observed that even though there was a mandate, there was no strategic guidance to manage the adoption process and achieve the desired results. Succar (2016) identified this issue and produced a maturity matrix that can help organisations recognise their capabilities and therefore take necessary steps in order to overcome some of the challenges faced.

In the USA, Sankaran et al. (2018) had carried out a national survey on 42 State Transportation Agencies (STA) on the usage of CIM (Civil Integrated Management). The results of the survey showed that 32 STAs use CIM 3D design tools for terrain modelling and only 16 reported they use it for structures and advanced visualization. The conclusions were similar to the other surveys in industry in the UK and abroad; there is a digital transformation occurring and there has been adoption. However, due to barriers such as contractual constraints and the reluctance to adopt new technologies, further research needs to be carried out for a smoother transition into implementing BIM and VDC on projects.

In a report to local authorities in the UK on increasing adoption of BIM, Catton and Parlikad (2015) analysed the main barriers to adoption and recommended solutions on overcoming these challenges. There were three broad underlying issues in relation to day to day adoption, which were legal issues, insufficient information quality, and lack of resources to address the first two problems while delivering a public service. The general observations were that the interviewed authorities were averse to implementing BIM systems as they were mis-sold to the sector, and there was generally a lack of 'good quality' data (this included imprecise data, different units, and varied naming conventions). The final issue was the lack of resources to enable this as there was uncertainty in the value of adopting these new processes and tools. To encourage adoption and give recommendations, UK Roads Liaison Group (2016) produced a code of practice for managing highway infrastructure. This document also refers to a document dedicated to 'Better Information Management' (BIM) for infrastructure bodies by the UK Roads Liaison Group (2016a). The document on BIM by the UK Roads Liaison Group highlights that when setting information requirements, it will be necessary to establish the business processes, but also take process change into consideration.

In their review on the various factors limiting the application of BIM, Sun et al. (2015) highlighted 5 areas where there were barriers to adoption. They were technology (included interoperability), cost (training, software and hardware), management (workflows, schedule and safety management), personnel (training), and legal (laws, regulations and contracts). The National Building Specification Surveys highlighted specific barriers including the lack of client demand, the lack of training, the cost of adoption and the lack of time to get up to speed being the most common issues faced by practitioners.

2.2.2.3 What are the benefits of adopting VDC/BIM?

Love et al. (2013) carried out an analysis on attempting to justify the investment in adopting BIM during asset management. They observed that there were intangible benefits of adopting BIM on projects and therefore looked beyond Return on

Investment (ROI) alone and attempted to further analyse and justify the use of BIM in asset management. Several authors and industry practitioners have identified that benefits in implementing BIM such as clash detection, scheduling, increased collaboration and accurate cost estimation.

Li et al. (2017) reviewed 1874 BIM-related papers to map out the knowledge domains of BIM to identify the key research areas. They identified 60 key research topics with the most important areas highlighted being information systems, 3D/nD modelling application, design sustainability, interoperability (IFCs), and real time communication. Zhao (2017) carried out a similar study which identified several 'co-citation clusters' which were similar to those identified by Li et al. (2017) but also included ontologies, laser scanning, and code checking.

Several organisations have started highlighting BIM 'uses' in order to identify the benefits and highlight what actions can be taken in order to effectively use BIM on projects. The most comprehensive list of BIM uses has been defined by Succar (2016b) which have been divided into various themes based on the type of model uses.

2.2.2.4 What are the differences between the various Standards, Methods and Procedures?

As will be discussed in the three industry projects (Chapters 4, 5 and 7) as well in the in-depth breakdown of the UK BIM standard methods and procedures (SMP), there are several shortcomings both in the UK standards as well as the international standards. As a result, a qualitative analysis was carried out to identify various strategies.

The two most comprehensive studies in this type of analysis of BIM standards was by Kassem et al. (2015) and Sacks et al. (2016). These two studies were used as a foundation for analysing various standards. In their review, Sacks et al. (2016) chose a sample of 15 different documents to carry out a qualitative analysis of various standards globally. These standards included:

- National, city or state standards
- Guides by large-scale construction owners
- Guides by universities and colleges

An inductive qualitative content analysis (Kohlbacher, 2006; Mayring, 2000) was carried out to build up on the findings by Sacks et al. (2016). An observation was made that the study by Sacks et al. (2016) had conducted reviews only on the BS 1192-4 and the PAS 1192-2:2013 when reviewing the UK standards. As a result, the other UK SMP's were analysed in a similar manner as a better understanding of the standards were gained from doing so. The BS EN ISO 19650-1, BS EN ISO 19650-2 and the relevant transition documents were analysed as well (British Standards Institution, 2019; UK BIM Alliance, 2019). The qualitative analysis of the standards focused on 10 key areas that were identified by Sacks et al. (2016) which were; Interoperability, Role of the BIM Manager, Modes of collaboration, Prequalification for designers, LOD specification, Operation and Maintenance requirements, BIM Execution Plan, Simulation and analysis, and schedule of payments. A summary of the findings can be found in Table 2-2, Table 2-3 and Table 2-4 with a more detailed breakdown in the Appendix A. The cells highlighted in green and yellow were made for the purpose of this research in addition to the standards that were reviewed by Sacks et al. (2016).

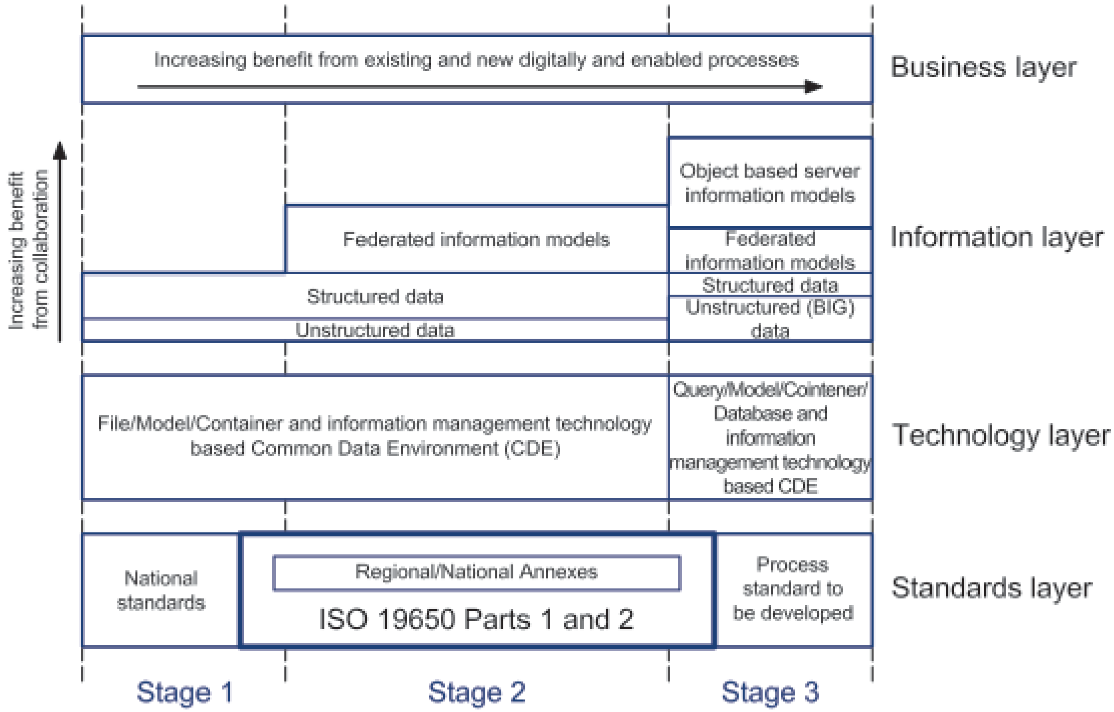


Figure 2-3 ISO diagram from the BS EN ISO 19650-1:2018 showing stages of maturity

In conclusion of the qualitative analysis of the standards, and observation was made that the ISO 19650 has closely followed BS1192 series of standards. At the time of review the BS 1192:2007+A2:2016 and the PAS 1192-2:2013 was being phased out in order to be replaced by the ISO 19650 Part 1 and 2 along with a transition guidance document; PD 19650-0:2019 (British Standards Institution, 2019). The BS EN ISO 19650 (UK Annex) refers to the rest of the BS/PAS 1192 suite and therefore a large part of the standards remained unchanged. A majority of these two new standards are similar to the standards they have superseded apart from certain details such as the terminology that is used as well as certain concepts such as the levels of information and detail.

Figure 2-3 which is taken from the ISO 19650-1:2018 highlights the various stages of development shows that the ISO 19650 1 and 2 were the second stage with the next stage focusing on process standards.

2.2.2.5 What are the requirements that have been set within the selected standards?

Upon the completion of the qualitative analysis of the standards, a conclusion was made that the UK and relevant ISO SMP's will be referred to when defining VDC processes. It was deemed to be necessary to then critically analyse these two sets of standards. This section of this chapter discusses the 1192 series of standards, the BIM protocol, BS EN ISO 19650 series, Uniclass, Government soft landings, and the Digital Plan of Works. Each of the mentioned standards prescribe the way stakeholders could implement the BIM process from how the information is expected to be structured and shared (BS1192) to how BIM objects should be classified (Uniclass). It also briefly discusses other standards that were considered including the National BIM Standards-United States (NBIMS-US) and other international standards and guidelines such that provided by the Federal Highways Authority (USA). The implementation of the relevant British standards on a project and the outcomes are described in Chapter 3.

Organisation	Year of publication, recent update	Organisational type	Interoperability	Role of BIM Manager
LACCD	2009	University	○	●●
GT	2011	University	●	○
USC	2012	University	●	○
Indiana	2009, 2012	University	○	○
Senate	2012	State owned company	●●	●●
Stasbygg	2013	State owned company	●●	
GSA	2009	Gov Dept	●	●●
COE	2009, 2010	Gov Dept	●	●●
VA	2010	Gov Dept	●	●●
Ohio	2013	State	●	●●
NATSPEC	2011	National	○	●
NBIMS	2012	National	●●	●●
Singapore	2012	National	●	●
CanBIM	2012	National	●	●
UK (S)	2013	National	●●	○
UK (G)	2013,2018	National	●●	●
ISO (UK Annex)	2018	International		

Table 2-2 Summary of qualitative analysis which includes findings that were made by Sacks et al. (2016)

Key

Highly Detailed - ●●

Detailed - ●

Few Details - ○

Organisation	Role of BIM Manager	Collaboration modes	Proposes IPD	Pre-qualification for designers
LACCD	●●	●●		○
GT	○	●	●	○
USC	○	○		○
Indiana	○	●●	●●	●●
Senate	●●	○		○
Stasbygg		○		
GSA	●●	●		
COE	●●	●		
VA	●●	●		○
Ohio	●●	●		●
NATSPEC	●	●●	●	○
NBIMS	●●	●		●●
Singapore	●	○		
CanBIM	●	●	●	●
UK (S)	○	○		●
UK (G)	●	○		●●
ISO (UK Annex)		○		●●

Table 2-3 Summary of qualitative analysis which includes findings that were made by Sacks et al. (2016) – including

Organisation	LOD Specification	Operation and Maintenance Requirements	BIM Execution Plan	Simulation and analysis	Schedule of payments
LACCD		●	○	●	
GT	○	●●	●	●●	
USC	○	●	○	●	
Indiana		●	●	●●	
Senate	●	●	●●	●●	
Stasbygg	●●	●	○	●●	
GSA	○	●●	○	●	
COE	○	○	●●	●●	
VA	●●	●	●●	●●	
Ohio	●●	○	○	○	●●
NATSPEC	●●	●●	●●	●	
NBIMS		○	○	○	
Singapore	●●	●	○	●●	●●
CanBIM	●	○	●	○	
UK (S)	●●		●	○	
UK (G)	●●	●●	●●	●	
ISO (UK Annex)	●●	●●	●	●	

Table 2-4 Summary of qualitative analysis which includes findings that were made by Sacks et al. (2016) – including O&M requirements and BEP

2.2.2.6 *Breakdown of the selected standards*

Based on the overall analysis of the standards, a decision was made that the UK standards and the ISO standards were to be analysed as they were the most comprehensive set of standards for BIM.

Roles

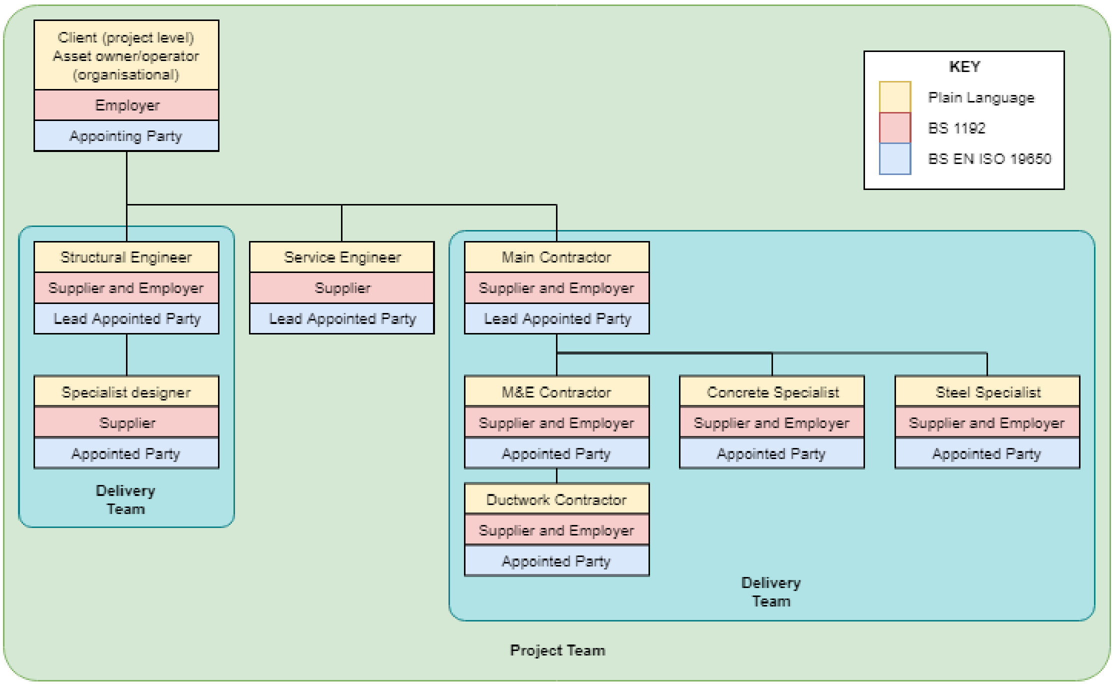


Figure 2-4 Simplified example of hierarchy of roles/functions according to the BS 1192 and ISO 19650 standards

As the research progresses, it will be important to define the various roles or functions of the parties that are involved in construction projects. The standards that have been selected to be used in the research are closely aligned, however one of the major differences are the naming of the roles on projects. Figure 2-4 shows a simple hierarchy on a project level with the various names given to each party according to the BS 1192 and BS EN ISO 19650 standards. As the research was carried out at a transition stage between the standards, in some cases the roles will sometimes be used interchangeably.

Information management

The BS 1192:2007+A2:2016 (2016) was the standard that defined best practice for how systems and requirements were to be setup on a project implementing BIM which has now been superseded by the ISO 19650 Parts 1 and 2 as of 2019. It prescribes how information can be classified and shared to ensure that there all disciplines could collaborate and provides a template for common naming conventions.

This standard was complemented by guidelines by Richards (2010) who further specified how the process could be implemented in construction. The RIBA Information Exchanges book by Fairhead (2015) gave checklists and covered the general information that is recommended to be exchanged throughout the lifecycle of an asset.

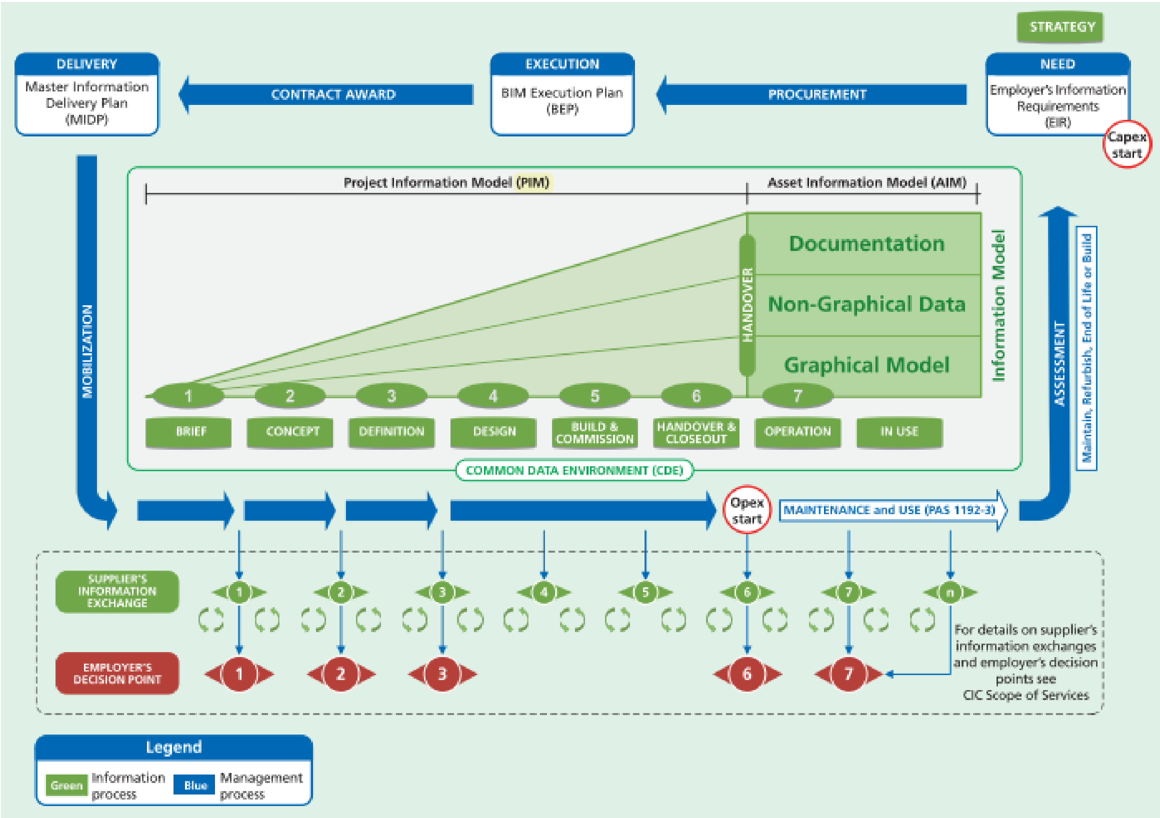


Figure 2-5 Phases of asset lifecycles covered by the PAS 1192:2 (Diagram taken directly from the PAS 1192:2

The standards prescribe how a Common Data Environment (CDE) is expected to be set up, the expected workflows, and the conventions that are recommended to be followed. In summary, the standards cover the ideal scenario in which information can be exchanged between disciplines and finally federated (Figure 2-5). However, in practice this can be challenging, and due to technical and human barriers, it might not be achievable without cost or major disruption to existing systems.

The PAS 1192-2:2013 (2013) builds on the above mentioned standard and focuses particularly on project delivery and how the Project Information Model (PIM), which is the information model which is developed during construction, can be developed.

From a supplier's point of view, this standard is important as it covers the main aspects of what is expected during construction. As shown in Figure 2-6, it covers the lifecycle of a project from the Strategic definition to Handover. The starting point was to refer to the documentation provided by the Construction Project Information Committee (CPIc), who are responsible for providing best practice guidance for Construction Production Information Exchange (CPIx). They provided BIM strategy templates that have been developed in consultation with the UK government BIM Task Group (Construction Project Information Committee (CPIc), 2015).

Government organisations started producing best practice guides such as templates by the Ministry of Justice (MoJ) (Ravenscroft, 2016), and the Interim Advice Notes (IAN 184/16) by the Highways England (2016) for data and CAD standards. It is extremely effective when stakeholders engage in the adoption of VDC, and it can prove to be of great value especially for larger projects. However, as results of surveys by organisations such as the National Building Specification (NBS) (2019) show, it is a major pain point for certain parties adopting the process. It can involve having to purchase new software, train employees, change processes and change IT infrastructure to name a few challenges. Especially moving further down supply chain, smaller suppliers and clients can find it extremely costly changing systems.

Then interpreting the standards can be challenging, with the most challenging being the exact definition of the Project Information Model (PIM) and the Asset Information Model (AIM). Their definitions have been left abstract which allows more flexibility for defining them from project to project. This is a case where terminology overlaps with existing concepts such as Health and Safety (H&S) files and Operations and Maintenance (O&M) manuals.

A similar complication/duplication can potentially occur with the likes of what is defined as Master Information Delivery Plans (MIDP) which is the compilation of several Task Information Delivery Plans (TIDP) which are expected to be produced by the suppliers. This again can tend to coincide with design schedules. What was experienced with MIDPs is that there can be a disjoint between the project schedules which can lead to complications during design and construction. Such duplications and additional work placed by such recommendations can generally lead to more paperwork and sometimes can be a hindrance to the progress of a project.

There are many acronyms that can prove to be challenging, one such example is be the 'Level of Definition' and is the collective term used for Level of model Detail (LOD) and Level of Information (LOI). Where the LOD and LOI is the description of graphical and non-graphical content produced respectively. This type of jargon can tend to lead to issues when defining this terminology in contracts (refer to the section on the BIM protocols).

The PAS 1192-3:2014 (2014) focuses on the process during the operational phases of a project and how the Asset Information Model (AIM), which is a model that is maintained from handover to the end of life of a project.

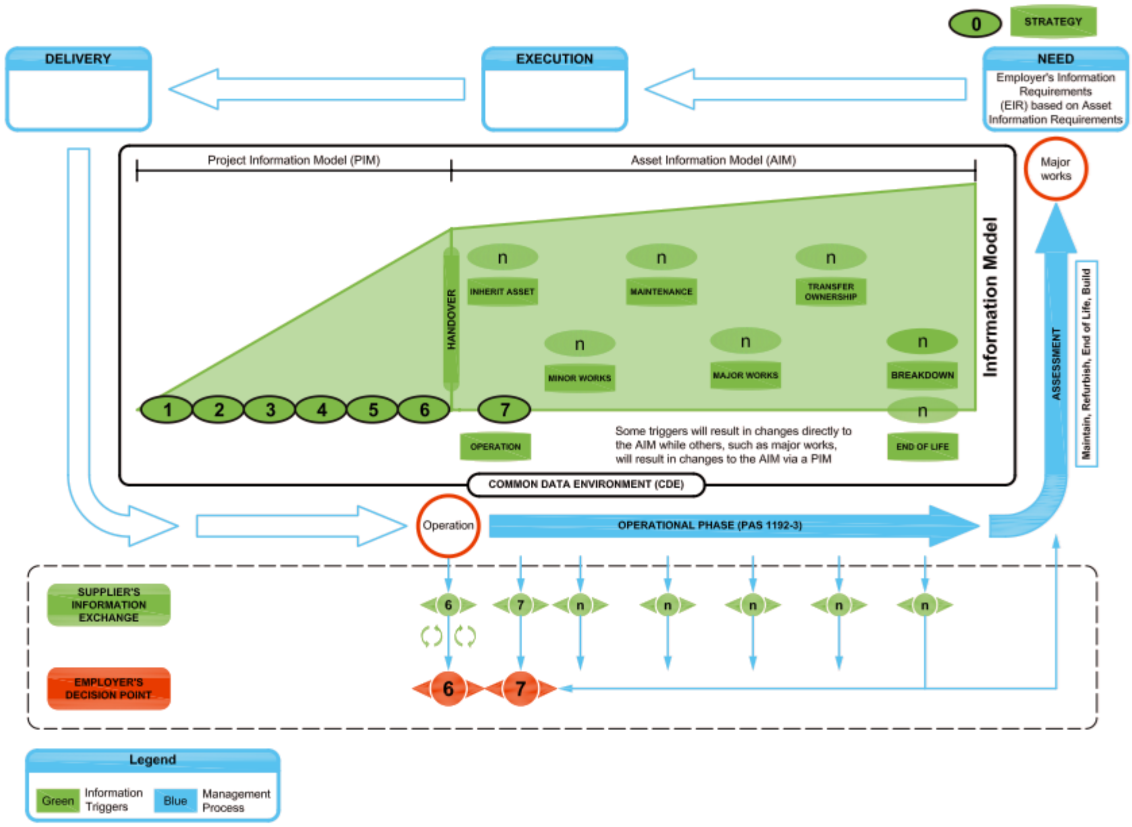


Figure 2-6 Phases of asset lifecycles covered by the PAS 1192:3 (diagram taken directly from PAS 1192:3)

This standard complements the PAS 1192:2 and is a specification to cover the lifecycle phases following handover. Due its connection to the previous standard, it does share certain challenges that are faced during construction in terms of definitions and processes. In an analysis of the legal implications of implementing the standards, Winfield and Rock (2018) highlighted that the ambiguity of the standards can be considered to be considered to be an advantage. However, this too can tend to lead to challenges, especially in highways and existing assets as it leads to changes to IT infrastructure and processes.

Structuring and Classification of Information

A common method of classification is needed, and **Uniclass 2015** regulated by the National Building Specification (NBS) (2017) is used for this purpose in the UK. It consists of 7 tables, that are arranged in a hierarchical manner, which ranges from project to product level. There still are issues with the classification from modelling to product information to cost information systems which can be problematic if not unified.

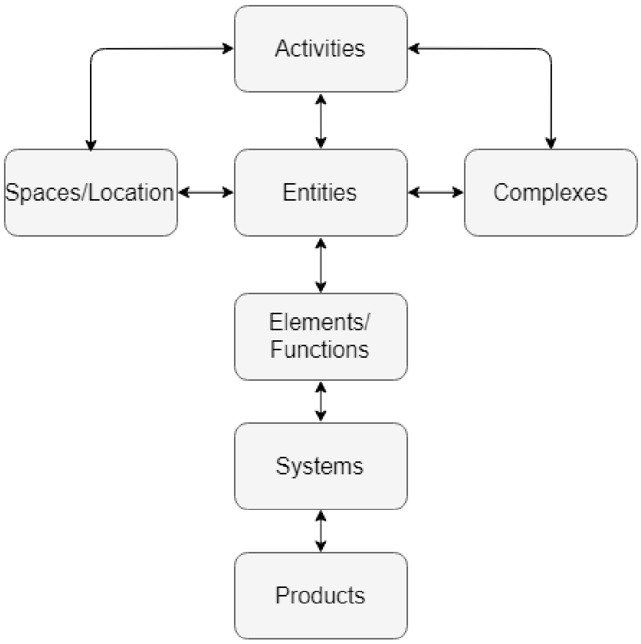


Figure 2-7 Uniclass 2015 table dependencies

This classification type has been referred to in the **BS ISO 12006-2:2015** (British Standards Institution, 2015) which is a framework for classification when organising construction information, and is complemented by the **BS EN ISO 12006-3:2016** (British Standards Institution, 2016b) which is a framework for object-oriented construction information.

This ISO 12006 series intends to introduce an overarching international classification framework which will then allow national classification systems such as Uniclass to be included. The BS ISO 12006-2:2015 provides guidelines for construction objects. Uniclass 2015 can be aligned to this classification system as shown in Table 2-5. The ISO 12006-3 then specifies a taxonomy model with the aim of being able to define properties and concepts by means of properties which are grouped and used to define relationships with other objects.

BS ISO 12006-2	Uniclass 2015
A.2 Construction information	FI: Form of information
A.3 Construction products	Pr: Products
A.4 Construction agents	–
A.5 Construction aids	CA: Construction Aids
A.6 Management	PM: Project Management
A.7 Construction process	–
A.8 Construction complexes	Co: Complexes
A.9 Construction entities	En: Entities
–	Ac: Activities
A.10 Built spaces	SL: Spaces and Locations
A.11 Construction elements	Ee: Elements
–	Ss: Systems
A.12 Work results	–
A.13 Construction properties	PC: Properties and characteristic

Table 2-5 Alignment of the two classification systems; BS ISO 12006-2 and Uniclass 2015. (British Standards Institution 2015; National Building Specification (NBS) 2017)

Another popular classification system is OmniClass (Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC), 2017) which is the North American equivalent of Uniclass. This system too is aligned with the ISO 12006-2.

Digital Plan of Work (DPoW) and Product Data Templates (PDT)

A **Digital Plan of Work** (DPoW) enables employers to define expected deliverables at each stage of a project. If used, it is expected to be available to all parties involved with a project to ensure that engineers are informed on what information to deliver and when. The **NBS BIM Toolkit** by the National Building Specification (NBS) 2015) is a free tool that has been created to be used as a DPoW. This is aligned with the RIBA stages and is a useful system for defining stage deliverables which are based on the Uniclass system.

The NBS BIM Toolkit, can produce Product Data Templates (PDT) which are spreadsheets with required information (As defined by the NBS). Each spreadsheet has particular asset type, with information references and details of each assets specifications as well as details such as installation dates. These spreadsheets once filled with the as-built information, known as Product Data Sheets (PDS), will be handed over to the asset operator or embedded within the digital model as required (refer to Figure 2-8 which is an example of a model with embedded as-built information). In the UK initiatives like BIM for Manufacturers and Manufacturing (BIM4M2) as well as organisations such as the Construction Products Association (CPA) (2016) and The Chartered Institution of Building Services Engineers (CIBSE) (2016) attempt to standardise templates and structures to exchange product information. In a Construction Sector Deal the Department for Business, Energy and Industrial Strategy (2018), the use of repeatable and machine readable product information using the CPA's LEXiCON was announced.

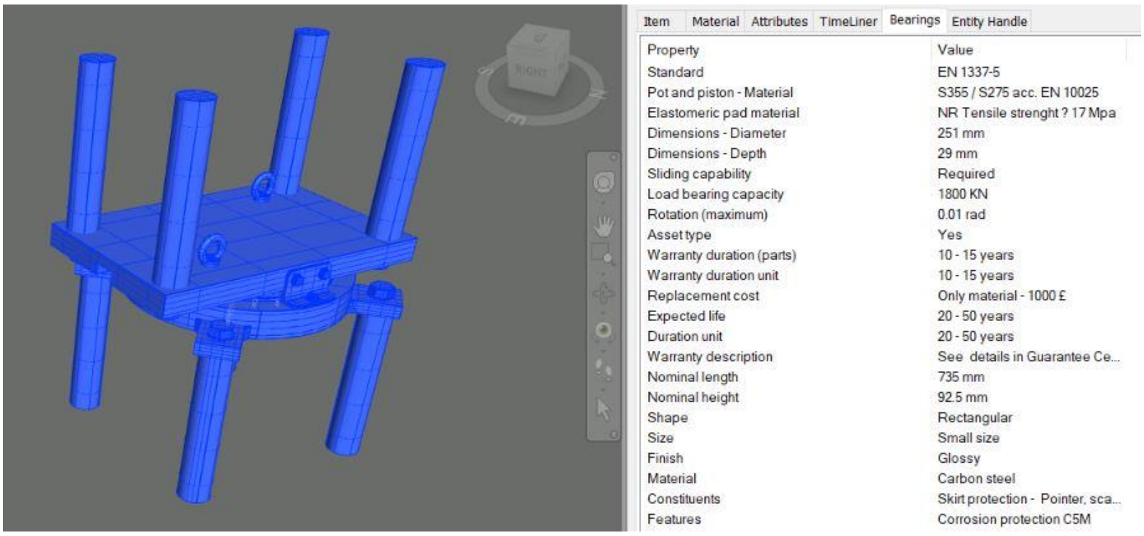


Figure 2-8 As-built model of a bridge bearing with data from PDT embedded within it

<u>Representation of structured construction information</u>

Industry Foundation Classes (IFC) specification is a non-proprietary data model which is used to describe construction information (BuildingSMART International, 2016a). It was originally created in 1995 by a consortium called the International Alliance of Interoperability (IAI), now known as buildingSMART, who committed to publishing this platform neutral data model. The main formats for this exchange schema (IFC) follow the STEP physical file structure according to the ISO 10303-21 following the IFC-EXPRESS specification (BuildingSMART International, 2016b), the XML representation which is ifcXML (Liebich and Weise, 2012), and ifcZIP (BuildingSMART International, 2016a). It has been observed that the schema changes regularly, with the 5th iteration being under development at the time of writing this thesis. Afsari et al. (2017) highlighted that for the ease of use in web applications, the representation of IFCs in JSON (JavaScript Object Notation) format is valuable, and therefore proposed an ifcJSON schema.

The IFC schema defines an entity relationship model. For example, when describing a window, this window will share generic properties with other windows in the that project (e.g. materials and sizes etc). Then this window (instance of the window) will have separate attributes which will define it (e.g. serial number, installation dates etc). Each of the above-mentioned properties are grouped into 'property sets' which are then referred to by the particular instance of an object. Elements also can be grouped into 'systems' which define various components which work together (e.g. drainage systems, water supply etc.). IFC then defines the relationship (e.g. site composition, storeys, spaces, and grouping of spaces) between these various systems and individual components. In its common form, IFC is an ASCII plain text file, and the schema defines how the plain text is turned into object aggregates with relations and type inheritance.

The goal of IFC is to provide a common schema that needs to be followed when using that format. It has been noted that not all the information is equally valuable to all parties involved on a project. Therefore, Model View Definitions (MVD) were proposed (BuildingSMART International, 2015a) which defines subsets of the IFC schema thus ideally providing various users different 'views' of the same project. There are several studies in creating MVD's such as that by Panushev et al. (2010) for precast/prestressed concrete, and Sacks et al. (2016b) for bridge inspections. One of the most commonly referred to MVD's is the Construction Operation Building information exchange (COBie) format.

The **BS 1192-4:2014** focuses on the UK usage of Construction Operations Building information exchange (COBie) which provides a common structure for exchange information. (British Standards Institution, 2014a).

Initiatives such as 'COBie for all' by the BIM Task Group (2013) have attempted to translate this concept into defining information on infrastructure projects. However, the Highways Agency (2014) in their Interim Advice Note (IAN) 184/14, described COBie as a 'stopgap' until the IFC standards are developed and supported by commercial software.

The Interim Advice Note mentioned in the previous paragraph was then superseded by the **IAN 184/16** (Highways England, 2016), which has referred to the provisions of **IAN 182/14** titled 'Major Schemes: Enabling handover into operation and maintenance', for asset coding and non-graphic data. With the latest version being the **IAN 182/14A** (Highways England, 2018). These latest standards do not mention the handover of information using IFC or COBie either with the document mentioning that COBie is 'likely to be the eventual mechanism for transfer of asset data'. This potentially can be due to hesitation with adopting the data schema as it is still in development (IFC for infrastructure) and also the issue of having to integrate these new schemas and file formats into existing asset management systems.

In the UK the COBie standards for infrastructure were first proposed by the BIM Task Group (2013) which attempted to breakdown this schema, originally designed for buildings, into an infrastructure context. The infrastructure view of COBie as proposed by the task group can be seen in Figure 2-9.

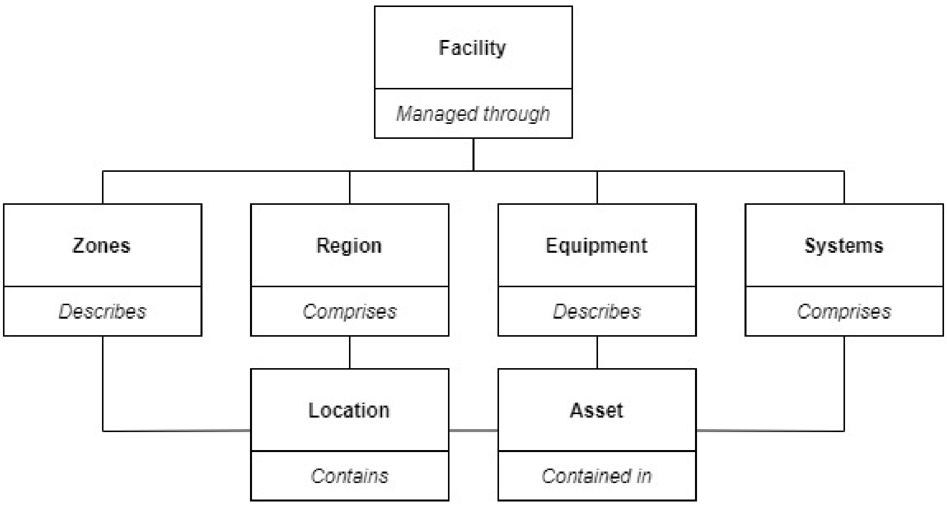


Figure 2-9 Infrastructure view of COBie (initially proposed by the BIM Task Group/AEC3 and then adopted by the British Standards)

This again is a challenge to adopt both for asset managers and suppliers and even though ifcAlignment (BuildingSMART International, 2015b) was developed since these standards were released, the development of IFC is in progress. Existing linear infrastructure asset management systems may have to evolve to accept such file formats and get value from the adopting files with schemas proposed in the standards.

COBie can be represented in spreadsheet form and therefore makes it easily accessible, which is an advantage. However, when using this type of schema specific proprietary software is generally expected to be used. This again can prove to be challenging and may not be of great value to asset managers with existing systems that may not be able to recognise such schemas. In the simplest form such information might be of more value to asset operators to receive information in Comma Separated Value (.csv) format in comparison to that following the proposed COBie schema.

Security and Protocols

The PAS 1192-5-2015 (2015) focuses on the vulnerabilities that implementation of BIM in accordance to the standards and protocols can bring. It then addresses the steps that need to be made to ensure that there is an appropriate security mindset when implementing the BIM process.

This standard covers the steps that need to be taken from an organisational level, to project level to ensure that best practice in relation to security is adhered throughout both for organisations as well as for individual projects. This standard will integrate on a project level via the EIR and Strategic Brief of a project, and through to hand over (Asset Information Model) which will be fed back into the asset management system.

From a contractual level, this is expected to be enforced on projects and contractual frameworks such as the New Engineering Contracts (NEC) (2017) (NEC4). The Joint Contracts Tribunal (JCT, 2016) had produced a practice note, Building Information Modelling (BIM) Collaborative and Integrated Team Working, to help embed the process into projects contractually.

The security standards are taken into consideration and the likes of commercial Common Data Environments (CDE) are capable of enforcing control on what information is shared as well. These standards work directly alongside the other sections of the BS1192 series along with standards such as the **BS ISO 55000** for Asset Management (British Standards Institution, 2014b).

The latest addition to the 1192 suite is the **PAS 1192-6:2018**, and it specifies the requirements for the sharing the collaborative sharing of H&S information for all construction projects from the outset. (British Standards Institution, 2018a).This standard helps participants on projects to create strategies that help facilitate the adoption of Health and Safety (H&S) practice within a BIM environment. Prior to this the National Building Specification (NBS) released a book (Mordue and Finch, 2014) with regard to helping reinforce best H&S practice with the aid of BIM.

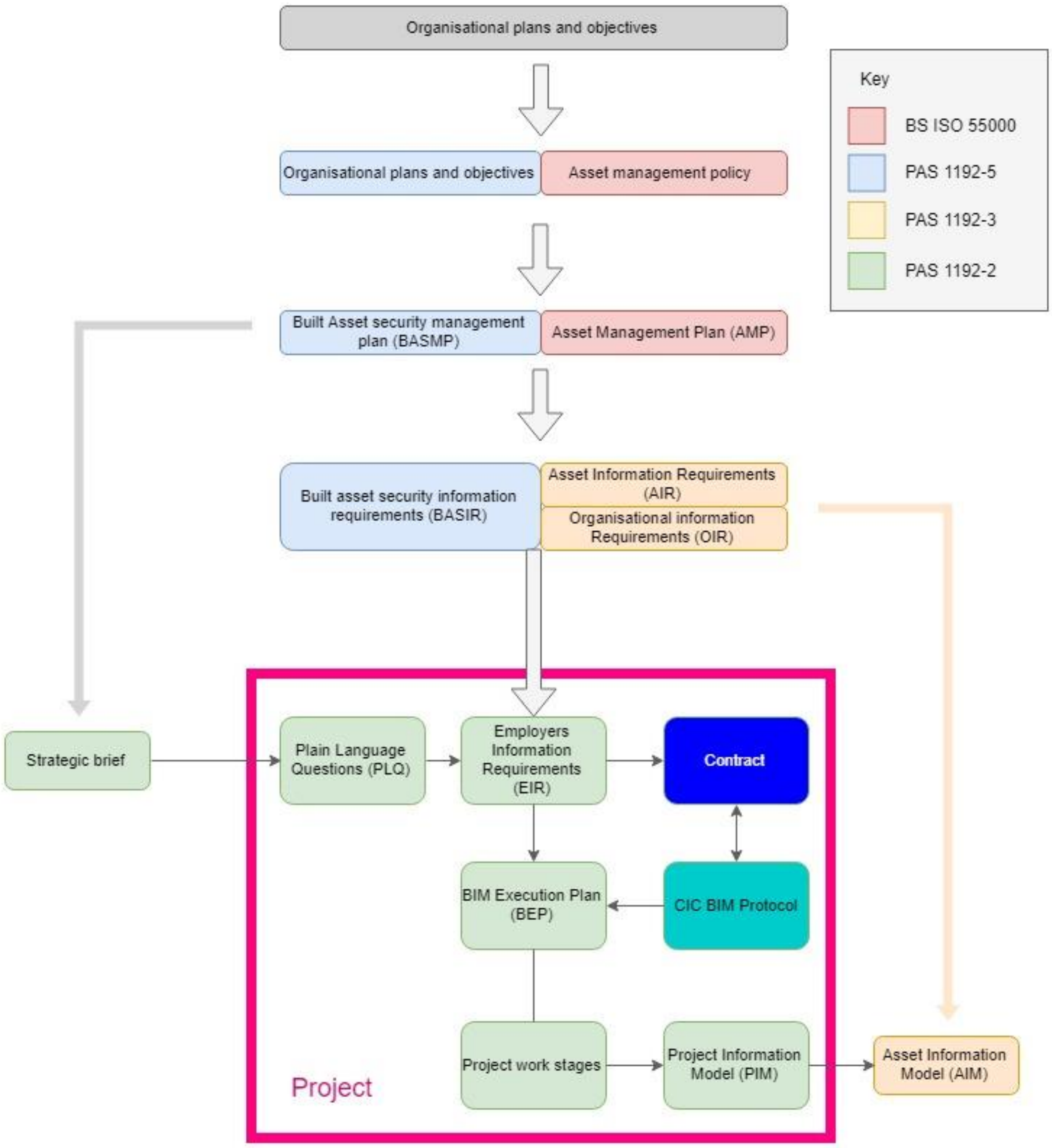


Figure 2-10 The interaction between various standards, and the integration of the security minded approach (based on diagram produced in the PAS 1192-5 by the British Standards Institution (2015)

Protocols and contractual documentation

The **Building Information Model (BIM) Protocol** (Construction Industry Council, 2018, 2013a) are supplementary legal documents which represents a requirement for Level 2 BIM. It is a contractual document which provides definitions of responsibilities and liabilities.

The BIM protocol was drafted for use in all common construction contracts. The protocol identifies what information models are expected to be produced and defines roles and what obligations they have in order to successfully deliver BIM on a project. It also provides a framework for a Model Production Delivery Table (MPDT) which can be used as a template to help define Levels of Detail (LoD) and helps users define at which stages these exchanges of information are expected to occur. The second edition of the Protocol was released in 2018 to cover the newer standards. It also has replaced the MPDT with a Responsibility Matrix and identifies EIR's and BEP's which helps identify and reflect these documents in contracts.

These protocols are essential in enforcing the process and also ensuring that each stakeholder remains compliant to the standards and protocols to provide consistency. However, he also believes that it also can be an indicator of the still relatively siloed nature of the industry due to the further jargon or renaming of existing systems the standards bring. It is commonly acknowledged that the standards cause confusion, and makes stakeholders hesitate to adopt the process.

In the National Building Specification (NBS) (2018) report on BIM in the UK, experts were interviewed with regard to contracts with regard to their views to the standards and protocols. Firstly, the interviewees were divided with regard to the flexible approach of the likes of JCT and NEC contracts, with some believing it was useful and the others considering it to be 'too light a touch'.

Then the report stated that there were concerns with regard to the terminology brought in. A couple of interviewees stated that the 'jargon in BIM is horrific' and it has lawyers 'bamboozled' (National Building Specification (NBS), 2018a).

The likes of the UK BIM Alliance are attempting to reduce such silos by producing documentation such as the 'Winfield Rock Report' (Winfield and Rock, 2018) which attempts to understand current perceptions of legal experts and then analyses the current challenges and potential solutions to them.

International standards

The National BIM Standards – United States (NBIMS-US) are built around international standards (ISO) using them as their core (including Draft International Standards (DIS) and Publicly Available Standards (PAS)). Then they use the technical publications (e.g. Reference processes) and deployment resources (e.g. contract specifications) to build around the core standards. The current version of these standards are referred to as NBIMS – US v3 which is an ongoing project of buildingSMART. One of the most significant drivers of the development of standards in the UK is due to the mandate the government enforced, however in the USA there has not been such a mandate. Therefore, the NBIMS-US may not have the same scope the likes of the 1192 series have.

As seen in Figure 2-11 buildingSMART International have organised building knowledge into four major domains. However, the NBIMS-US acknowledges that their standards intend to cover very few of the above-mentioned domains.

Design	Procure	Assemble	Operate
Requirements	**Suppliers**	**Quality**	**Commission**
Program	Qualifications	Testing	Startup
Schedule	Availability	Validation	Testing
Quality	Stability	Inspection	Balance
Cost	Capacity	Acceptance	Training
Site	**Material**	**Safety**	**Occupy**
Zoning	Submittal	Requirements	Leasing
Physical	Selection	Logistics	Building Management
Utilities	Purchase	Training	Security
Environmental	Certification	Inspection	Tenant Services
Form	**Contracting**	**Schedule**	**Modify**
Architecture	RFQ	Fabrication	Assessment
Structure	RFP	Deliverables	Refurbish
Enclosure	Selection	Resources	Renovate
Systems	Agreement	Installation	Demolish
Estimate	**Price**	**Cost**	**Maintain**
Quantity	Quantity	Productivity	Prevention
System Price	Unit Price	Solicit	Schedule
Comparison	Labor	Pricing	Warranty
Escalation	Equipment	Selection	Contract

Figure 2-11 Topics that have been proposed by buildingSMART international which is an expansion of their tetralogy (Design, Procure, Assemble and Operate) (National Institute of Building Sciences, 2015a)

However, in their scope document for the **NBIMS-US v3**, the National Institute of Building Sciences (2015) states that the standards are designed for two audiences; Software developers (vendors included), and for implementors (i.e. engineers, architects, owners etc.).

Various national standards too have been created, including the Common BIM Requirements 2012 (Senate Properties, 2012) in Finland, the Statsbygg BIM Manual Version 1.2.1 (Statsbygg, 2013) in Norway, Singapore BIM Guide Version 2.0 (Building and Construction Authority, 2013), and the NATSPEC National BIM Guide (NATSPEC, 2016) in Australia.

International standards **BS EN ISO 19650-1** and **BS EN ISO 19650-2** have been produced with the intent of creating a framework for information management. It has also been clearly stated in the related transition documents and guidelines by The British Standards Institution (2019) and the UK BIM Alliance (2019) that they supersede the **BS**

1192:2007 + A2:2016 and **PAS 1192-2:2013**. However, they collectively cover almost identical topics.

2.3 Process and decision management review

Following the conclusion that there is a need for processes to be clearly defined in order to ensure that there is a streamlining of the SMP, literature regarding technology and standards used to record and analyse workflows was studied. Therefore, this section of the review aims to answer the question below:

1. What research has already been carried out with regard to VDC/BIM and processes, and how were the processes modelled?
2. What are the standard modelling languages and tools that are used to map processes?
3. In what relevant domains has the chosen modelling method being implemented in?
4. What are the capabilities of the various tools?
5. Which tools are the most suitable for the purposes of the research?

Once the above questions have been answered and a suitable tool/set of tools had been established, it was important to establish an approach for implementation. It was important to establish:

1. How could the tools be linked to a BIM environment?
2. What will the architecture of the system be?

2.3.1 Existing research on processes and information exchange

2.3.1.1 What research has already been carried out in relation to VDC and processes, and how were they modelled?

As was observed by the likes of Kassem et al. (2011) and later by Bartley et al. (2016), that by being able to use diagrams with a known syntax and notation is a good alternative to prose when describing a system. They both used the Integration Definition for Functional Modelling (IDEF0) to model information flows. Bartley et al. (2016) chose this method, as it was considered to be an advantage as it does not have chronological continuity or sequence and does not assign specific roles. This approach was deemed to be advantageous as they believed that in highways projects, due to the varied nature of procurement and contexts it has the potential to be more effective.

There has been a great drive both in industry as well as in academia to combine the two domains to automate certain tasks within defined processes. In industry there has been the implementation of Robotic Process Automation (RPA) as described by Browne (2018), where the Hampshire County Council have used this technology to automate certain tasks. In the case of the Hampshire councils they use RPA to automate repeatable tasks that do not need human judgement, in their case was to handle and process claims arising from incidents in their highway's networks. Their initial analysis showed that they can automate 3 parts out of their 8-step claims process which showed that they had the potential save an estimated 200 days per annum in total.

García-Domínguez et al. (2012) observed that BPMN, which is a solution for bridging the gap between business process design and the implementation of those process, has gained a considerable following. They observed that at the time there were over 73 implementations by vendors, which has vastly increased in number since then. This notation and modelling standard is regulated by the Object Management Group (OMG) (2011) who have since then also released Decision Model and Notation (DMN) which complements the BPMN and can be used alongside it. The aim of DMN is to bridge the gap between business decision design and its implementation (Object Management Group (OMG), 2016).

Alreshidi et al. (2015) proposed a 'cloud-based BIM governance platform' where they used BPMN and UML (Unified Modeling Language) (Object Management Group, 2017) to do so. This platform which was named 'GovernBIM', was created with the aid of using BPMN to describe overall processes, activities and data flow. The UML was used to provide a detailed description of the platform's expected procedures, rules and activities. The results of this research included the processes that is be expected to be followed in relation to the proposed GovernBIM platform. Alreshidi et al. (2015) initially based the processes on the predicted capabilities and use cases for the platform. In their later work on the platform, Alreshidi et al. (2018) further explored the issues with industry experts where the findings showed there is an existing need to have a governance platform developed on top of cloud infrastructure to facilitate the handling of construction information.

Dimyadi (2016) explored the possibility of creating formalised executable workflows related to Compliant Design Procedures (CDP) to guide the automated audit of digital to models against local regulations. A client/server web application was developed using Microsoft SQL Server as an underlying database to store data. In the web application that was developed, the bpmn.io JavaScript library created by Camunda (2018) was used to render the workflows graphically.

Jallow et al. (2017) proposed a framework to help manage client requirements to improve the quality of built facilities and their related services. It was an enterprise architecture framework for electronic requirements information management where they propose the management of the content of documents rather than the conventional document-centric orientation to managing the information. It also proposed that a business process management (BPM) approach to managing processes activities to improve control and visibility.

2.3.1.2 What are the most common modelling languages to map processes?

Kopp et al. (2009) made a comparison of process modelling languages which included Business Process Execution Language (BPEL), Window Workflow Foundation (WF), Event-driven Process Chains (EPC), and Business Process Model and Notation (BPMN). This study anticipated the release of BPMN 2.0 by the Object Management Group (OMG) (2011) but showed that at the time of the study, BPEL was geared towards automated execution of process models while BPMN was mainly used for process documentation. However, since the publication of the BPMN 2.0 standards, studies such as those carried out by Geiger et al. (2015) and Dumas et al. (2018) have highlighted that a shortcoming of BPEL is that it does not provide visual notation as clearly as BPMN 2.0, and therefore BPEL is largely being replaced by BPMN 2.0. Weidlich et al. (2008) noted that there are challenges in mapping between the two standards and therefore a decision had to be made as to which standard was the most suitable.

Upon reviewing applications between Robotic Process Automation (RPA) and Business Process Management (BPM) tools, several differences between the two were observed. The main difference being that RPA was case specific and are configured to complete routine and repetitive tasks, however BPM tended to be able to be able to adapt to various software technologies and focuses on performing processes and does not entirely depend on automation.

Kasse et al. (2018) explored the compliance of BPMN, as it is a concern that regulatory requirements need to be set when working with control flows. However, in the case of the research carried out, the flow of information was to be project/network specific. Their work covered the concern over security, product and service quality and privacy. In future work carried out in this subject area, it is essential that these concerns are addressed.

Further, BPMN 2.0 works alongside decision modelling notations known as Decision Model and Notation (DMN) which is also manged by the Object Management Group (OMG) (2016). According to Janssens et al. (2016) prior to DMN, decisions in enterprise models were not considered to be a separate entity but were embedded within process models or in the form of knowledge models or ontologies. This was complex to maintain and therefore was not ideal as requirements were likely to be changed over time.

Janssens, Bazhenova, et al. (2016) carried out further research into understanding how DMN can be integrated with BPMN and suggested what are known as Decision Requirement Diagrams (DRD) which can consist of various types of elements such as decisions, input data, business knowledge models and knowledge sources. Then the second level to the above mentioned DRD is the declarative FEEL (Friendly Enough Expression Language) language which is used to describe the logic behind every decision (Camunda, 2018b). As DMN and BPMN are designed to complement each other, it is possible to then integrate this decision logic with processes similar to that as described by Debevoise and Taylor (2014).

The use of DMN has gained popularity in several fields including that of Blockchain where Haarmann et al. (2018) explored the blockchain process and the of decisions on blockchain. They explored the mapping of the FEEL language with contract-oriented programming language Solidity which was then to be run on the Ethereum blockchain. The intention was to be able to run decision models on a blockchain to ensure they can be audited, secured and are transparent.

Following the review of the most commonly used methods of modelling processes, and their various relevant applications, a decision was made that the BPMN 2.0 standards were to be used. This decision was made based on the ability to easily maintain and change processes as required. Also, the flexibility of using other types of notation such as DMN was deemed to be a strength in using BPMN 2.0.

2.3.2 Business Process Model and Notation (BPMN)

Prior to the release of BPMN 2.0 by the Object Management Group (OMG) (2011), BPMN and BPEL were used in conjunction as the former was a powerful tool to map processes while the latter was more useful for technical users. As was concluded in the review of the various process mapping tools, a decision was made that the BPMN standard should be used to map the processes for this research. However, to use the tool effectively it was important to identify previous applications of using this method, and what tools are suitable for this purpose. This sub-section will aim to answer the above questions.

1.1.1.1 Which relevant domains has the chosen modelling method being implemented in?

BPMN is used widely in various domains including supplementing Interaction Models used to create Information Delivery Manuals (IDM) (BuildingSMART International, 2010). The IDM standards were developed by buildingSMART in order to understand the type of information generated and processes implemented on construction projects in order to develop Industry Foundation Classes (IFC). IDM's used Interaction Models such as those proposed by Dietz (2006) and Hoogervorst (2018) were used to specify ontological transactions and the associated actor roles.

In order to control complex collaborative physical processes management, Grefen et al. (2018) analysed the possibility of integrating Business Process Management (BPM), the internet of things (IoT) and Distributed Analysis (DA). As shown in Figure 2-12 the authors suggest that a relationship between the three technologies have great potential. As observed by Grefen et al. (2018) and Mohammadi et al. (2018) is that there is a significant levels of research being carried out in linking decision making/Machine Learning (ML) with IoT.

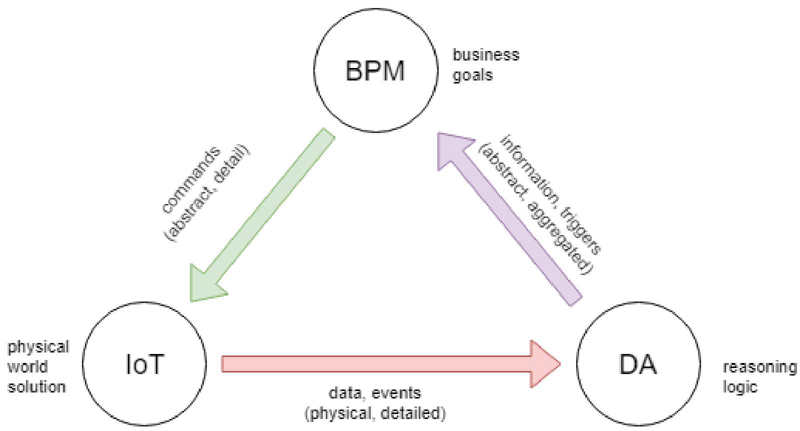


Figure 2-12 The expected interaction between BPM, IoT and DA according to Grefen et al. (2018)

With regard to the linking of BPM with IoT there has been significant work that has been carried out. Meyer et al. (2013) observed a lack of modelling concepts to represent sensors and actuators of the IoT and their native software components in a business process model. Meyer et al. (2015) has conducted work on attempting to tackle the issue of attempting to express things of the Internet as elements in a BPM. However, it was observed that the ML field is not strongly linked to the field of BPM. Studies such as those carried out by Tang et al., (2019) show that there is an increasing interest in integrating BIM with real-time data from the IoT. Given the potential that has already been identified between the three domains, it would be useful to explore the link between BPM and BIM.

*1.1.1.2 What tools can be used? And which **is** be the most suitable?*

Chinosi and Trombetta (2012) gave their initial observations as soon as the BPMN 2.0 standard was first introduced with its own native XML serialization which made it completely independent from languages such as WS-BPEL (Web Services Business Process Execution Language). They believed that there will be a slow transformation into BPMN as the standard for representing processes graphically.

Apart from the BPMN processes there are two other forms of standard notation that complement the BPMN standard. They are Decision Model and Notation (DMN) (Object Management Group (OMG), 2016) and Case Management Model and Notation (CMMN) (Object Management Group (OMG), 2014). DMN is a relatively recent standard but as observed by Figl et al. (2018) it is gaining vast popularity as it is heavily related to expressing decision logic.

The reason as to the decoupling of processes from decisions can been justified by the Separation of Concerns (SoC) practice in computer science, as referred to by Biard et al. (2015). Case management too is separate from processes and decisions as unlike workflows that specify what *should* be done, it specifies what *can* be done (Marin, 2016).

Dumas et al. (2018) defined Business Process Management Software (BPMS) as a system that supports the design, analysis, execution, and monitoring of business processes on the basis of explicit process models. The most comprehensive categorising and analysis of the spectrum of BPMS types was by Dumas (2013) who split the system into four main categories based on their functionality as shown in Figure 2-13.

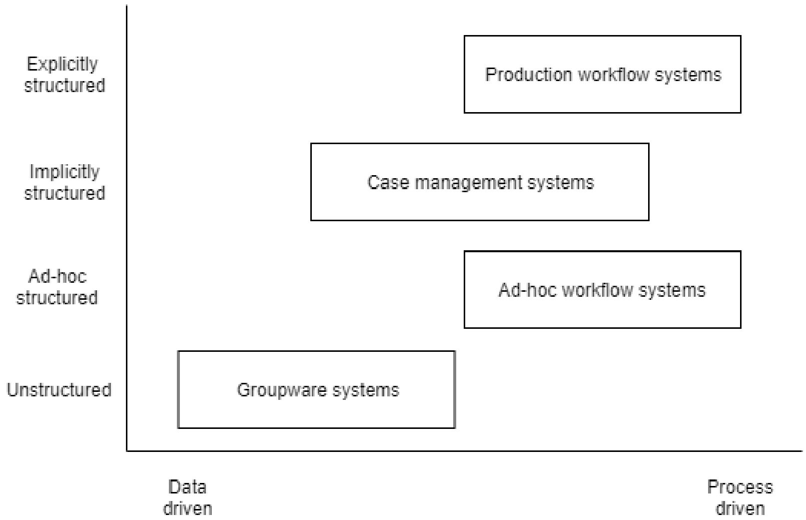


Figure 2-13 Types of BPMS according to Dumas (2013)

It will be essential to identify the various solutions that are available within these various categories for the implementation in the context construction information workflows. Table 2-6 shows the four categories that were defined by Dumas (2013) with additions of examples of systems reviewed as a part of this research. It has been noted that this technology and its standards are advancing rapidly and eventually a more updated version of the systems was produced by Dumas et al. (2018).

Given the aims of the research, the category of production workflow systems was explored in depth in relation to the other systems. There were several factors which were to be considered when reviewing the available tools which took into consideration whether the engines are open source, user friendly, had a useful modeller and have features such as processing DMN.

The review of the various solutions were influenced by work such as that carried out by Meidan et al. (2017) as they did a comprehensive analysis of some of the most popular opensource tools that were available at the time of review. The examples of tools that are given in the production workflow systems section in Table 2-6 were tested in order to identify the most suitable tool for the purposes of this research.

The rough testing carried out on these platforms showed that the Camunda BPM platform was the most suitable. An evaluation carried out by Meidan et al. (2017) which tested the modelling capabilities, design, monitoring and control, execution, and deployment of various opensource solutions revealed that the Camunda and jBPM software solutions were the most suitable for the purpose of the research.

System type	Description	System examples
Groupware systems	These systems are used to be able to easily share documents and directly communicate with other users. The strengths of these systems is that they provide high operational flexibility. The weaknesses are that these systems do not support business processes.	IBM Notes (IBM, 2018a)
Ad-hoc workflow systems	These are systems which have an initial set of process cases which can then be adopted as needed. Therefore, to ensure successful implementation of such system the users will be expected to have a relatively advanced understanding of how the tools work and have an understanding of the processes fully to deviate from the initial requirements.	TIBCO BusinessWorks (TIBCO, 2018) Comala Workflows (Comalatech, 2018)
Production workflow systems	This is the most prominent type of BPMS and this type of system does not allow deviation from the process and the underlying logic within the processes. Dumas (2013) further classified these system as either administrative or transaction processing where the former is where a large portion of the work is performed by people and the latter being for process that are almost fully automated.	Activiti (Activiti, 2016) Flowable (Flowable, 2016) Camunda BPM (Camunda, 2018c) Bizagi Studio (Bizagi, 2017) Signavio (Signavio, 2017) IBM Business Automation Workflow (IBM, 2018b) jBPM (jBPM, 2017) Bonitasoft BPM (Bonitasoft, 2017)
Case management systems	These systems are available for processes that are not completely specified. These systems are usually fully aware of the precise details of the data belonging to a case.	PEGA Case Management (PEGA, 2017) i-Sight (i-Sight, 2017)

Table 2-6 The 4 types of BPMS systems according to Dumas et al. (2018) with system examples which have been added over the course of the research carried out for this thesis

1.1.1.3 What will the architecture of the system be?

The findings made over the course of the literature review showed that there was a need to align BIM processes with existing constructor business processes. In order to align and then govern these processes, process management systems had to align with BIM environments. A high level architecture was presented by Goonetillake et al. (2018) where construction information models and process models will interact with each other. A decision was made that the BPMS will interact with external web applications as described in Figure 2-14.

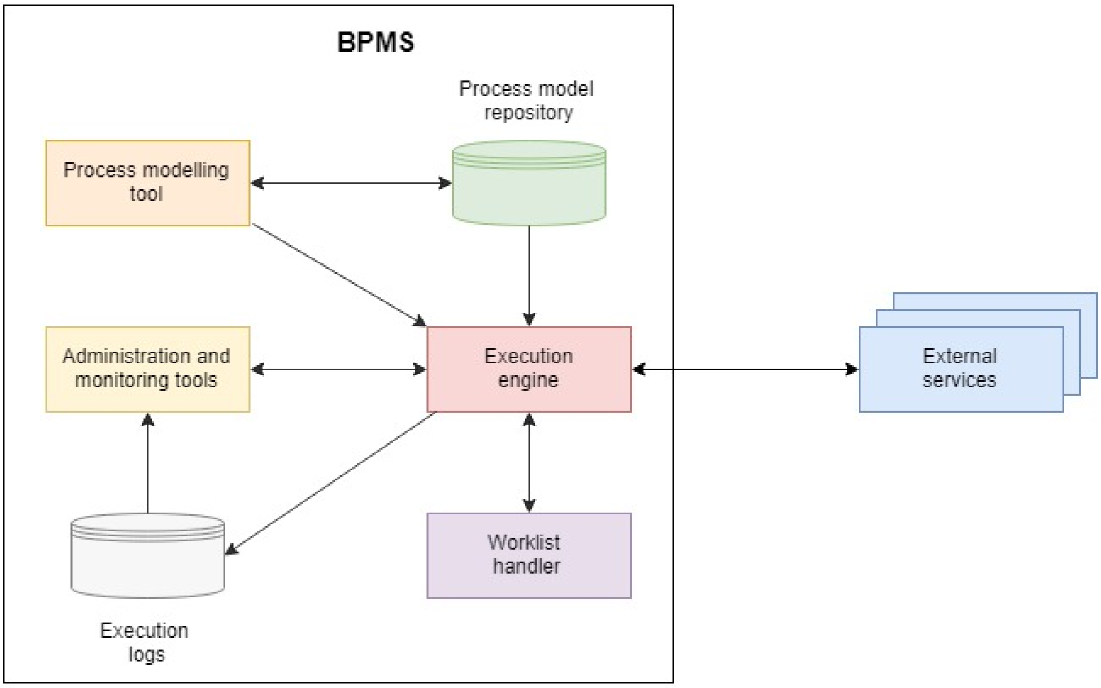


Figure 2-14 Architecture of a BPMS (Dumas, 2013)

Based on the manner that a BPMS interacts with external applications, a prototype system was developed at a later stage of the research. A detailed architecture of the BPMS and the application it interacted with has been described in Chapter 6.

2.4 Discussion and research gaps

The findings made during the literature review led to the formulation of the research hypothesis and questions that were presented in the introduction to the thesis.

2.4.1 Asset Information Management in linear infrastructure projects

The total road length in Great Britain was estimated to be 255,000 miles in 2015 (Department for Transport 2016). This was an increase of less than 0.1% from the previous year and only a 2.4% increase since 1995. The latest report (Department for Transport 2018) also shows that the change in the last two years was almost negligible. This shows a large expanse of road networks in the country, and even though they are split into several regions and managed separately, the individual networks within these regions can be considered large. These networks also reflect the above statistic which shows there is a relatively small amount of expansion within these networks.

To maintain these assets a large amount of data needs to be collected, stored and processed. If misinterpreted, the adherence to existing Digital Construction standards has the potential of producing large volumes of highly detailed construction information being collected and stored. This can be counterproductive to the asset managers as they will have to store, manage and query these large volumes of information to benefit from it.

Bartley et al. (2016) stated that most highways projects have paper-based systems even though they function electronically. An observation was made that there have been attempts to formalise document management via Electronic Document Management Systems (EDMS), but it had not become engrained still at the time of the study.

In a discussion with industry experts in the UK, Kenny (2017) showed that practitioners are now facing the challenge of 'information overload'. It is therefore extremely important to highlight which LOD is needed at each milestone as stated by Sacks, Gurevich, *et al.* (2016). Once the appropriate 'level of detail' of the information to be collected has been established, the next challenge is integrating this new construction information with existing asset information. The current standards also refer to certain interoperable file formats which tend to follow certain schemas, and information is generally structured based on these schemas. An observation was made that asset managers frequently find it unfeasible to integrate this new information into their existing systems without a certain amount of change, as it can be unfeasible to transform their existing asset information to fit into these new formats of information.

It is therefore important to establish how construction information can potentially be translated seamlessly into existing asset management systems. If this is not defined clearly, there generally can be a large volume of potentially useful information which will go to waste. An observation was made that certain parts of the standards can be abstract thus leading to the hesitancy in adopting them. The reason as to why the adoption of the BIM has been relatively slow especially on infrastructure projects can be attributed to this issue. Therefore, there is a need to understand the type and volume of information that is produced on infrastructure projects, and then analyse how they ideally should be produced in order to utilise this information effectively.

2.4.2 Alignment of digital construction processes

Arayici et al. (2011), Sebastian (2011) and Mom et al. (2014) all argued that the adoption of BIM requires the re-engineering of current construction processes. Significant progress has been made towards the adoption of digital construction processes by industry as the flow of construction information has been streamlined, and awareness has risen exponentially in the UK since the announcement of the mandate for the adoption of BIM that was set for April 2016. The National Building Specification (NBS) BIM Report (2018) shows the results of a survey carried out to assess current levels of adoption. In the survey, it was found that only 4% of respondents thought the government mandate was successful with 37% feeling that it was only quite successful. The results from this survey also reported that a majority of those professionals surveyed felt that the government was not doing enough to enforce and embed the process into their projects. Some of the specific barriers that were identified in the survey was, the lack of client demand, the lack of an established contractual framework for working with BIM and the lack of time to get up to speed with requirements. Similar observations will be made when implementing the SMP's on infrastructure projects as a part of this research project in Chapter 3.

Interoperable construction information schemas such as Industry Foundation Classes (IFC) (British Standards Institution 2016), and still have not been fully developed for infrastructure. As was stated in their annual report for 2017, buildingSMART had a project underway to simulate the adoption of the IFC Alignment standard (BuildingSMART International 2017) Which will then be used as a baseline for IFC Bridge and Road. There are several software vendors, such as Autodesk, Bentley, Nemetschek and Graphisoft, who are developing software solutions that will help structure construction information efficiently.

Creating a system that is platform neutral, is easy to use, and also enforces the exchange of information in a formal manner is important. It is also equally important to recognise that each organisation will have its own individual requirements and systems already in place, and therefore there needs to be a certain level of flexibility to enable them to adopt these new systems. Therefore, a conclusion was made that there is a need to analyse and develop a system where BIM processes can be aligned with existing processes and then be automated in order to control the flow of construction information.

2.5 Conclusion

The literature reviewed throughout this chapter highlighted that there is a need to align BIM/VDC processes with existing processes. In order to govern these processes, various tools were analysed to understand which tool is the most suitable for this research. This chapter led to the formulation of the research questions stated in Chapter 1, which were answered over the course of this research project. Chapter 3 will provide a breakdown of the chapters based on the research questions and the methodologies that were used in order to answer them.

Chapter 3 Methodology

This chapter will introduce the overarching methodology that was used when carrying out this research. An overview of the philosophical underpinnings will be given, followed by a detailed explanation of how each research question was approached. Finally, an overview of the chapters and the corresponding phases of this research will be provided.

3.1 Research design

In order to explain the philosophical underpinnings of this thesis, the research 'onion' (Figure 3-1) that was proposed by Saunders et al., (2016) was referred to explain the epistemological approach applied in the thesis. Each layer of the diagram factors the various stances taken when collecting and analysing the data in order to answer the research questions.

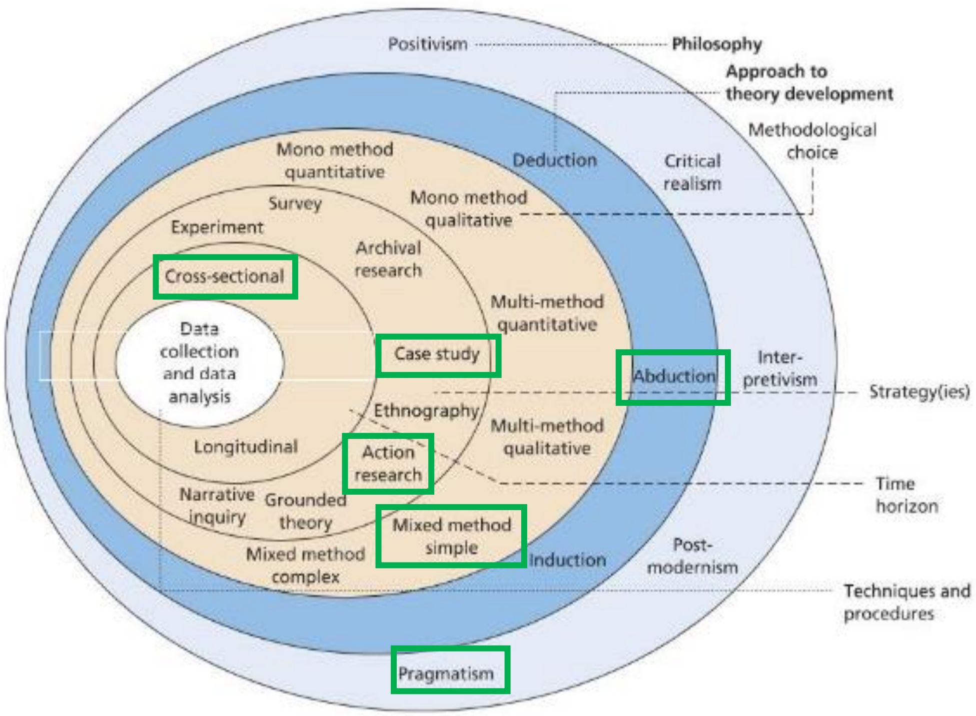


Figure 3-1 The 'Research Onion'

The *philosophy* of the research overlapped with more than one of the stances described in the diagram. The research that was carried out had an overlap between organisational processes and the implementation of ICT in the construction domain. The choice of philosophical stance overlapped in this thesis as the research aimed to analyse the state of the art and the information produced when implementing BIM on infrastructure projects in order to understand the impact both existing processes as well as the final outcomes. Due to the nature of the research focus, there was an overlap between the philosophical stances that were taken. The positivist philosophy helps develop a hypothesis based on observable phenomena and aims to giving an objective interpretation of the tests that are carried out. Therefore, hypotheses generated using this stance can be tested, verified through quantifiable data and can be replicated in order to generate the similar results. This stance generally leads to law-like generalisations, which can then be used to predict certain behaviours. Critical realism differs to positivism as critical realists' question existing theories with the belief that there are new methods that can be explored. In comparison an interpretivist approach leans towards qualitative studies. On the other hand, the philosophy of ***pragmatism*** recognises that a combination of a critical realist and interpretivist approach would be affective as it leads to approaching the research by analysing both quantitative results as well as qualitative.

The *theory* was developed using an abductive approach as it is a combination of deductive and inductive approaches. Deduction requires the formulation of hypotheses based on existing theories, testing this hypothesis to confirm or reject it before finally revising the theories if necessary. Induction involves the searching of patterns resulting from observations made on results. Based on these observations, theories will be developed and tested. ***Abduction*** was the chosen as this approach begins with an observation and then the formulation of a plausible theory based on this. The abductive approach therefore tends to use elements of both the deductive and inductive approaches. In order to disseminate this theory further and establish an approach to reaching the research objectives; the process discovery approach was used to identify particular processes (RQ 3) and the Design Science theory was used in order to develop and assess a potential solution (RQ 6).

The objective was to analyse the existing state of the art, critically review existing processes, developing a system, and then finally defining a framework based on the findings made. This required a combination of both quantitative and qualitative *methodological choices* in order to achieve the objectives set at the start of the research. Therefore, a decision was made that a ***mixed method*** was to be used when attempting to reach the objectives. This involved understanding domain specific processes and information requirements which involved the gathering of qualitative data. Then a system was to be developed that aimed to resolve some of the issues that were identified and could be tested against the initial findings.

A combination of *strategies* had to be used. In order to answer some of the research questions, there was a need to apply BIM on an infrastructure project as it was important to understand the way information is stored and used when managing assets. An Action Research strategy involves the direct engagement and collaboration with an organisation in order to diagnose problems in order to then take further action. Once the actions that needed to be taken were established via the use of the action research strategy, there was a need to explore methods to solve the identified problem. This was done by using a ***Case study***, an A***ction research*** strategy and Design Science similar to that done by Baskerville et al., (2009) and Sein et al., (2011). Table 3-1 shows a breakdown of the research questions and the research strategies used in order to start answering the questions. The details of the stages, and how each of the strategies were carried out have been discussed in more detail in the next two sub-sections.

Finally, when considering the *time horizon* of the research (Figure 3-1), it can be either cross-sectional or longitudinal. Longitudinal research involves repeated measurements of the same sample of population over a period of time. In contrast Cross-sectional studies occur at a single point in time. As the research focused on existing construction processes and the transformation of them, and each of the research stages were carried out at times, the research that was carried out was ***Cross-sectional***.

	Strategies	RQ 1: How is BIM/VDC implemented on linear infrastructure projects and what kind of information is generated during this process?	RQ 2: What are the main challenges that are faced when implementing BIM/VDC on this type of linear infrastructure project?	RQ 3: Upon identification of the main causes that hinder the adoption of BIM/VDC and affect the development of the Asset Information Model (AIM), how can current construction processes be redefined to alleviate these issues?	RQ 4: Can processes and information requirements that have been defined be automated, and what type of system can execute and govern these requirements?	RQ 5: Can the defined processes and system be adapted on an infrastructure project and what steps need to be taken to do so?
Eastern Bay Link	Case Study	X	X	X	-	-
Workshop series	Action Research (Process Discovery)	X	X	X	X	-
Technical development	Action Research (Design Science)	-	-	-	X	-
	Action Research	-	-	-	X	-
Validation		-	-	-	-	X

Table 3-1 Methodological choices

3.2 Research strategies

The challenge with the adoption of the BIM open standards in infrastructure is the large footprint of the projects. For example, as of 2017 it was estimated that there was 246,700 miles of road in Great Britain (Department for Transport, 2018). This road network will continue to expand, but also will need to be constantly maintained. It will prove to be challenging as well as unfeasible to integrate existing information of such expansive networks into the proposed BIM exchange formats within a short period of time. Along with this, the volume of data being generated throughout the lifecycle of the assets would prove to be challenging to manipulate and store.

Aligning existing construction processes with the BIM processes have proven to be challenging. In their reviews of the implementation of BIM on infrastructure projects, both Bradley et al., (2016) and Costin et al., (2018) had identified that there was a gap in the knowledge related to the alignment of business processes with the standards and technology related to BIM.

Bartley et al. (2016), and Mazairac and Beetz (2013) had observed that a large volume of construction information produced on projects was document based still. However, it was still unclear why this occurs, what the alternatives are, and whether any intervention is needed or not. In order to do so, a case s had to be taken as this helped answer the first two research questions. The expectation was to confirm that the problem areas identified in previous research still exists, but also to analyse a Project Information Model (PIM) and Asset Information Model (AIM) to understand the breakdown of the information produced. It was anticipated that this implementation and detailed breakdown of an information model will aid with the identification as to why information is produced in this manner, and what can be done by asset owners and managers to improve the quality of information handed over to them. Gathering a breakdown of a PIM, analysing the processes that were carried out when developing it, and recording the related problem areas were expected to help make comparisons with potential solutions that were to be presented at the latter stages of the research.

The answers to the first two research questions were then expected to influence the stance taken when analysing RQ 3. The outcomes of the initial implementation were to be compared with similar infrastructure projects in order to confirm the initial findings. This was expected to be done by consulting experts in a series of workshops, with the aim of understanding the flow of information over the lifecycle of assets. The aim was to map out generic workflows and exchange requirements as it would be useful to mitigate the issues faced on future projects. This stage was also expected to help with ensuring that the information that was collected during the case study represented the state of the art.

Once these processes and requirements were identified, addressing the next research question (RQ 4) was expected to help identify how the findings made when answering RQ 3 could be practically enforced on projects. In order to do so, a prototype system was to be developed which was ideally able to parse project specific processes and information requirements to enforce them when building and operating an asset. Answering RQ 5 helped test the findings that were made over the course of the research and was expected to present a practical solution to the problems that were identified at the initial stages of the research.

The research was therefore broken down into three main phases:

1. Implementation of BIM/VDC Standard method and procedure (SMP) – Initial analysis of the outcomes and information produced on large infrastructure projects.
2. Process discovery – Analysis of the processes currently implemented globally and the expected outcomes that are generally expected when implementing VDC on infrastructure projects.
3. System development – Technical development based on the findings made during implementation.

The three phases were expected to answer the 5 research questions, but also lead to the development of a framework that would allow users to replicate the work in order to set their own process and information requirements (Figure 3-2).

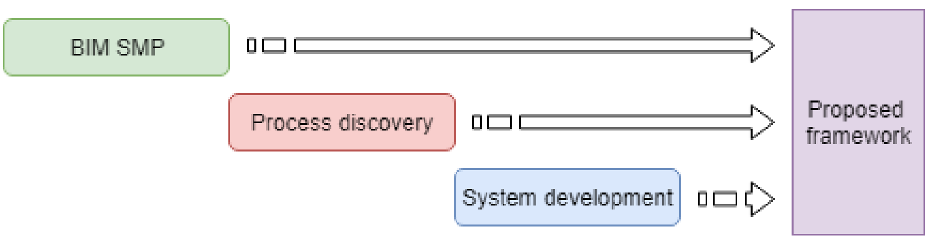


Figure 3-2 Three main themes that were addressed to formulate the framework

As was observed by Miettinen and Paavola (2014) there was a “BIM utopia”, where there is an assumption that the implementation of it in construction projects will lead to better collaboration, interoperability between tools, improved flow of information over the lifecycle of a project, and an increase in productivity. An observation was made by implementing the BIM/VDC process in industry that it was taken for granted that implementing BIM processes will always produce positive results. However, as was observed by Sackey et al. (2015), it is important to address the sociotechnical issues and it is important to recognise that alignment of new processes with the existing construction context can be challenging. Understanding the limitations of what VDC can achieve and the technological limitations needed to be considered. Therefore, an approach was taken to first critically analyse the current state of the art and propose a solution which has the potential to help aligning existing processes with those proposed by the new SMPs.

Sections 3.1.1, 3.1.2 and 3.1.4 discuss the main themes that were addressed over the course of the research which eventually led to the framework that has been developed as illustrated in Figure 3-2.

3.2.1 Phase 1 - BIM SMP

The SMP for BIM were analysed in depth in the literature review, and the interaction between the various standards were presented in Figure 2-10 (Literature Review). The next stage was to then implement these standards on a project to analyse the outcomes. It was also extremely beneficial to understand the outputs following implementation as this will provide in-depth details of how they can be improved on future projects. These outcomes were also useful to compare with the final solution that was to be presented at the end of the research.

The implementation of the SMP's on an infrastructure project was to support the findings made in the literature review and also to categorize the main problem areas that can be faced. The categorisation of these issues was beneficial as they can then be referred to in future projects to identify whether they are common issues faced in industry. The findings made on this project were presented to the asset owners and operators of the asset that was built. These findings were then further compared over a course of a series of workshops with industry experts.

The workshops that were planned for the latter stages of this phase were to be also used to identify the approaches taken on other projects and the manner in which the standards are interpreted based on specific asset management plans.

3.2.2 Phase 2 - Process discovery

Once the research gaps were identified and the main problem areas were categorised, workshops were arranged in order to define the manner in which processes can be identified and modelled. The research therefore moved towards engaging with other experts during the workshops and providing insight into the knowledge gained over the course of Phase 1 of the research.

The series of workshops which were organised with the assistance of industry partners in order to analyse the flow of information that takes place over the lifecycle of infrastructure assets (Highways and Airports). The main lessons learned during the implementation project in Phase 1 of the research were presented to the engineers and discussed. Then further discussions were carried out focusing on the types of information that is exchanged as well as the current processes that are implemented on various projects.

This phase explored how processes and information requirements can be recorded (discovered), and then transformed to align with new standards and technologies. This phase was expected to produce generic process maps, information requirements, and also a set of scenarios that are generally followed on infrastructure projects that implement BIM.

3.2.3 Phase 3 - System development and framework

This phase of the research was aimed at taking the knowledge gained during the first two phases of the research, and then propose a framework to implement this on other projects. This phase also involved a prototype of system linking structured construction information and processes to parse the information that was gained over the second phase of the research. The framework, and system that was proposed at this phase was to culminate towards being the most significant contribution of the thesis.

3.3 Techniques used at each stage

The previous sections outlined the 3 main phases of the research that were carried out, and the manner they were to build towards the body of knowledge. Figure 3-2 shows the main objectives of each project that was used for this research. This section will discuss the resources that were available to achieve the objectives that were set at the start of the research. It will also discuss the processes at each phase which answer the 5 research questions.

3.3.1 Implementation of SMP

This phase aimed to answer research questions 1 and 2; *How is BIM/VDC implemented on linear infrastructure and what kind of information is generated? Then, once these standards are implemented what are the main challenges that are faced?*

The methodology was formulated based on the literature review that was carried out at the initial stages of the research. Following the establishment of the various steps that were needed to be taken, a linear infrastructure project where the relevant standards were to be implemented was used to complete the first phase (BIM SMP, Figure 3-3). The project had to comply with the BS 1192 series of standards and other supporting documents as well as have an EIR with a corresponding BEP created. A commercial Common Data Environment (CDE) was used with access given to project participants along with basic training as required.

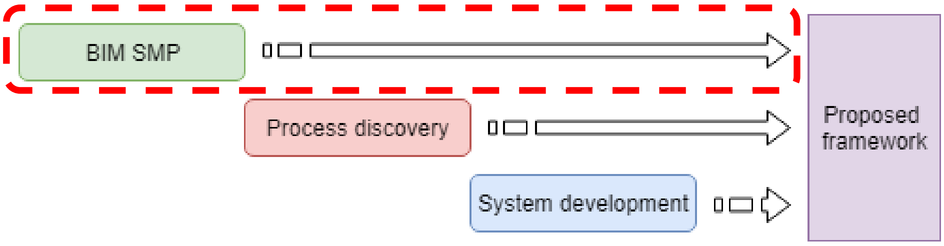


Figure 3-3 Phase that was covered during the initial implementation

This project was expected to answer research question 1; as it gave an insight into how standards are interpreted and the issues that are faced during implementation. The expected outcome of answering this question was to identify overarching problems that are faced when implementing VDC processes on a project, but also to analyse the outcomes of a project that has implemented them on a project.

Having a breakdown of the type and volume of information produced was useful, as it was not possible to find an accurate breakdown of an AIM or PIM in the literature. This information was expected to aid understanding how further improvements can be made to create a more robust AIM, and how the information should ideally have been represented. To confirm these findings that were made, a series of workshops with industry partners were set up to confirm that the information collected during the initial project represented the state of the art. This was expected to answer research question 2 and confirm the findings.

Given the findings of the literature review, issues in terms of the ambiguity of the current as well as the lack of maturity of existing technology was anticipated. The next two major phases of the research were formulated in anticipation of the possible challenges that can be faced when implementing this phase of the research.

3.3.2 Process discovery

This phase was executed when the initial implementation had been completed, and was to answer research question 3; *Upon identification of the main causes that hinder the adoption of BIM/VDC and affect the development of the AIM, how can current construction processes be redefined to alleviate these issues?*

This step focused on construction processes and the recording of them in a standardised manner (Figure 3-4). The aim was to confirm that the results from the initial implementation but also to then identify generic processes that occur when collecting asset information. This stage was also important to identify various common scenarios that could occur when implementing the standards.

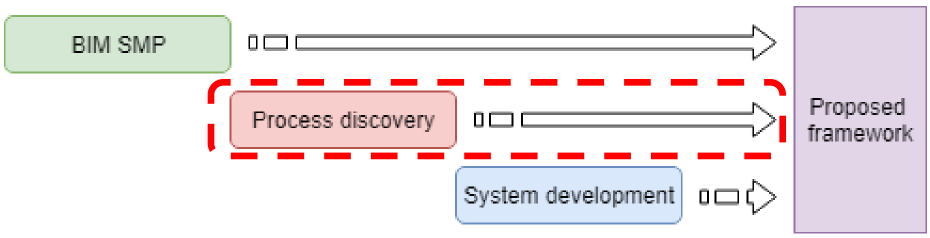


Figure 3-4 Process discovery phase

The identification of common scenarios and the recording of processes were to help with recognising how processes can be transformed to adopt new SMP's and technology. The aim was to also explore the possible strategies that can be used to identify processes and record them. The next two subsections discuss the methods that were taken into consideration when implementing this phase.

3.3.2.1 Process modelling

According to Dumas (2013) and Dumas et al. (2018) a BPMN model can be characterised by three properties:

1. Mapping – Mapping a real-world phenomenon and modelling the object
2. Abstraction – It will only document the relevant aspects of the subject
3. Purpose – Based on the purpose of the mapping certain elements can be omitted

There are two main purposes when modelling processes which are organisational design and application system design. *Organisational designs* are conceptual in nature and are there to allow people from a non-technical background to understand. As a result, details such as data types, mappings or system interfaces have to be defined. *Application system designs* are more IT related and can be executed on process engines. Freund and Rücker (2016) proposed a similar system where high-level strategic process maps can be created, and then based on these maps, human and technical process flows were to be identified. They observed that it is necessary to define human process flows and technical processes as this helped with the identification of tasks that can be automated by the process engine.

The BS ISO/IEC 19510:2013 (2013) was followed when mapping BPMN 2.0. The basic elements that will be used when mapping processes in this research will be 'events' (start and end events), 'activities' (task boxes), and 'gateways' (to control the divergence and convergence of sequence flows). Each of these elements will be connected by 'flow objects' (arrows) in order to illustrate the sequence of tasks. All the processes were mapped from left to right, beginning with a start event, then having tasks and gateways to describe the processes and then finishing with an end event. In order to highlight the exchange of data, 'data objects' can linked to the tasks.

To distinguish participants in a BPMN process, 'pools' and 'lanes' are used. According to the standards, a pool is a graphical representation of participants in a collaborative process. Lanes generally are sub-partitions of the pools and are useful to organise and categorise certain activities within a pool. In the context of this research, pools were used to distinguish organisations, and the lanes within them represented specific roles within the organisations.

As a result, an initial strategic process map was to be created for the purpose of allowing all participants to get a broad understanding of the information exchange process. This strategic process map was then to be used to create technical and human process flows which will then be used as a formal representation of the processes that should be used.

3.3.2.2 Process discovery methods

When gathering information about processes, it is important to identify the methods in which this can be done and understand their capabilities. Dumas et al., (2018) had carried out a comprehensive analysis of the methods for process discovery. They were:

1. Evidence based discovery – Typically involves studying how an existing process works by either analysing related documents or by making observations
2. Workshop based discovery – Having a series of workshops with domain experts to get a deep understanding of the processes
3. Interview based discovery – Interview experts to understand how processes are executed

Table 3-2 shows the comparison of the various methods according to Dumas et al. (2018). A decision was made that the latter two methods were the most suitable for the purpose of the research as it was anticipated that they will be the most useful for recording project specific processes. It was also anticipated that the combination of workshops and then interviews will negate the relative lack of objectivity in these methods. There were a confirmed set of milestones that were set in advance and therefore time consumption was not considered to be a defining factor for this research.

Aspect	***Evidence-based***	***Workshops***	***Interviews***
Objectivity	*High*	*Medium-high*	*Medium-high*
Richness	*Medium*	*High*	*High*
Time consumption	*Low-medium*	*Medium*	*Medium*
Immediacy of feedback	*Low*	*High*	*High*

Table 3-2 Relative strengths and weaknesses of discovery methods (Dumas et al., 2018)

As a result, a combination or workshops and then interviews were used as they were considered to be the most suitable methods for this research. Once the human and technical process flows were identified, a system was to be developed in order to parse the technical process maps that were defined, and then link them to a BIM environment. As a result, a methodology had to be formulated to aid the development of this system as discussed in Section 3.2.3.

3.3.3 Design Science methodology and framework

Chapter 6 and 7 will cover the third phase of the research and answer research questions 4 and 5; *Can processes and information requirements that have been defined be automated and what type of system would be able to execute and govern these processes? And can the defined processes and system be adapted on an infrastructure project and what steps need to be taken to do so?*

These two research questions were asked simultaneously as the process that was used to define this phase was iterative and eventually led to the proposal for the framework (Figure 3-5). As a result, Chapter 6 covered the technical developments of the research while Chapter 7 focuses on the processes and validation of the framework.

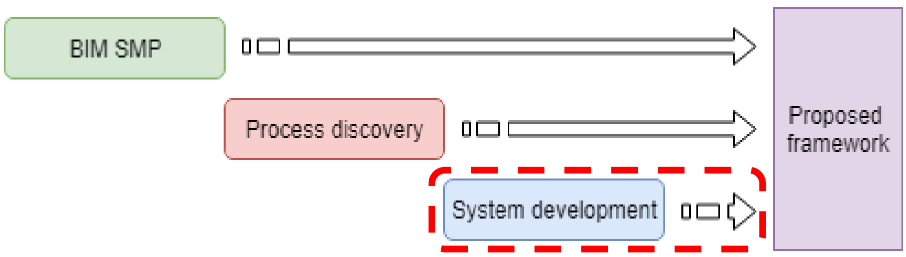


Figure 3-5 System and framework development phase

Apart from the input from the previous stages, experts involved in an infrastructure project were consulted to ensure that project specific requirements are recorded and aid the development of the system.

van Aken (2004) suggested a methodology defined as design sciences whose ultimate objective is to develop valid and reliable knowledge to be used in designing solutions to problems. Therefore, the aim of this methodology is to develop knowledge that can be used in designing solutions to problems in the field in question. As observed by Hevner et al. (2004), Design Science (DS) creates and evaluates IT artefacts intended to solve identified organisational problems.

Peffers et al. (2007) recommended a process for the effective undertaking of the Design Science (DS) methodology, which has been broken down into relevant stages, actions, and sources of information as shown in Figure 3-6.

The process proposed by Peffers et al. (2007) was a result of previous influential work that had been carried out on Design Science. For *Stage 1,* an observation was made that studies such as those carried out by Nunamaker et al. (1990) and Walls et al. (1992) emphasized theoretical bases, while engineering researchers such as Eekels and Roozenburg (1991) and Archer (1984) had focused on more applied problems. Then Takeda et al. (1990) had suggested enumeration while need identification had been suggested by Rossi and Sein (2003). Then they had evaluated the work carried out by Hevner et al. (2004) on Design Science research.

Stage 2 involved the definition of objectives for the solution of the problem identified in Stage 1. Some researchers focused on transforming the defined problem into system objectives. Walls et al. (1992) referred to these as 'meta-requirements' and Eekels and Roozenburg (1991) referred to these as 'requirements'. However it was observed that researchers such as Archer (1984) treated this almost as an outcome of defining the problem. It had been deduced that it was necessary to differentiate stage 1 from stage 2, as it is important to ensure that the performance of the solution could be determined.

Stage 3 focused on the design and development of the system, which is the core of DS. An observation was made that all the above mentioned authors focused on this stage, with some breaking this stage into smaller activities and others such as Hevner et al. (2004) who define this as an 'iterative and incremental activity'. Hevner et al. (2004) suggested an iterative process for the DS method which was useful for tackling this research problem. Therefore, an iterative process has been added to this approach as shown from Stage 2 to 5 in in Figure 3-6.

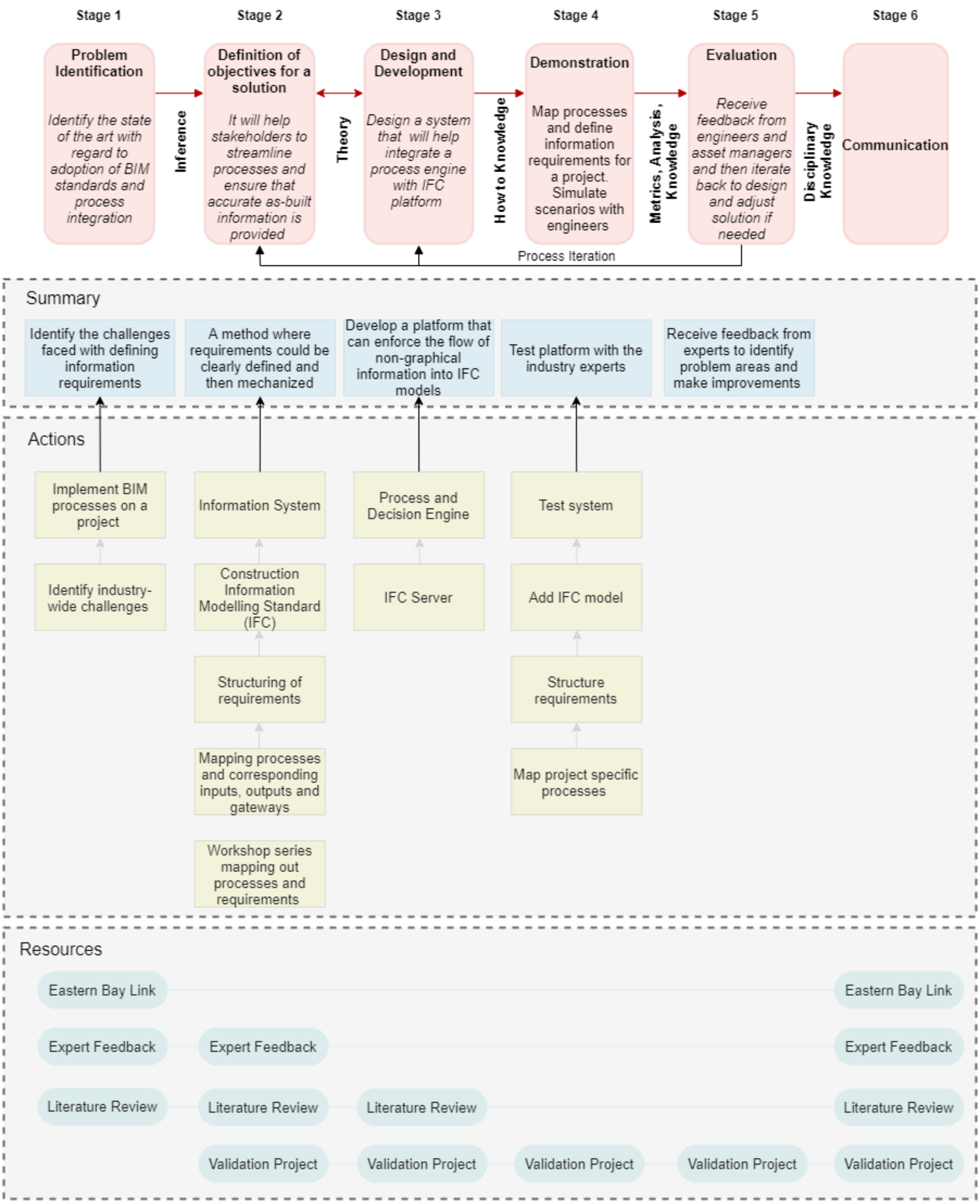


Figure 3-6 Summary of the Design Science approach used for this research

For *Stage 4* and *Stage 5*, Nunamaker et al. (1990) considered the testing and evaluation to be one phase which then should be considered as a component of the evolution of the development phase (Stage 3) similar to that as Walls et al. (1992). Vaishnavi et al. (2004) and (2017) in their ongoing review of Design Science (DS) research in Information Systems have come to a similar conclusion where these two stages are closely interlinked. A decision was made that these two stages would closely follow each other, but should also be distinguishable from one another as prescribed by Peffers et al. (2007) as this helps identify the changes with more clarity.

In the construction domain, this methodology has been used previously to solve a varying range of challenges. For example Raju and Ahmed (2016) developed an ontology-driven learning object repository for construction by following this method. Another example is that of Ding et al. (2017) who developed an IFC based quality monitoring and control system. A decision was made that using the DS method when developing the system is the most suitable given the expected aims of the research.

3.4 Conclusion

The core methodology used to conduct this research project has been outlined in this chapter. First, the main phases of the research were identified along with the objectives for each of them. Then the research questions were referred to stating at which phase each of those with be answered and what type of techniques were used to answer the question and test the initial hypothesis. Based on the findings made, a framework was developed to aid project engineers identify information requirements and align processes in order to meet the. The framework was developed to aid the analysis of project specific requirements which then leads to the establishment of project specific processes, information and system requirements. Implementing this will lead to the creation of a system where these processes can be executed over the lifecycle of a project based on bespoke information requirements.

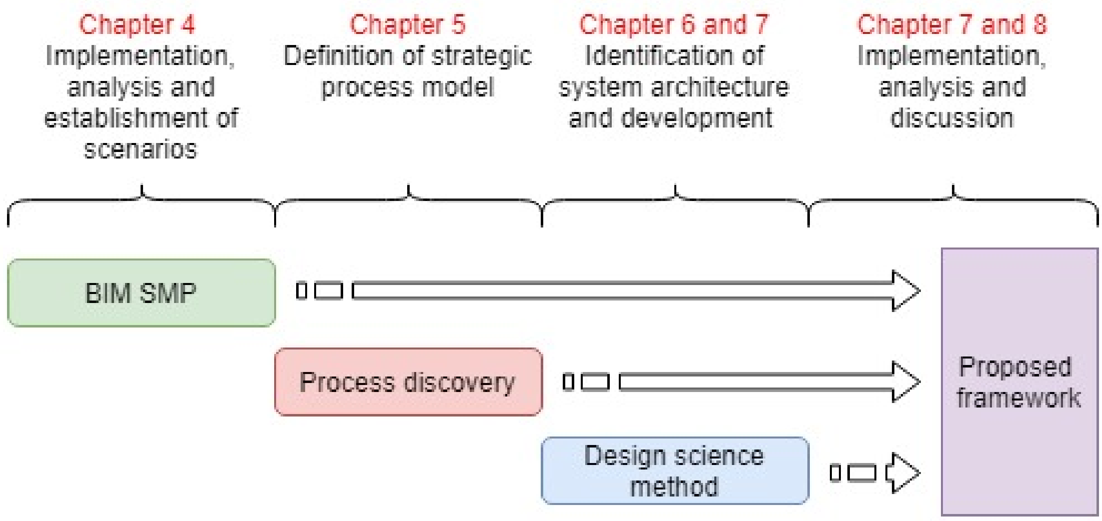


Figure 3-7 The stages lead to the formulation and testing of the framework to be proposed

The main phases of the research along with the chapters that will cover then have been given in Figure 3-7. The design science method was implemented in chapter 6 and then a framework was formulated in the following chapter which will help users define system and information requirements as well as processes. The framework was tested on a project in order to validate it and produce what can be defined as a digital plan of work such as that discussed in Section 2.2.2.6. The expected outcome of the research is to present the state of the art, propose a framework, and present a protype digital plan of work (DPoW) which will be able to parse processes and information requirements that are added to it.

Chapter 4 Initial implementation – Eastern Bay Link

As discussed in the methodology chapter the first phase of the research involved the implementation of BIM/VDC (Virtual Design and Construction) on a linear infrastructure project according to the standard method and procedures of implementing BIM. This chapter will outline the approach that was taken and the interpretation of the standards during implementation. It will then present the outcomes and the information that was gathered to create the Asset Information Model (AIM). The aim of this stage of the research was to implement and analyse existing processes and identify how Employers Information Requirements (EIR), BIM Execution Plans (BEP) and other related documentation will influence projects. The outcomes expected to help identify problem areas, identify what issues may occur when implementing BIM processes, and the information that is produced currently on large infrastructure projects.

4.1 Revisiting the research questions

This chapter aims to address research questions 1 and 2 of this thesis:

How is BIM/VDC implemented on linear infrastructure projects and what kind of information is generated during this process? And

What are the main challenges that are faced when implementing VDC on this type of linear infrastructure project?

The first question will be answered by the formulation of a strategy and implementing it on the highways project; the Eastern Bay Link (EBL). The strategy presented will be based on the guidelines given in the BIM standards and protocols, the outcomes will then be presented and analysed. To answer this research question, the industry partners were advised as to how the BIM processes were to be implemented. Prior to construction, the implementation plan was approved by all the project stakeholders to ensure that the processes that were proposed as a part of the research complied with existing standards and did not hinder construction. The Project/Asset Information Model (PIM/AIM) produced as a result of this was also expected to be used as a comparison to the final outputs of this research.

Question 2 will be answered by analysing the lessons learned during implementation and attempting to categorise them based on the areas of the framework they can potentially affect. To validate the results of this chapter, the information produced will compared to other projects in the next phase of the research.

4.2 Project outline

Construction on the Eastern Bay Link (EBL) commenced in early 2016 and the link road was opened in June 2017 in the Cardiff Bay area to improve access to the Cardiff Bay and the Enterprise Zone. The project once complete was to link the A4232 at the Queensgate roundabout with the Ocean Way roundabout as shown in Figure 4-1.

The link road cost £57.3 million according to the Welsh Government (2017), where the main contractors were the Dawnus Ferrovial Agroman Joint Venture (DFAJV). It had an Early Contractor Involvement (ECI) contract which was split into two stages with a lead designer and specialist bridge designer who were involved. The link road is 1.2km long which consists of a composite 700m long viaduct which crosses the dock in that area. The viaduct itself had two concrete sections with the composite section crossing a railway line running within the dock area. It was required by the asset owner that the industry BIM standards at the time were adhered to.

Figure 4-1 The footprint of the Eastern Bay Link in the Cardiff Bay area (image taken from article by the British Broadcasting Corporation (2017)*)*

4.3 Project requirements and standards implemented

The design was to comply with the standards and advice notes contained in the Design Manual for Roads and Bridges (DMRB) and included the Local Council's design standards as applicable. One of the requirements was that the BS 1192 suite of standards and guidelines were adhered to, to coincide with the mandate set for the implementation of 'BIM Level 2' in the UK. The standards that were used for this project is summarised in Table 4-1.

At the time of the project, the BS 1192 suite of standards, the BIM protocol (1st edition), and documents such as the Government Soft Landings and other related standards were referred to. The literature review and the next few chapters will also consider the ISO 19650 and the 2nd edition of the BIM Protocol by the Construction Industry Council (2018) and compare the differences.

Reference	Title
BS 1192:2007+A2:2016 (2016)	Collaborative production of architectural, engineering and construction information – Code of practice
BIP2207 (2010)	Standard Framework and Guide to BS 1192
PAS 1192-2:2013 (2013)	Specification for Information Management for the capital/delivery phase of construction projects using building information modelling
PAS 1192-3:2014 (2014)	Specification for Information Management for the operational phase of assets using building information modelling
PAS 1192-5-2015 (2015)	Specification for security-minded building information modelling, digital built environments and smart asset management
Building Information Model (BIM) Protocol - first edition (Construction Industry Council, 2013b)	Standard Protocol for use in projects using Building Information Models
Government Soft Landings (Cabinet Office, 2015)	BIM soft landings - Cabinet Office

Table 4-1 Main standards, guidelines and protocol used for the project

4.4 Implementation strategy

Based on the project outline and the requirements that were set, a suitable methodology had to be set to ensure that the requirements were met, the standards were adhered, and the benefits of implementation were realised. The framework and guide to the BS 1192 (BIP2207, 2010) was used along with the RIBA plan of work guide for information exchanges (Fairhead, 2015) to initially set up the processes.

The information delivery cycle described in the PAS 1192:2 is shown in Figure 4-2, along with its corresponding construction stages. At the initial stages of the project, an Employers Information Requirements (EIR) was produced (Capex start in Figure 4-2), which sets the information requirements during for the project.

In response to this EIR, a BIM Execution Plan (BEP) was produced to ensure that the information requirements were met. The BEP also included a Master Information

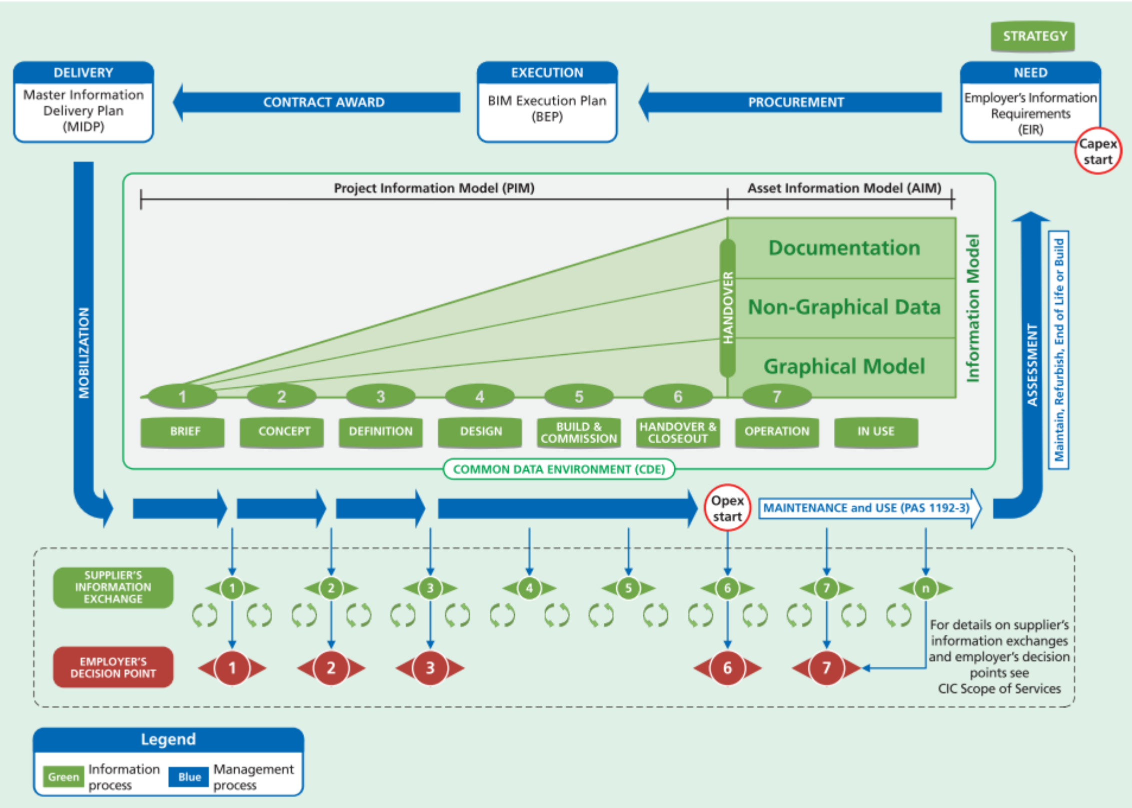


Figure 4-2 Phases of asset lifecycles covered by the PAS 1192:2 in accordance to the PAS 1192:2

Delivery Plan (MIDP) which is a table stating the various drawings that were expected to be produced over the course of the project. It was essential that the MIDP was setup at the early stages of the project, but it was extremely important that it was aligned with the project program to ensure that the information was delivered on time.

There were several areas that had to be covered to ensure the successful implementation of Virtual Design and Construction (VDC) on the project. The areas were; the initial establishment of a method of controlling construction information, the creation of graphical and non-graphical information, and then handing over the information to the asset operator and owner.

4.4.1 Information management

The information that was produced over the course of the project had to be shared on a platform that had the capability of sharing information, publishing the information as required and then finally archiving it as required. The BIP2207 (2010) which is a standard framework and guide to adopting the BS1192 produced by the British Standards Institute (BSI) was used to ensure that the information was exchanged in accordance to the standards.

4.4.1.1 Common Data Environment

A Common Data Environment (CDE) had to be set up to ensure that there was a common platform in which all the project information was to be shared on. Viewpoint 4Projects (2018) was used as a project CDE and was set up as required. The designers used the workflow as described in the standards; first the information had to be first developed between various disciplines in Work In Progress (WIP) folders. Then the verified design data had to be shared with the project team once the lead designer had reviewed and approved the design.

The asset owners/operators were expected to access the shared folder to check and sign off the design information. This information should have been then transferred in packages as agreed upon in the MIDP. This information was then to be sent in a published documentation folder which contained the information that was accessible to the whole project team.

The published information had to be labelled based on their purpose (e.g. Tender, costing, contractor design, fabrication, for construction or as built). Once the asset had been built and the information was remeasured and verified as built, it was stored in an archived section which included information such as; as built drawings, as constructed models, asset data, operation and maintenance manuals, H&S files etc.

4.4.1.2 Information management

The information that was published on the CDE had to be controlled to ensure that the information that published was current and had a reliable audit trail. Due to the scale of the project, the number of suppliers was vast and therefore the information that was produced had to be controlled to ensure that information produced was consistent.

The CDE itself did not have the capability of being set-up to produce relevant meta-data for individual files automatically. Therefore, the information from the various suppliers was to be given to a document controller with a register that produced unique asset identifiers based on the type of information within the document. This information then was published in the appropriate container as required.

A specific file naming convention was not defined by the asset owners and therefore the naming conventions prescribed by the BS 1192 as well and the Interim Advice Note (IAN) 184/14 by Highways Agency (2014) was used to produce the file identifiers. The unique identifier was produced by combining:

[Project]-[Originator]-[Volume]-[Location]-[Type]-[Role]-[Number]

Where the 'Project' was an acronym for the projects name, the 'Originator' the name of the organisation producing the file, and 'Volume' was the type of asset, for example structures or even temporary works. The 'Location' was the section of the project the information was produced for, the 'Type' ranged from drawings to an early warning document and finally, the 'Role' of the originator of the document and the identifier ended with a unique numeric ID for that document.

An asset register which was able to generate these unique identifiers was created to ensure that there was no duplication of identifiers as the codes were generated within it. The unique code that was created on the register was to be copied into the file metadata.

Other than for the ID at the end, all the other fields had specific acronyms which were defined in the BEP. A schedule was created which allowed the document controller to the fields and create an ID based on the selected fields. The program then generated a unique code which was copied and pasted when uploading the files onto the CDE to ensure that there were no inconsistencies.

The designers were given the responsibility of uploading and sharing their information from within their designated area in the CDE or equivalent. The CDE had the capacity of keeping tracking of versioning, dates, times, approval statuses and several other fields of metadata.

4.4.2 Graphical and non-graphical information

First, the possibility of using standards such as Industry Foundation Classes (IFC) was explored. However, a decision was made that the use of IFC's and its Model View Definitions (MVD) was not feasible to use on the project. Further, the asset owners had not set a requirement for the delivery of information in this format therefore a decision was made to use proprietary file formats to produce graphical asset information.

Model authoring tools had to be established to ensure that the designs of various parties were aligned, and the various disciplines would be able to communicate with each other. The roads were modelled using Autodesk Civil 3D (Autodesk, 2018a), Autodesk Revit (Autodesk, 2018b) for the structural elements, and AutoCAD (Autodesk, 2018c) for 2D drawings and a certain part of the structure. Autodesk Navisworks (Autodesk, 2018d) was used to federate the various models and coordinate between the various disciplines to ensure that clashes did not occur. Navisworks was also ultimately used to embed data within the 3D geometry as required.

These authoring tools had specific functions depending on a country's standards, for example Civil 3D had its own country kit for the United Kingdom and Ireland, which can help define elements exactly according to the standards. The expectation was that the designers produced 3D coordination models on Revit and Civil 3D which would first be clash checked on Navisworks before being exported in the required manner to be used by engineers on site.

Certain suppliers had the capability of producing 3D models of the products that were to be installed. As a result, certain elements such as bridge bearings and bridge expansion joints were modelled by suppliers and were handed over as as-built models as shown in (Figure 4-3).

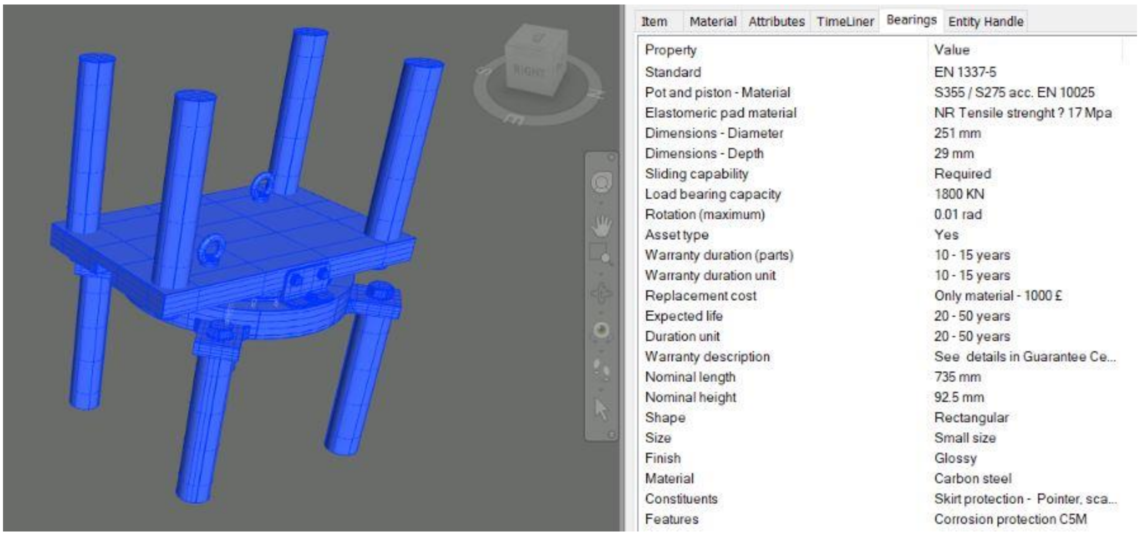


Figure 4-3 A model of bridge bearing that was used along with embedded information taken from Product Data Sheets (PDS)

Further, the National Building Specification (NBS), (2018b) has a BIM object library and they also have a tool, NBS Chorus (National Building Specification (NBS), 2018c), which synchronises specifications to aid collaboration. However, these tools were not well suited for infrastructure projects at the time of implementation and the technology had not matured enough to author graphical information using these libraries.

4.4.3 Product Data Template (PDT)

Apart from collecting documentation from suppliers, it was important that, where required, non-graphical information was collected in a machine-readable file format. Certain asset operators would have their own object libraries or Product Data Templates (PDT) which can help enforce the recording of accurate non-graphical information. Organisations such as the National Building Survey (NBS) (National Building Specification (NBS), 2015b) and the Chartered Institution of Building Services Engineers (CIBSE) (The Chartered Institution of Building Services Engineers (CIBSE), 2016) have generic PDT's that are freely available.

	2	4	4	4	4	4
Reference	**Description**	**Manufacturer**	**Standard**	**Pot and piston - Material**	**Pot and piston - Corrosion protection**	**Elastomeric pad r**
ModelReference	Description	Manufacturer	Standard	PotAndPistonMaterial	PotAndPistonCorrosionProtection	ElastomericPadMa
A reference for the system or product	*A description of the type of object to detail any design intent.*	*The Manufacturer of the Pot bearings.*	*An example value being To BS EN 1337-5.*	*An example value being Carbon steel.*	*An example value being To BS EN 1337-9.*	*An example value Natural rubber (NR*

Figure 4-4 A screenshot of some of the fields from a template for the bridge bearing

Commercial solutions exist which provides users with an easy to use graphical user interface and have an asset database. However, templates such as those by the NBS are in spreadsheet format Figure 4-4 with a series of fields which are expected to be filled by the suppliers. This information can then be embedded within the models and therefore provide users with a more accurate as-built representation of the asset.

4.4.4 Extraction of as-built information

At handover, the expected outcome was that the requirements that were given in the EIR documentation will be met which will help transform the Project Information Model (PIM) into an Asset Information Model (AIM). The AIM was expected to be a collection of graphical and non-graphical information that represents the as-built asset and can be handed over as a part of the Health and Safety files at the end of the projects. Due to the asset management systems that the information was to be integrated into, the information that was to be handed over were primarily in a file format.

4.5 Processes

There were a series of processes that were expected to be carried out when creating, sharing and then gathering information generated for the project. This section will outline certain processes that were to occur over the course of the project to ensure that information was shared as appropriate. The challenges faced when attempting to implement these processes will be then discussed in Section 4.6. These processes were added into the BIM Execution Plan for the project, and therefore they were followed over the course of the project. They were developed based on existing processes while factoring in the BIM standards, and the Common Data Environment that were used for the project.

4.5.1 Document control on site

The manner in which information that was produced on site was recorded and uploaded into the CDE had to be established. This process had to be established at an early stage to ensure that the naming convention mentioned in Section 4.4.1.2 was followed. The process as shown in Figure 4-5 was established and the document controller and the engineers were notified of the procedure.

Most of the information had to be produced in document format as that was the most suitable option given the information requirements. As was mentioned in Section 4.4.1.2, the information that was published on the CDE was sent through a document controller who ensured that it was placed in an appropriate location.

4.5.2 Design documentation and scheduling

Figure 4-7 and Figure 4-8 show the design documentation and mobilization processes. Figure 4-6 is the process that was to be used when creating the 4D schedules. The models that were produced by the designers were to be used to visualise and aid the creation of construction schedules. It was critical that models that were produced by the designers were accurate to ensure that the schedules that were created were reliable.

Over the course of the project, the level of detail of the graphical model proved to make the implementation of 4D challenging. As highly detailed 3D models were not created, apart from a few instances, it was more suitable to not depend on them for the scheduling.

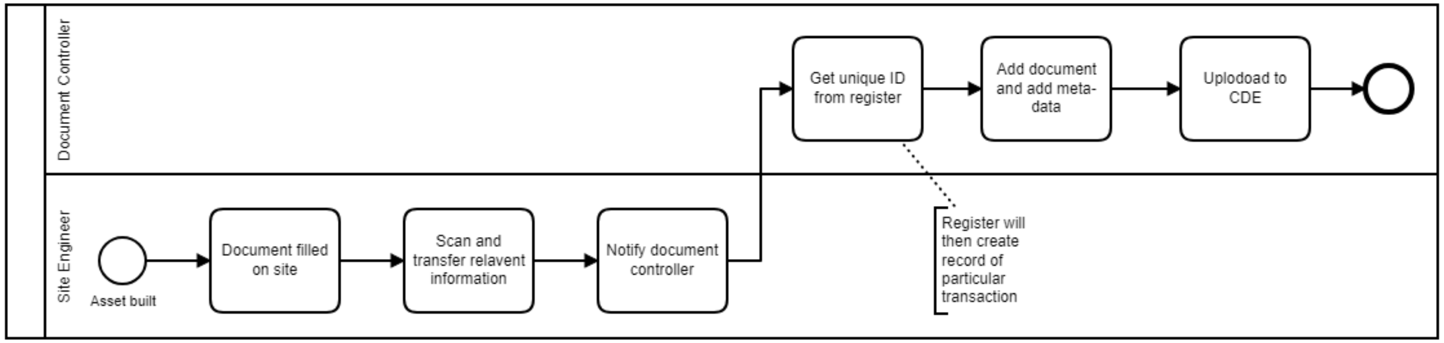


Figure 4-5 Document control on site

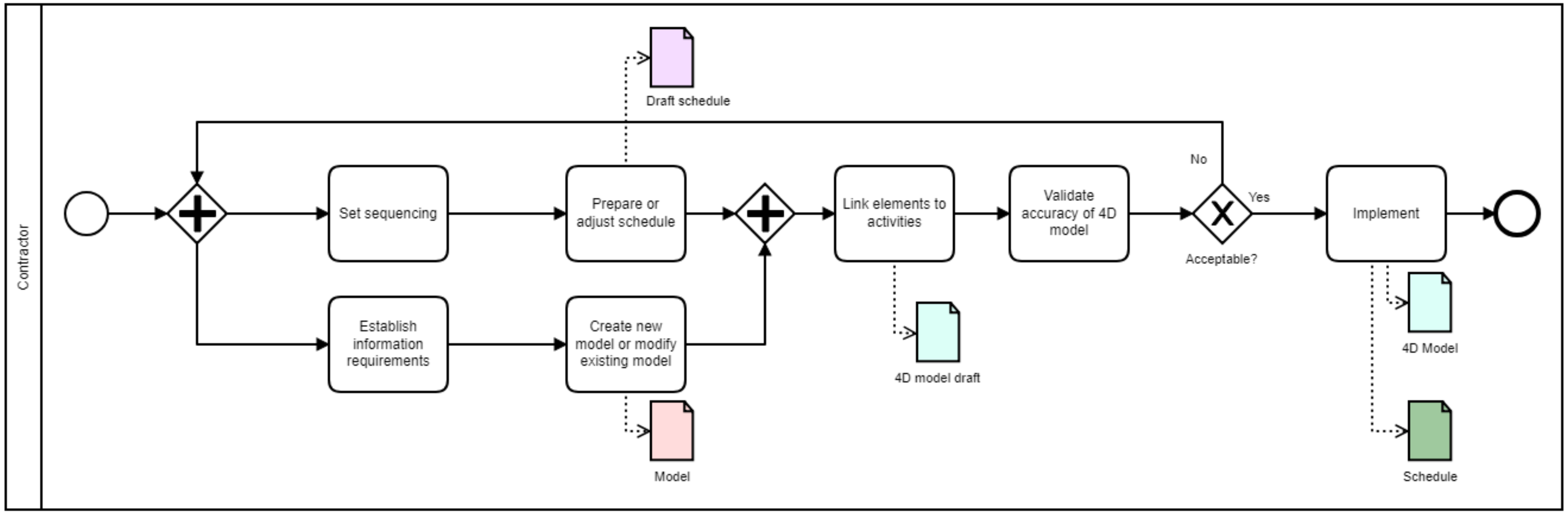


Figure 4-6 4D scheduling

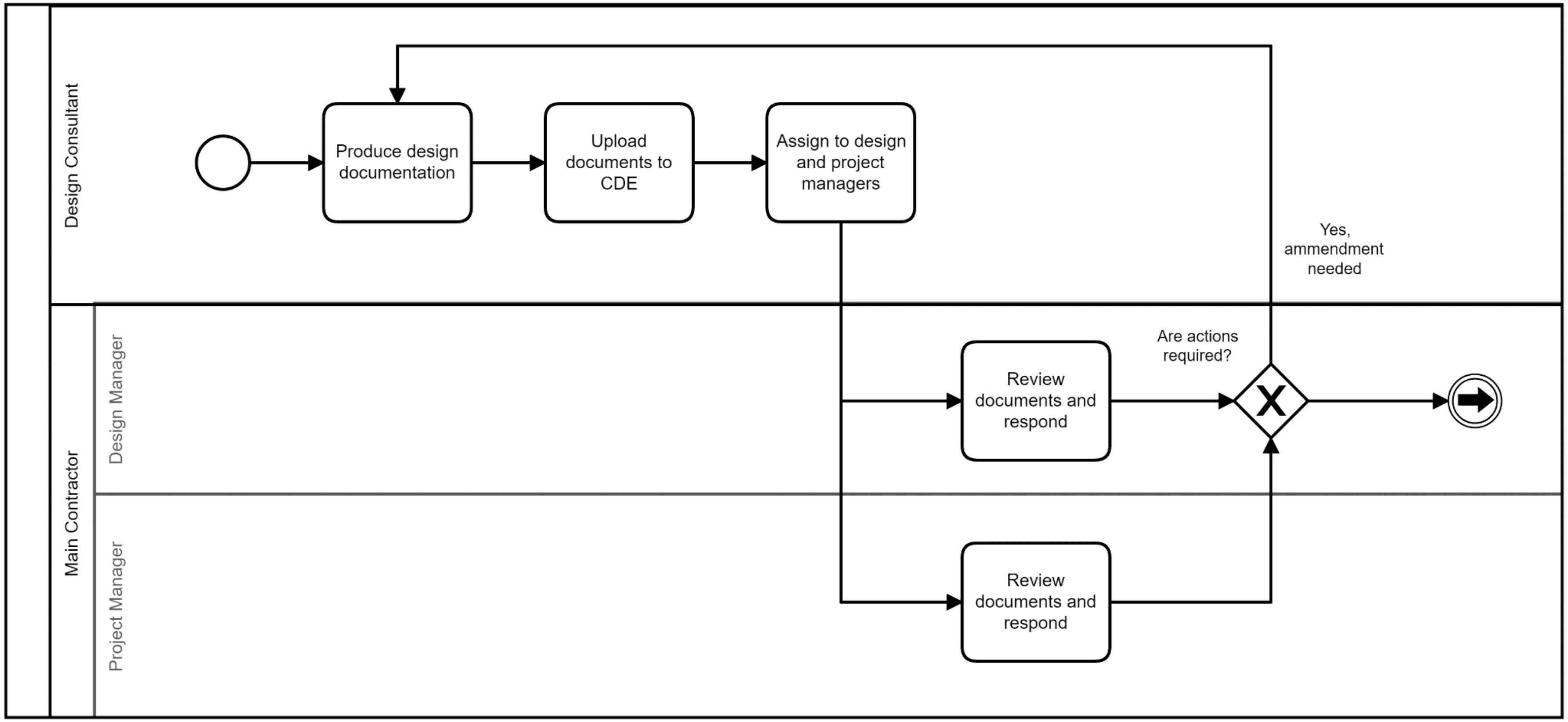


Figure 4-7 Design documentation - approval

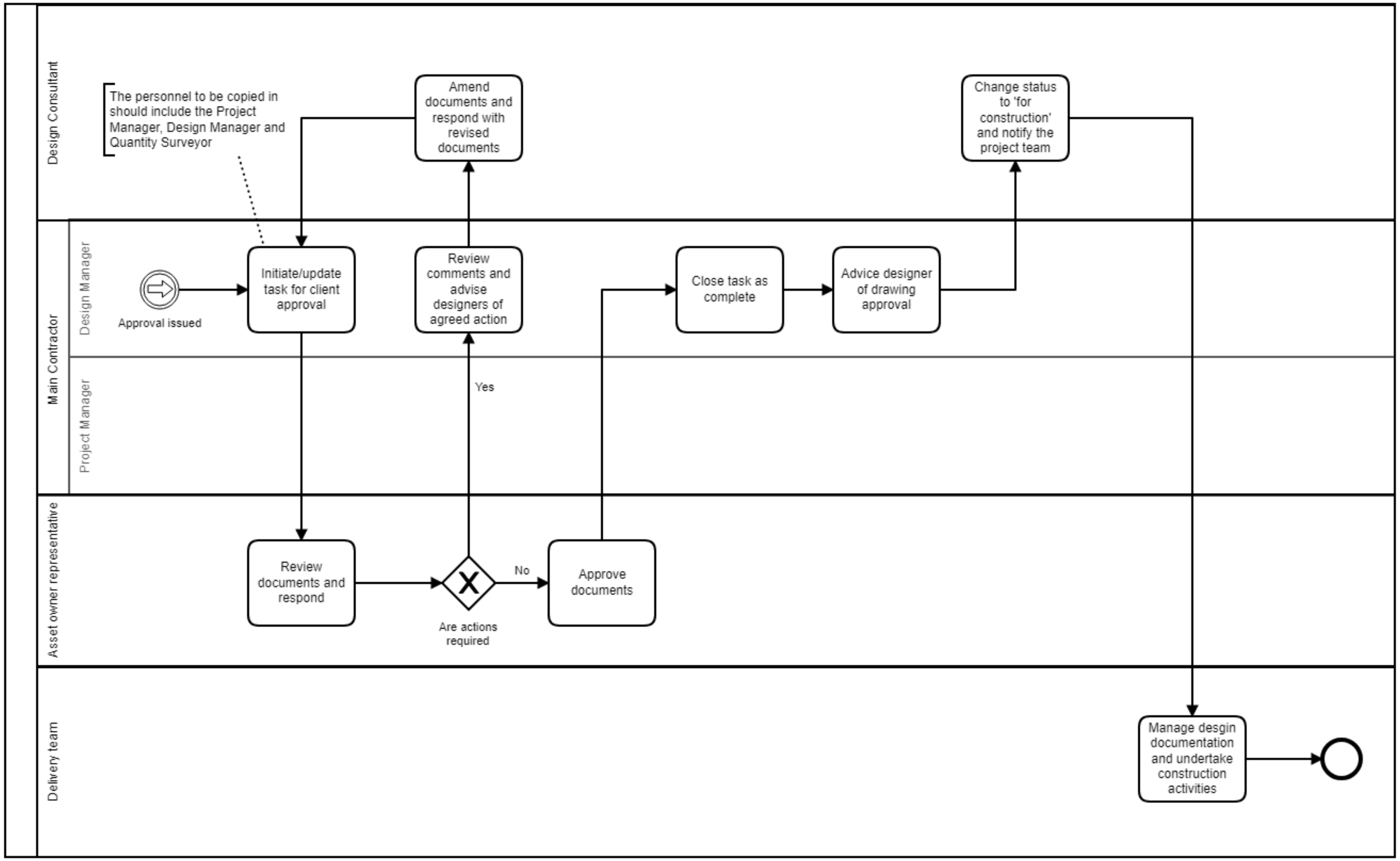


Figure 4-8 Design documentation - mobilization

4.5.3 Queries and requests for information

Figure 4-9, Figure 4-10, and Figure 4-11 show the processes that was expected to be used for raising Technical Queries (TQ), Contractors Requests For Information (CRFI), and Requests For Information (RFI) respectively. As can be seen in the processes, the CDE was utilised for communicating and then storing the information for these requests for information and technical queries. The relevant documents were archived in a container with the relevant metadata attached to them.

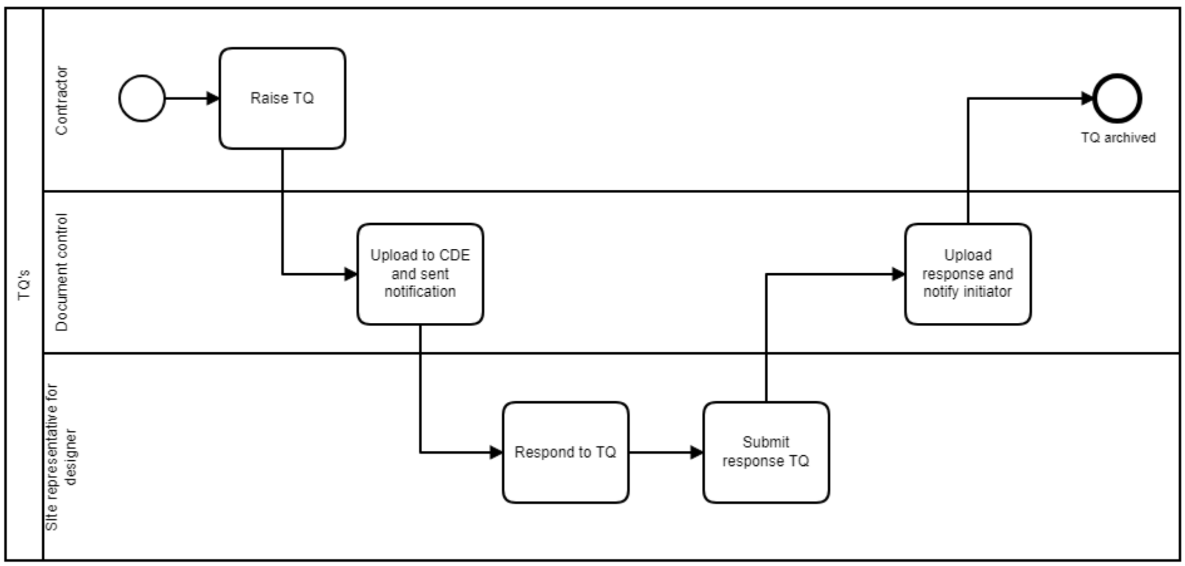


Figure 4-9 Technical Query (TQ)

Figure 4-12 and Figure 4-13 show the processes that were to be followed during the non-conformance reporting (NCR) procedure. Figure 4-12 shows the stage of the process where the issue has to be raised and remedial action is communicated. Figure 4-13 then shows the communication of the action to be taken and the updating the appropriate register.

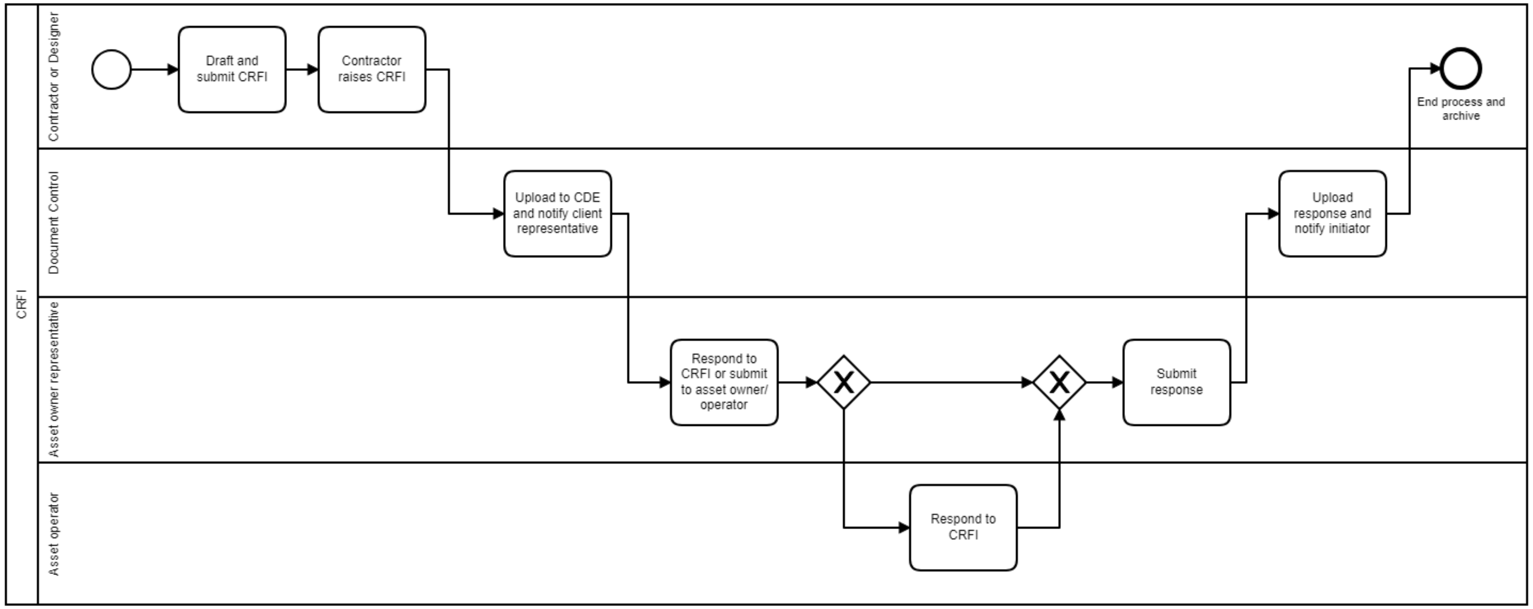


Figure 4-10 Contractors Request For Information (CRFI) process

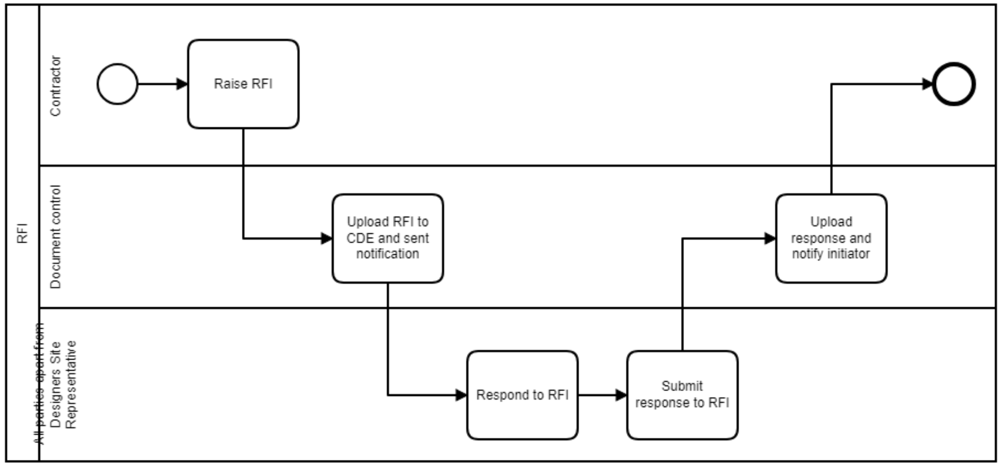


Figure 4-11 Request For Information (RFI) (for correspondence between contractor and any party apart from designers and asset owners

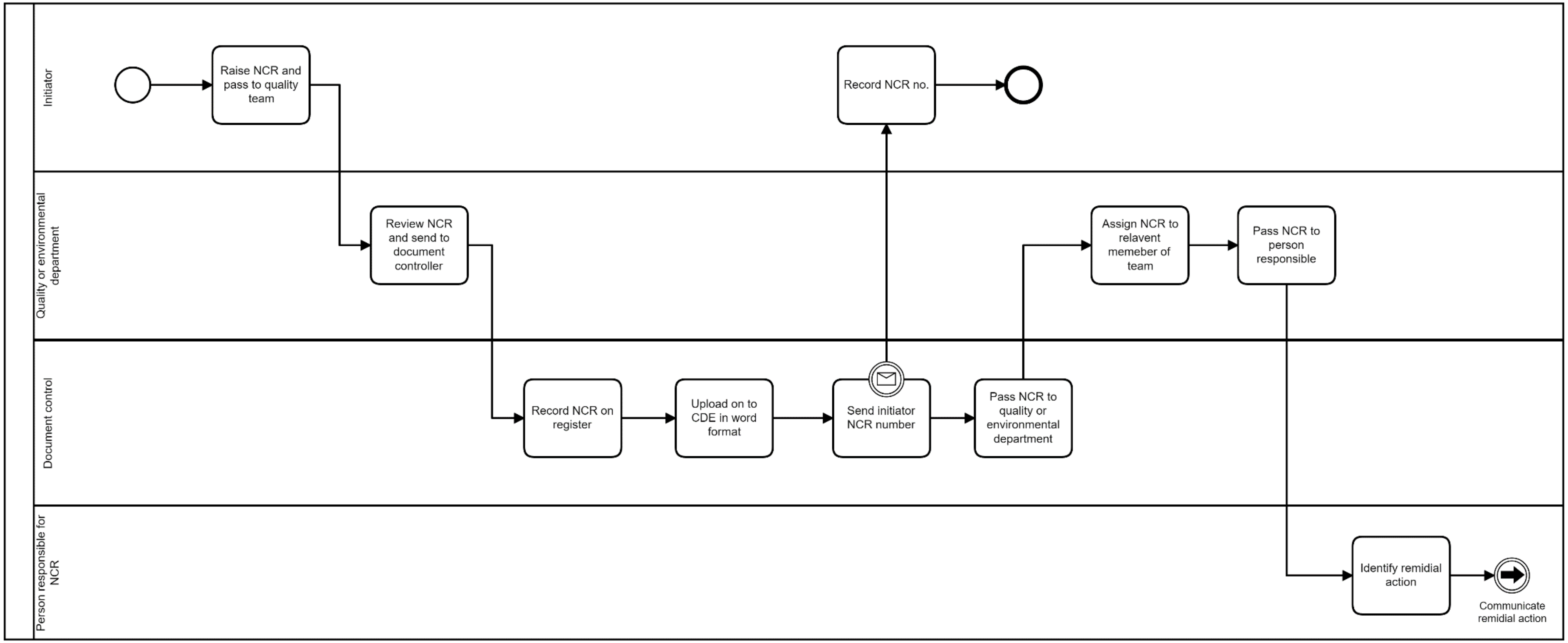


Figure 4-12 Non-Conformance Report (NCR) procedure – Raise and communicate remedial action

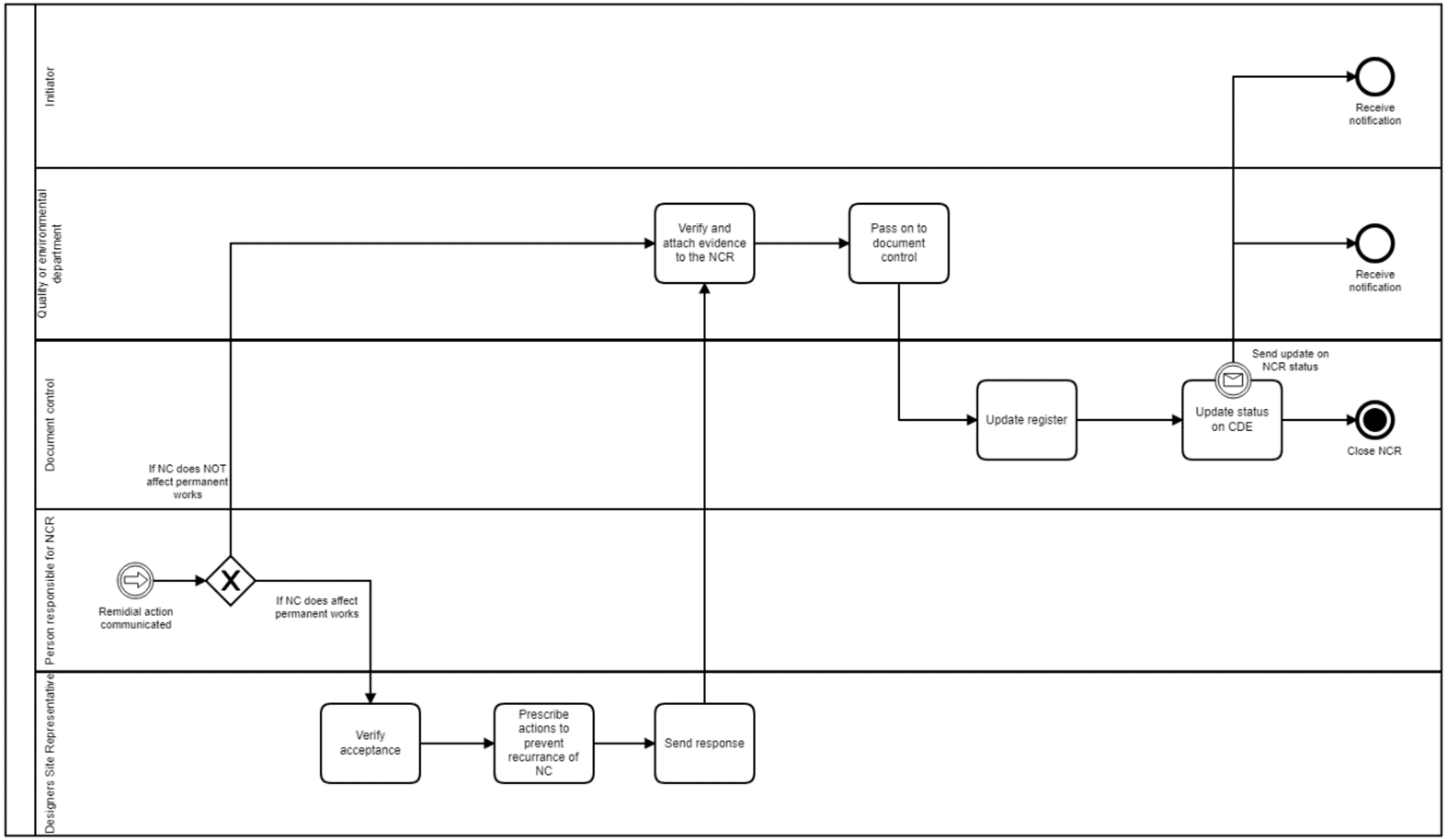


Figure 4-13 Non-Conformance Report (NCR) procedure – Communicate and close

4.6 Outcomes

The processes described in Section 4.5 were enforced by adding them into the project BIM Execution Plan (BEP), which was then approved by all parties involved in the project. The adherence to the BS 1192 ensured that the design was delivered via a coordinated 3D model, project information was managed via a common platform (the project CDE), and certain asset information was delivered in accordance to the Employers Information Requirements (EIR) document.

The implementation of the processes ensured that the BS 1192 series of standards were adhered to, while taking into existing standards and processes. The aim was to maintain a coordinated 3D model with relevant non-graphical information associated with it. The project CDE was set in accordance to the PAS 1192:5:2015 which ensured that the various organisations on the project were given access only to the relevant 'containers' with the platform. This ensured that information was gathered, named, and stored in accordance to the BEP. As a result of the implementation of these technologies and the change to the processes, a transformation was made from a largely paper based exchanging of information to this information being digitised and controlled from a single source (Project Information Model (PIM).

By implementing the processes described in Section 4.5, a robust audit trail was maintained as the CDE kept track of changes and additions of information within it. The federated 3D model (a combination of the models created by the various construction disciplines) was used for detecting clashes. There were instances where due to the schedule and lack of 3D detail, there were multiple clashes which had to be rectified. The following of the 4D scheduling process was useful for rectifying such issues.

Based on the execution plan that was put in place, the information was maintained in a manner that ensured that there the information was tagged with the relevant metadata, the information was available only for the relevant parties, and archived as appropriate in manner to be handed to the organisations that required the information to operate the asset. This information, referred to as the Asset Information Model (AIM), contained both graphical and non-graphical information that would be recognised by asset management systems.

Analysing the breakdown of a PIM and AIM was valuable, as the literature review did not reveal any studies which revealed this information. By being able to analyse the AIM it was then possible to understand the requirements that can be set in future projects and understand why information was produced in a particular manner.

4.7 Analysis

The processes were implemented, and the project was delivered on time and within budget. However, there were several challenges that were faced that could have either been avoided or were not possible to overcome given the state of the art at the time. This section has been split into two main sections which will discuss the challenges faced as well as the information that was produced and handed over. The potential answers to the research questions were explored, and has been discussed in further detail in Section 4.8.

4.7.1 Challenges faced

The standards that were specified were adhered to, however, there were several challenges that were faced which reduced some of the benefits of using VDC on the project. Lessons learned were recorded, and a summary of these can be found in Appendix B of this thesis.

The various challenges were broken down into three main categories which are:

1. Technological
2. Standards and process related
3. Human

It is important to ensure that there is a suitable framework in place to address these challenges and ensure that VDC can be implemented effectively. There were several ***technological*** barriers such as the functionality of software as well compatibility between discipline specific software. It was evident that the capacity to implement these processes varied depending on the capacity of the suppliers to adopt new technology. Surveys such as those carried out by the NBS show that there is a rise in the uptake of BIM within small to medium enterprises (SME's), however, there still is a level of technological immaturity which can potentially lead to problems with authoring and sharing information models. As was mentioned in Section 4.4.2, a decision was taken that IFC or its MVD's, COBie for all suggested by the BIM Task Group (2013), for example, will not be used for the project. It was not considered to be feasible to record as-built data in this format as the asset management systems associated with this project did not have the capacity to recognise this schema.

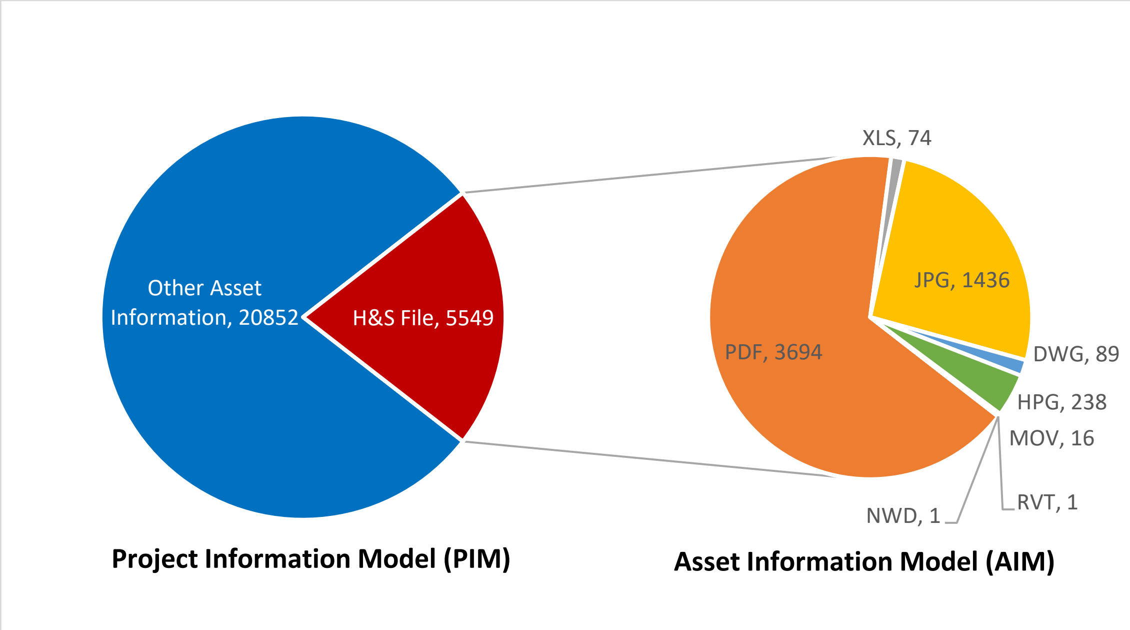
Processes had to be established and then enforced on the project. However, there was a lack of a suitable contractual framework in place to ensure that the processes were enforced and followed. An observation was made that since then contracts such as the NEC4 (NEC, 2017b), and the JCT (2016) have been introduced to make allowance for the inclusion of BIM within the contracts. In terms of interpreting ***standards***, Winfield and Rock (2018) produced a report which analysed the legal challenges that are faced during the implementation of BIM in which they carried out an online survey of 158 participants and one-on-one interviews with 44 experts. They reported that all the participants of the interviews had a different definition of what Level 2 BIM was. This type of issue was reflected on the EBL, as the standards were written in a manner which they can be loosely interpreted. Therefore, it was evident that each participating organisation implemented these standards in a varied number of ways.

Some of the ***human*** factors can be attributed to the lack of maturity in the existing technology. There is a certain lack of confidence in the models that are produced as there are certain error that were seen. This tends to result in a combination of 2D drawings being used alongside the 3D models being used to visualise certain parts of the project.

4.7.2 Information produced

The Project Information Model (PIM) contained a total of 26403 files, and a total of 5549 files were used from that when integrating the information into the asset management system. This is just over 21% of the total information that was collected over the course of the project. From a contractor's perspective, having access to all this information is valuable especially over the liability period. A full breakdown of the PIM can be found in Appendix C.

Figure 4-14 shows the breakdown of the information that was produced over the course of the project. The most used file format is PDF with 66.5% of the AIM consisting of this file format and a further 25% in the JPG format. These documents consisted of certificates, drawings, and maintenance manuals which is an integral part of the information that was to be handed over. It is important to highlight that the information such as concrete cube strength and other quality assurance related information was stored in the PDF format. This does not necessarily reflect the state of the art as it was observed that on other projects that this information was documented using formats



which were machine readable. However, at the time of setting up of the CDE, a decision was made that given the information requirements that were set for the project, it was not of value to ensure that this Level of Information (LOI) (in accordance to the PAS 1192-2:2013 2013) was achieved.

Figure 4-14 The PIM and a breakdown of the AIM that was derived from it.

Instructions were given to the project document controller on what type of metadata was to be included against each of the documents that were uploaded on the project CDE. It was ensured that the file naming convention followed what was prescribed in the BS 1192:2007+A2:2016 (2016) and the guide to the initial standard BIP2207 (2010) was a useful supplement. Apart from the basic file naming, additional meta data such as a description, author, revision, status, and date modified were included.

Figure 4-15 is a breakdown of the file sizes of the PIM, which will give an appreciation of the volume of information that was produced. There was a total of 5549 files transferred to the client asset management system with total size of 27.1 GB. The federated model was a Navisworks (.nwd) which was a collection of over 40 smaller models of various disciplines ranging from the structural models to the drainage and alignment models. The creation of the federated model involved converting each of the native files to cache files compatible with Navisworks (NWC). All these cache files were then referenced via a feature on Navisworks to create a 'NWF' file. The NWF file is created by externally referencing the relevant cache files (NWC).

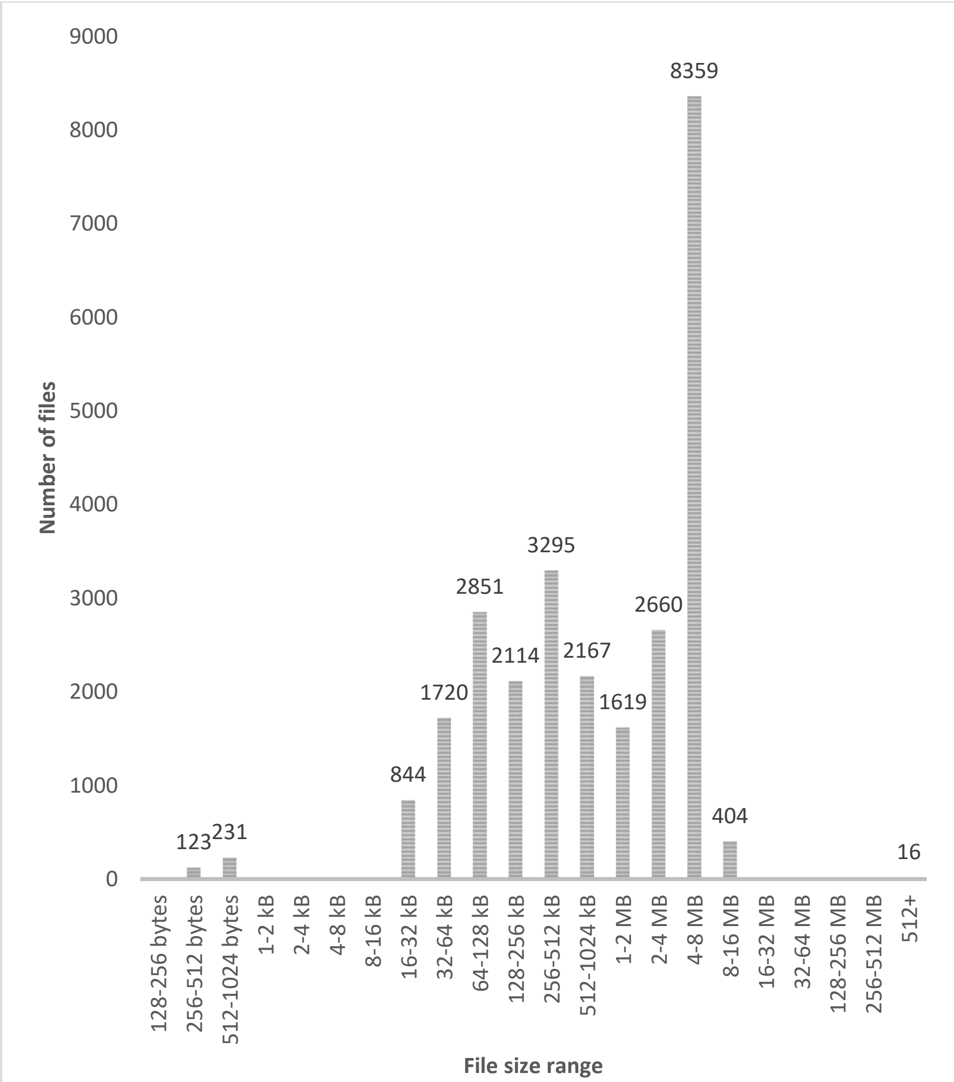


Figure 4-15 File size range and corresponding number of files

Navisworks also had the functionality to query databases (Microsoft Access – Database Management System (DBMS)). The information from the various databases were to match up with the Globally Unique Identifiers (GUID) of each element and embed the information within the properties of each element. Once the databases matched up with the individual elements, an NWF file (as described in the previous paragraph) was created which directly was referring to the databases it was linked to. This NWF file was published as an NWD file; which is a 'snapshot' of the federated model. Even though the NWF had 'live links' to the various resources, it carried the risk of being broken when transferred, and it also required a significantly powerful computer to navigate through the NWF as it was linked with a total of 50 models and databases. The final NWD file of the federated model was around 86.5MB in size.

The IAN 184/16 (Highways England, 2016) was referred to when attempting to understand the best approach to take to eventually share the as-built information. It was observed that in these standards the use of dwg, dgn, rvt, and the ifc formats were acceptable. But they did acknowledge that there is no used open format for CAD. At the time of delivery, the IFC standard was not mature enough to use IFC for bridges. It was also important to note that the asset operators and owners would not have seen great value in receiving these new types of file formats.

4.8 Discussion

Mazairac and Beetz (2013) and Bartley *et al.* (2016) had observed that a large volume of the information collected in practice were largely document based. This observation made by these authors were reflected in the information output of the Eastern Bay Link project as well. The transition that has to be made from Level 0/1 to Level 2 BIM is great, and due to certain ambiguities in the standards, different parties coming into a project such as the EBL will have a varied range of competencies and interpretations of what can be achieved from it.

In their survey of the legal and contractual barriers of BIM, Winfield and Rock (2018) observed that each of the 44 experts that were interviewed had a different definition of what 'BIM Level 2' was. Therefore, it is extremely important to define what Level 2 BIM means to all parties before starting on a project (as of February 2018 there still had not been a formal definition of what BIM Level 2 was). Most of the challenges that arose over the course of the EBL can be attributed to the ambiguity of the standards and the supporting documents for implementing BIM/VDC.

Over the course of the project, it was evident that there was hesitation in the sharing of 'native files' (editable models and drawings). This hindered the implementation of processes such as those described in Figure 4-6 (4D scheduling). The hesitation of sharing these files by the designers were attributed to concern regarding intellectual property rights as this could have allowed the other parties involved on the project to change the information that was given over to them. It would have been valuable if contractual frameworks addressed this potential issue which can give consultants more confidence in sharing this information with other parties.

Even though processes were agreed on at the start of the project, and the standards were expected to be followed, there were challenges that were faced due to there being no framework to establish a precise method in which information should be shared. The aim of the next step of this thesis was to understand the various scenarios that occur on projects that implement BIM and identify issues that can hinder adoption. Then establish a mechanism in which certain process will be enforced to ensure that construction information is shared as necessary.

This phase of the research involved gathering data and processes in order to make a comparison with the final solution that was to be presented at the end of the research. Even though the processes were implemented, and the AIM was produced in accordance to the requirements that were set, a conclusion was made at this stage that there was still a need to streamline the flow of information. By efficiently managing the flow of information on projects such as the EBL, the transition of construction information into the operational stages of an asset was anticipated to be smoother. This type of transition would then be useful for asset managers/operators as they will receive the information in a useful format and the governance of processes may help improve confidence in the accuracy of the AIM. It was therefore necessary to understand how processes could be mapped out in a machine-readable format, and then governed on projects such as the Eastern Bay Link. Existing processes will be explored in the next chapter, and then tested in Chapters 6 and 7 in or

4.9 Conclusion

This chapter aimed to answer research questions 1 and 2:

How is BIM/VDC implemented on linear infrastructure projects and what kind of information is generated during this process?

This case study outlined the approach taken to implement VDC processes on a project and the manner in which standards were interpreted in accordance to the information requirements that were set at the start of the project. Then the data that was produced at this stage was analysed further to establish the type of information that is generally produced on linear infrastructure projects. Answering this research question contributes to:

- Understanding the challenges that can be faced when attempting to align BIM processes with traditional processes.
- Understanding what a useful Asset Information Model (AIM) contains and what ideally can be done to make more use of the asset information produced. The outcome showed that 21.02% of the PIM was eventually used to create the AIM.

What are the main challenges that are faced when implementing VDC on this type of linear infrastructure project?

The processes and lessons learned were analysed to answer this research question. The instances were recorded to aid with defining why these issues were faced. Answering research question 2 led to:

- The categorization of the main problem areas during implementation which were; technological, processes, and human related.
- Potential solutions to those problems to help alleviate the impact of these limitations on other linear infrastructure projects.

Chapter 5 Process discovery – Workshop series

This chapter will discuss the second phase of the research as defined in the methodology (Chapter 3), which involves the discovery and recording of processes which influence the collection and sharing of construction information. The previous chapter showed that even though that processes were in place and the standards were followed, there was missed potential in digitising the construction information in a manner which would help asset owners and operators easily access and change asset information. It also showed that due to the ambiguity of some of the standards, there can be a range of ways in which they are interpreted, leading to a potential lack of collaboration between organisations working on a project. The various challenges that were faced at a project level were discussed and will be shown to the industry experts engaged in this phase of the research to be verified. This chapter will first discuss this verification and then present a range of specific processes that might be adopted to enhance the implementation of BIM on infrastructure projects in general.

5.1 Revisiting the research questions

This chapter aims to address research question 3:

Upon identification of the main causes that hinder the adoption of BIM/VDC and affect the development of the AIM, how can current construction processes be redefined to alleviate these issues?

To answer this research question, a decision was made that engaging with a range of different experts would be necessary to get a valid answer which could reflect what occurs in industry. The experts would have a background of implementing digital construction processes on linear infrastructure projects, and a knowledge that covers the life cycle of these assets.

The methodology for this chapter was discussed in Section 3.2.2 and will be expanded on here. The chapter will also look at the technological, process and human barriers as defined in the previous chapter with the aim of validating the findings of the previous chapter.

5.2 Chapter outline and objectives

The Ferrovial Centre For Asset Management (CAM) had arranged a series of workshops which were considered to be an ideal source of information for this phase of the research. The workshops were attended by various stakeholders that the CAM were associated with which consisted of contractors, designers, asset owners and operators. The intended outcome for the organisation was to ensure that their SMPs were aligned globally, and by doing so, ensure that they were adopting best practice.

The aim for this research project was to engage with these parties who had already had or were in the processes of adopting VDC on their projects. The ability to engage with a varied range of industry experts provided an ideal environment to understand the challenges that are commonly faced on linear infrastructure projects, and also to work towards proposing a practical solution to overcoming some of these challenges. Therefore, this chapter will elaborate on the stage of the research that involved the gathering and analysis of data which leads to the formulation of the innovative element of this research project. The workshops benefitted from the input of information that was provided from this PhD research project, as the lessons learnt and processes adopted over the course of the (Chapter 4) were to be used as a contribution.

5.2.1 Project scope

Table 5-1 shows a summary of the roles and number of participants from the various organisations that attended the series of workshops. The workshops were used to understand the perspectives and approaches of each of the various parties engaged in the workshops when implementing digital construction processes on their projects or network of assets. Observations were made that many of the organisations had overlapping roles depending on the projects they were engaged in. Therefore, a decision was made to avoid strictly following the 'functions' defined in the ISO 19650 but rather to define them in the manner shown in the table. All the participants tended to have roles as BIM Leads or Managers and therefore brought information from a broad range of projects. Further, the asset operators/owners who attended the workshops managed multiple facilities/projects and therefore, even though there were fewer participants from those categories, they brought in knowledge from a network of assets.

Role	Number of participants
Asset operators	3
Employers/ Asset owners	6
Suppliers	14

Table 5-1 Number of participants engaged in the workshop series

The workshops were spread over several days and had specific themes on each day with the relevant specialists who attended them. The themes of the various workshops were:

1. Operations and Maintenance bidding
2. Operations and Maintenance
3. Design and Build bidding
4. Design
5. Design and Build delivery and handover
6. Common data hierarchies

The intension was to use this series of workshops to understand the mechanisms and the processes within each of the first 5 stages mentioned above, and to get an appreciation of the common data hierarchies within each of the stages.

When the workshops were carried out the BS 1192 series of standards were referred to, however the eventual introduction of the BS EN ISO 19650 standards (as of 2019) was anticipated.

5.2.2 Objectives

The main objective of this phase was to record the information requirements and processes carried out when constructing and digitising linear infrastructure projects.

In order to align traditional processes with VDC processes, it was also considered to be important to understand how asset owners interpret the standards and how the flow of information is influenced as a result. Therefore, the various scenarios that might occur based on how asset owners implement BIM on their projects was recorded. This was felt to be a valuable contribution as asset owners could take these scenarios into consideration when producing their project Employers Information Requirements (EIR).

Then to answer research question 3, the methodologies defined in Sections 3.2.2.1 and 3.2.2.2 were executed in order to record processes and information requirements that can typically be carried out on linear infrastructure projects.

5.3 Approach taken

The three tasks that comprised this phase of the research were:

1. Validating the findings made during the initial implementation
2. Identifying the various scenarios and documentation that needs to be evaluated when producing information requirements
3. The recording of construction processes and exchange requirements

5.3.1 Validation of previous findings

The implementation of the SMP on the EBL project (Chapter 4) showed that there are numerous barriers to aligning VDC processes with existing processes. The barriers were broken down into three categories which were; process related, technological and human barriers. In order to validate the findings of Chapter 4, the various discussions that were held during the workshops were recorded. These findings were then compared to the information that was gathered over the course of the EBL to confirm that the knowledge that was gained reflected the state of the art.

5.3.2 Identifying various scenarios

One of the initial observations was that due to a lack of clear definitions and frameworks to enforce the execution plans, the full benefits of using BIM are not seen. The workshops were attended by experts who implemented BIM on projects based on their interpretation of what BIM Level 2 was (Section 4.7 discussed the ambiguity of the related standards and definitions that led to the varying range of interpretations). An observation was made that based on the interpretation of the SMP on a project, the way in which VDC processes where implemented varied and therefore led to a range of project outcomes. Therefore, over the course of the series of workshops the various project outcomes and barriers were recorded and categorised. The findings showed that there were three main sequences of events that occurred on projects that influenced the flow of information on projects. It was anticipated that if each of these three scenarios were identified, these findings will be valuable when planning to implement BIM on future projects.

5.3.3 Recording processes and information requirements

As was stated in the literature review (Section 2.4.2) there was a need to align existing processes with VDC processes. Therefore, several processes were recorded over the course of the workshops to get an understanding of how information is exchanged over the course of a project. The processes and information requirements recorded in this phase of the research will also be useful as they will define the basic tasks that are performed when collecting and exchanging construction information.

Guidelines for recording processes by Freund and Rücker (2016) and Dumas et al. (2018) were deemed to be essential sources of reference for the purposes of this stage of the research. Freund and Rücker (2016) suggested two models should be considered:

1. Strategic process model – Gives a process overview which is logically abstract and is easy to comprehend
2. Operational process model – Logically specific and can be categorised as either human or technical workflows. Identifying these processes help select processes that can or cannot be automated or semi-automated.

This workshop series was approached mainly with a focus on defining strategic process models. The operational process models that were created will be presented in more detail when presenting the development of the prototype process management system.

Based on the literature review that was carried out, a decision was made that the workflows will be mapped and recorded using Business Process Model and Notation (BPMN) (Section 2.3.2).

A decision was made that the Camunda Modeller was the most suitable tool to map out BPMN processes, as it had features such as the capability of simulating scenarios, as well as creating and previewing HTML forms. It provided an interface with the ability to draw out most of the standard BPMN 2.0 symbols (British Standards Institution, 2013), and it had a feature that ensured that basic rules were followed when creating a process map. There are several plugins for the tool including a simulator which roughly checked whether the mapped-out processes were machine readable, and a feature that added tags so that users can understand the functions of the components of a diagram. There is a tab in the tool which enables users to visualise the underlying XML code that defines the process maps. To ensure that the basic rules were being followed, a tool called BPMN lint (bpmn.io, 2018) was used to scan the diagrams and make checks against a predefined set of rules.

As will be discussed in more detail in the next two chapters, the mapped-out processes will then be deployed onto a platform which can parse and then run the processes via its BPMN engine. The Camunda modeller also had a feature which was able to directly deploy processes onto the platform, which was a powerful feature which was invaluable when testing the various iterations of the process maps.

Table 5-2 shows the order, theme, inputs/outputs, and a description of each of the workshops that were carried out. Certain participants attended multiple workshops in order to carry out discussions and challenge certain issues in case there were conflicting opinions. Each of the attendees listed in the table have been labelled with a letter at the end which helps show who attended each of the workshops (Asset Operators (A-C), Asset Owners (A-F), and Suppliers (A-N)). The generic information that was gathered over the course of these workshops was then expected to help with establishing project specific processes and exchange requirements.

No	Theme	Attendees	Inputs	Outputs	Description
1	Information Gateways and Requirements	Supplier (A), Asset Owner (A), Asset Operator (A)	Standards, previously implemented processes, and EIR's.	Generic set of gateways with processes and information requirements.	Carried out to get a general understanding of when information is expected to be exchanged over the lifecycle of an asset and generic processes.
2	Design and Build workshop (Overall)	Suppliers (B), Asset Owner (B), Asset Operator (B)	Generic set of gateways with processes and information requirements.	Overall processes and information requirements.	The aim was to understand the overall tasks carried out over the D&B stage of a project. The suppliers and asset owners were both present in order to ensure that all the main tasks were agreed on.
3	Design and Build (Bidding)	Suppliers (B)(C), Asset Owner (C), Operator (C)	Overall processes and information requirements.	Detailed processes and exchange requirements up to the bidding gateway.	The aim was to breakdown the overarching processes into more detail in order to understand the stages at which tasks are carried out. One of the suppliers (B) from the previous workshop attended which helped with critically reviewing the processes.

No	Theme	Attendees	Inputs	Outputs	Description
4	AIR's/Common Data Hierarchies	Suppliers (B)(D), Asset Owner (C), Asset Operator (B)(C)	Information from other projects.	Understanding of generic requirements and documentation that is exchanged.	An initial review of the type of information that is generally exchanged and the way it is stored and used.
5	Design and Build (Delivery and Handover)	Suppliers (E)(F)(G)(H), Asset Owner (C), Asset Operator (B)(C)	Information from Design and Build (overall), and AIR workshops.	Defining common exchange formats, processes and information requirements.	The AIR workshop was used in order to understand the main expectation from asset owners and operators when receiving asset information. Having some participants from the previous workshops as well as from Suppliers, Asset Owners and Operators helped with agreeing on processes.
6	Operation and Maintenance (Bidding)	Supplier (I)(J), Asset Owner (B)(D), Asset Operator (B)	Relevant information from previous workshops.	Defining of detailed processes and information requirements.	A combination of Suppliers, Asset Owners and Operators helped come to a common understanding of the processes and information exchanged and the tasks carried out.

No	Theme	Attendees	Inputs	Outputs	Description
7	Operation and Maintenance	Supplier (B), Asset Owner (D)(E), Asset Operator (B)	Overall processes and information requirements.	Defining of detailed processes and information requirements.	Information, especially from the AIR workshops were analysed to ensure that the processes and requirements were agreed upon.
8	Operation and Maintenance	Supplier (K), Asset Owner (E)(F), Asset Operator (C)	Information from previous workshop presented in order to see whether a consensus had been reached.	Agreement that the generic processes, requirements, formats etc. defined in the previous workshops were relevant for other projects. Minor amendments	This workshop was used to help confirm that the previous findings represented the state of the art in O&M.
9	Design and Build	Supplier (A)(D)(L)(M), Asset Owner (B), Asset Operator (B)	Information from previous workshops.	Agreement that the generic processes, requirements, formats etc. gathered in the previous workshops reflected the current state of the art. Minor amendments.	This workshop was used to help confirm that the previous findings represented the state-of-the-art D&B.

No	Theme	Attendees	Inputs	Outputs	Description
10	AIR's/Common Data Hierarchies	Supplier (L)(N), Asset Owner (B)(C), Asset Operator (A)(B)	Information from previous workshops.	Finalisation of findings which confirmed that the information gathered represented the state of the art.	This final workshop ensured that all the parties present agreed on the exchange requirements and the processes that were defined.

Table 5-2 Workshop themes, aims and general notes

5.4 Common problem areas

Over the course of the workshops there were several common 'pain points' that were identified when implementing VDC processes on projects. Table 5-3 shows the various challenges that were faced by participants over the course of the lifecycle of a linear infrastructure asset that were recorded by the author.

Table 5-3 is a combination of challenges faced by asset owners, operators, lead appointed parties and appointed parties. All the challenges that were faced fell within the three categories that were defined during the Eastern Bay Link (EBL) project.

In Chapter 4 the challenges that were faced during the Design and Build (D&B) phase of the EBL and the information that was produced at handover were discussed. The findings of these workshops confirmed that these challenges were typical of those faced by many engaged in projects similar to the EBL.

Technological	Processes and SMP	Human/Administrative
Common coordinate standards are an issue and therefore there is a need for co-ordinate transformations between various tools	Standards are not followed or interpreted differently by the various participants. It was observed that this leads to the flow of information not occurring especially at handover	Commercial barriers such as the use of multiple tools based on organisational requirements lead to issues when exporting information
During reactive maintenance, information tends to be shared manually as a lack of consistent or due to non-digitised information. As a result, information in systems can sometimes be out of date	Assumptions are made that processes could be reused among different projects rather than having project specific processes. This has led to the information being produce not being suitable for specific clients or projects and quite often could contradict what is stated in the EIR and the BEP	Lack of competencies that are suitable for implementing VDC. It was noted that across the various stages of an assets lifecycle, there are several silos in the training and knowledge of certain participants which could potentially lead to the breakdown of the flow of information
Lifecycle cost is increased as in several cases asset owners for example have multiple siloed systems (e.g. GIS system, Transportation Management Software and SharePoint Severs) which then could lead to the poor quality or lack of site information	Terminology could vary on a local level leading to a need to change certain specifications to ensure that processes are carried out as needed by the asset owner	Poor quality information can be provided by asset owners/operators leading to an increase in risk and cost as a result. In more than one instance, lead appointed parties stated that they encountered gaps in maintenance records, if they found any.
Vendors of authoring tools tend to update their software annually leading to possible inconsistencies are possibility of information being lost if models are created on a different version of the software. Several participants stated that 'round tripping' can occur, where information is	Handover is done in one go at the end of the project ('data dump') which is inefficient as in several instances the receiving party has not satisfied with the information. This leads to a wastage of time and money while the information handed over in a manner that is acceptable.	Asset changes not captured consistently leading to inaccurate asset information. Asset operators stated that there can be large backlogs in the modification of records, this eventually leads to the loss of fidelity of maintenance information.

exchanged between various tools leading to a loss of information		
Asset owners and operators both stated that there are challenges with 'legacy data' which can be challenging to integrate into newer systems. It was noted that this can prove to be true in linear infrastructure due to the vastness of the network of assets	Overarching governance processes are not well defined due to various requirements set between various organisations. It was observed that on a local level that depending on available resources standards, systems and therefore requirements could change	Existing information is produced in 2D (PDF) in most cases leading to the need to carry out new surveys in order to reduce risk. Further the asset operators find this disadvantageous as most information is stored at a file-level rather than an object-level
Design change is siloed and quite often a single source of truth cannot be established. This was attributed to the available technology and leads to a lack of collaboration between functions and disciplines. During the design workshops, several participants stated that a single source of truth with various 'views' (or lenses as described by Succar, (2015)) would be useful.	There is a gap between current processes and those that are required to ensure that new SMP are effective. This could also lead to either the EIR or BEP not being followed or the SMP not being adhered to	Information is still quite regularly expected to be recorded on paper which is then scanned and uploaded on to the relevant system
	As-built information gets captured at the latter stages of a project which could lead to unnecessary rework or poor-quality data being produced	Operators stated there is a lack of confidence in the asset information that is produced and even if the information handed over is correct most asset managers would not be confident in the information they received. Further operators stated that

		information is regularly duplicated which can also lead to confusion
	In certain instances, supply chain is expected to define the manner in which information should be produced when handing information over to asset owner/ lead appointed party	
	Snagging/ punch list process needs more refinement as it would be valuable in reducing risk during operation.	
	Asset owner/ operator sometimes does not provide specific naming conventions leading to information not being easy to query. Several examples of design data rather than as-built data being handed were given.	
	The defining of LOD is not acceptable in some cases which leads to the information produced not being suitable for reuse	

Table 5-3 Categorised challenges and examples (D&B and O&M)

5.4.1 Technological issues

The main technological issues were with coordinate transformations when migrating between various tools. Further, authoring tools can vary depending on the information requirements. Once the software tool to be used has been established, the version of the tool can potentially affect the information that is shared.

It was also possible to see what the knock-on effects were that caused problems on the EBL were. For example, during the design workshops, the participants stated that they had issues with design changes and the siloing of various disciplines. This led to issues with the design when attempting to build it on site.

5.4.2 SMP and process issues

The adoption of new Standard Method and Procedures for digital construction and their related processes led to the greatest number of challenges that were faced throughout the lifecycle of an asset or a network of assets. Issues that were brought up regularly in all the workshops were with the interpretation of the standards as there sometimes were clashes between current processes and those proposed by the SMPs.

An observation was made that, in many cases, at handover, all the information was transferred at once to the asset owners and operators. This can lead to rework on some of the as-built information as it can be, for example, in a format that is not compatible with the existing asset management systems. It is therefore important to ensure that all parties agree what asset information and what format it is in to ensure that no costly rework is required. Several participants, and especially those involved in the design and built phase of projects, stated that Levels of Detail (LOD) were not defined clearly enough, which leads to the models not being suitable for use. For example, the 4D processes mentioned in the EBL project (Section 4.7) was not executed frequently as a result of this problem.

From an operations and maintenance (O&M) point of view, it was observed that appointed parties tend to produce information at the latter stages of construction, which can lead to delays and rework. Further, there were instances where “issued for construction” models were handed over rather than “as-built” models leading to an inaccurate representation of the built asset. This can lead to complications during maintenance and, due to a lack of confidence in the as-built information surveys have to be carried out.

5.4.3 Human and administrative factors

The most common issues in this category were the lack of confidence in the information that was available and the lack of knowledge of VDC processes and related technologies. During maintenance, existing data backlogs were an issue, and this therefore led to inconsistencies. Further, a large proportion of the information was produced as flat files/databases (often PDF or in spreadsheets) which was cumbersome to update and tended to be error prone.

A large proportion of the challenges that were faced in this category were a result of the knock-on effects caused by the technological and process related challenges that were faced.

5.4.4 Discussion

The three categories and the issues that were highlighted under each of them showed that there were several common challenges that were faced by the participants of the workshop. It was also possible to appreciate why these issues arose when implementing VDC projects such as the EBL.

5.5 Identification of scenarios

Once the categories of common problem areas were confirmed and suitable examples identified, the next objective was to understand the various scenarios that occur when defining information requirements, execution plans, and implementing a contractual framework. These scenarios (Shown in Table 5-4) will contribute towards answering the research question relevant to this chapter as they aided the identification of factors that eventually affect the quality and the usability of the Asset Information Model (AIM). As a guideline to define these scenarios, Figure 5-1 (defined during the literature review) was used.

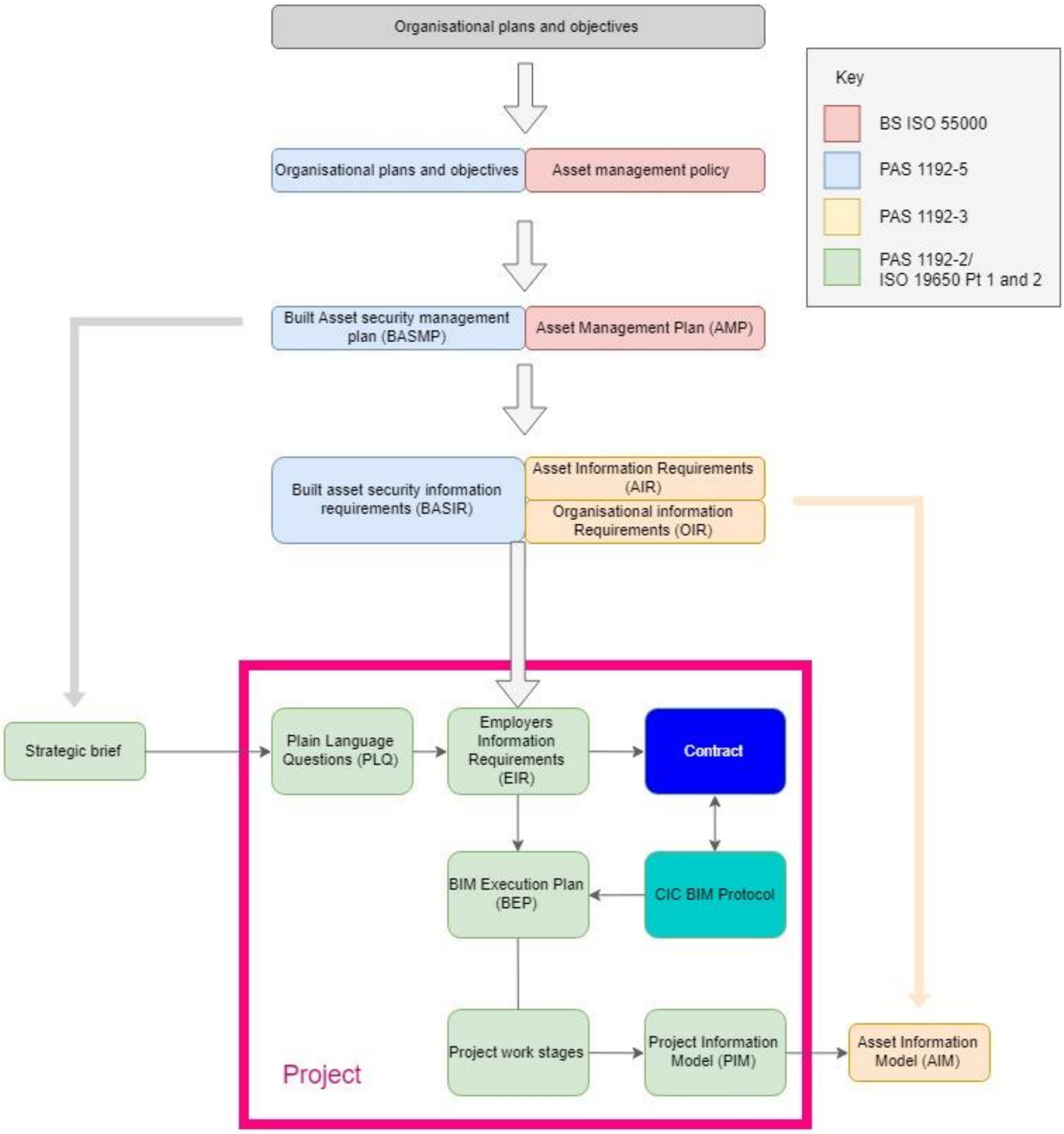


Figure 5-1 Integration of the various standards that were analysed (based on diagram produced in the PAS 1192-5 by the British Standards Institution (2015)

Stage	Scenario 1 - BS 1192 series of standards (refer to figure 14 literature review)	Scenario 2 - Following generic templates	Scenario 3 - Limited requirements and competency assessments placed during tender
Procurement	Decision is made to adopt BIM standards for the project	Decision is made to adopt BIM standards for the project	Decision is made to adopt BIM standards for the project
Procurement	Asset management policy and objectives are reviewed	Input from consultant or a template to create asset information requirements	EIR might not be included in tender documentation or is non-specific only requiring that 'BIM Level 2' standard is achieved by suppliers. Sometimes generic templates are used by asset owner which are not suitable for the asset type that is to be built. Sometimes suppliers propose requirements which specifically reflect their view of implementation. There is no incentive for suppliers to abandon traditional processes or to implement digital construction processes for anything other than design and construction
Procurement	Asset Management Plan (AMP) is created	The EIR is formulated based on the information requirements established previously	
Procurement	AIR, OIR, PLQ's and BASIR are reviewed		
Procurement	Asset owner compiles requirements to form EIR		
Procurement	EIR placed into tender documentation	EIR placed into tender documentation	
Procurement	Tenderers respond to EIR via a pre-tender BEP	Tenderers respond to EIR via a pre-tender BEP	
Award contract and mobilize	Preferred bidder mobilises plan	Preferred bidder mobilises plan	Preferred bidder mobilises plan
Award contract and mobilize	PIM developed in accordance to the plans	PIM developed in accordance to the plans	PIM developed in accordance to the plans
Award contract and mobilize			Asset owner dissatisfied by approach or sets additional requirements based on PIM that has been sent for review.
Award contract and mobilize	Works completed and AIM produced	Works completed and AIM produced	Rework of certain sections based on asset owners' feedback
Award contract and mobilize			Works completed and AIR produced

Table 5-4 Methods in which BIM is implemented on various projects

5.5.1 Scenario 1

Scenario 1 is the ideal scenario where all the standards are adopted in full and the steps in Figure 5-1 are followed accordingly. In this type of scenario, the asset owners/operators tend to be prepared and, in some cases, will already have their digital component libraries which in turn helps appointed parties provide homogenous information.

Based on asset management policies as defined in the ISO 55000:2014 (Asset management) (British Standards Institution, 2014b) and ISO 55001:2014 (Management system requirements) (British Standards Institution, 2014c) an Asset Management Plan (AMP) should be formulated. The asset management plan will ensure that these standards align with the organisational plans of the asset owner and are appropriate to the scale of the organization’s assets. It will have to be periodically reviewed and updated to ensure that it is aligned with the organisation’s requirements.

This AMP will then help formulate the Asset Information Requirements (AIR) and Organisational Information Requirements (OIR) as defined by the PAS 1192-3. As can be seen in Figure 5-1, this should be closely aligned with and should influence the development of the Asset Information Model (AIM). These organisational requirements should then be the driver for the implementation of the project’s digital construction processes. They should enable the development of a project Employers Information Requirements (EIR) document which should be included in~~to~~ the tender documentation as well as relevant Plain Language Questions (PLQ).

During the tender process the prospective lead parties (as defined by the ISO 19650) should produce pre-tender BIM Execution Plans (BEP). In some instances, during the tender process asset owners will review this pre-tender BEP and responses to the PLQ’s and will provide Interim submission feedback. This then allows the potential lead parties to adjust the BEP to align more closely with the EIR.

Once the lead appointed party is selected, the BEP will be mobilised. Ideally the BIM Protocol and a suitable contractual framework (e.g. partnering contracting approaches such as the NEC 4) will be selected, which will then be enforced over the course of the project. This leads to a Project information Model (PIM) being developed in accordance with the asset owner’s/operator’s requirements and to the works being completed and the Asset Information Model (AIM) being produced with a minimum amount of rework or additional information having to be collected.

5.5.2 Scenario 2

An observation from the workshops was made that this was the most common sequence of events that occur on infrastructure projects. It is seen in this scenario that the crucial initial review of the asset management policy and AMP does not occur when creating the EIR. Instead, the EIR is created based on templates or in some cases via the advice of external consultants. The problem with this approach is that the AIM that is produced over the course of the project may not align with the asset owner's AMP at handover.

On a project level, the lead appointed parties and appointed parties then mobilise the agreed BEP. As was discussed in the previous subsection there is a possibility of other potential issues occurring at a project level, however, the lack of a bespoke EIR is particularly likely to lead to issues associated with the creation of the AIM.

In cases where the asset owner/operators have limited capability for utilising the AIM, the lead appointed party often experiences that a large volume of the collected information goes to waste as it cannot be used during the operation of the asset. On other projects, the asset owners/operators realise that the PIM is not being developed in a manner that can be used during operation and maintenance. As a result, they require the lead appointed party to carry out further work to ensure that they produce a satisfactory AIM.

This scenario, in certain cases, can work in favour of the asset owner/operator if the EIR that is produced and placed within the tender documentation closely aligns with the appropriate asset information requirements.

5.5.3 Scenario 3

The frequency of this scenario occurring is expected to reduce over time as asset owners become more aware of the benefits of using VDC on their projects. However, currently it occurs when EIR's are not placed within the tender documentation but are only introduced once the appointed party has been engaged. As the workshops were with participants who were aware of digital construction processes, it was observed that organisations that were lead appointed parties/appointed parties on a project were expected to drive implementation forward by the asset owner.

The appointed parties reported that this was very challenging to enforce as usually there would be no contractual framework in place to enforce the implementation of digital construction processes on the project. As a result, the view of most of the appointed parties (at the time of writing) was that they would tend to defer back to traditional processes. As a consequence, it was generally agreed that if this scenario occurs on a project, the lead appointed party should be forced to ensure that the digital construction standards are adhered to.

In this scenario, there can be a large waste of information at handover as there is likely to be a large volume of information that cannot be utilised, or the asset owner/operator is not satisfied with the AIM. This leads to additional work to get carried out in order to get the asset information in a format acceptable to the owner/operator.

5.5.4 Discussion

The basic interactions between the SMPs related to VDC process and asset management were analysed and then three scenarios were defined based on the information gathered over the course of the workshops. Identifying these scenarios aids the creation of strategic process models as defined in Section 5.3.3. The scenarios are also beneficial when it comes to the creation of the overall framework, as it helps define the tasks that need to be considered and carried out in order to ensure that the information that is produced is useful over the lifecycle of an asset.

5.6 Processes

As was observed throughout Sections 5.4 and 5.5, there were challenges faced in the processes and SMP which influenced the flow of asset information. This section will explore processes and will present process maps that were put together based on the methodology discussed in Section 3.2.2.

A strategic process model, which is a process map that will give a logically abstract high-level overview of the exchange of information (described in section 5.3.3), based on the scenario formulated in Section 5.5.1 will be created. Then operational process models will be created based on the strategic process model.

Operational process models can be broken down further into human and technical workflows (Freund and Rücker, 2016). The relevant human workflows will be discussed in this section, and technical workflows will be discussed in more detail when developing the prototype system in Chapter 6.

The tools used for recording both the strategic and operational workflows have been described in Section 5.3.3. During the workshops they were recorded by hand, then modelled in a BPMN authoring tool and then finally linted (rule checked).

5.6.1 Strategic process model

Figure 5-2 and Figure 5-3 describe the strategic process model between the start of a linear infrastructure project and completion of construction. The intention is to define the point at which VDC related documentation should be produced as well as used. It is beneficial to understand the overall tasks that are linked together to affect the documentation and provide clarity to the strategic aims of the project. These strategic process models are useful to gain an understanding of the overall processes, which then can be used to create detailed operational process maps.

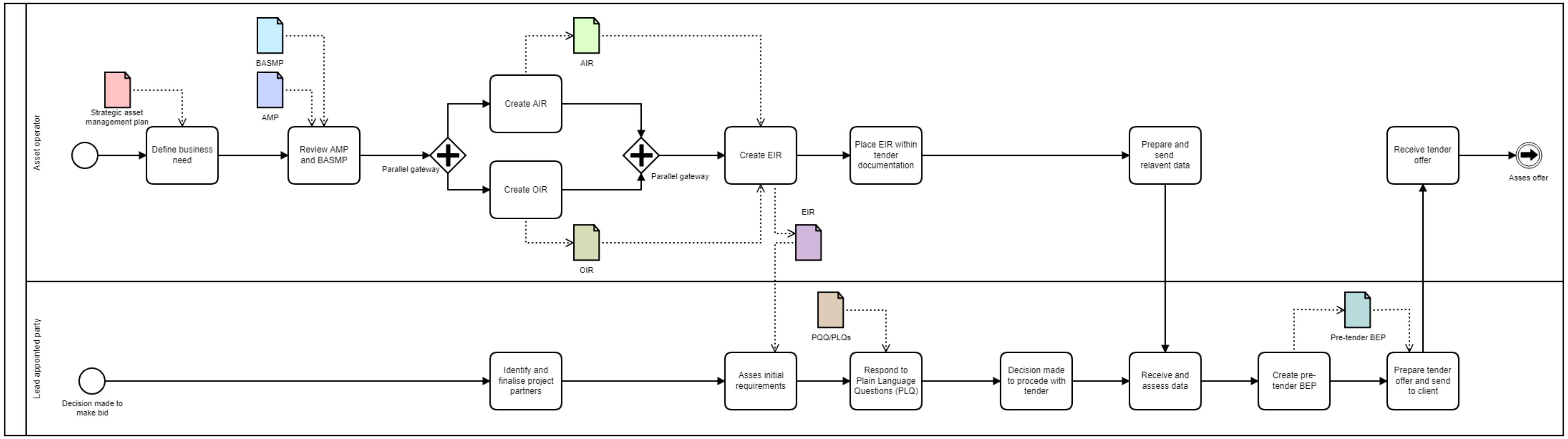


Figure 5-2 Pre-tender documentation - strategic process model

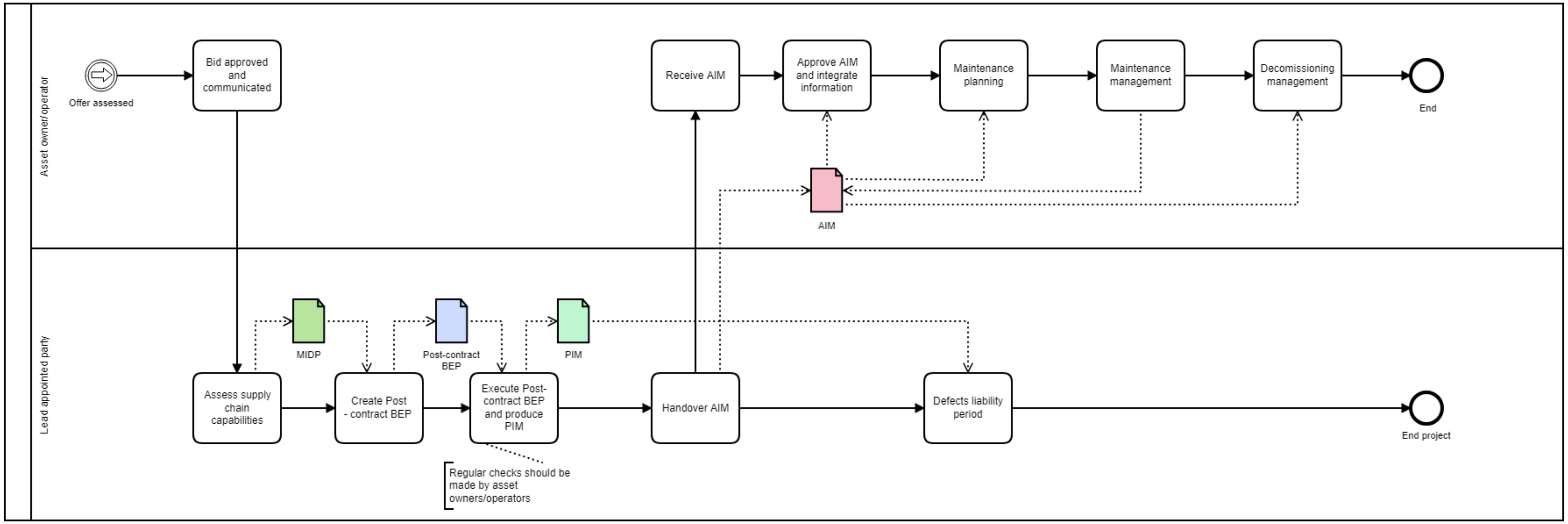


Figure 5-3 Mobilisation of BEP to closedown - strategic process model

5.6.2 Operational process models

Once the process was outlined in a strategic model, it was mapped at an operational level as described in Section 5.3.3. These operational models are valuable for understanding the specific tasks that have to be carried out and contribute towards the creation of models which can be parsed by the workflow engine. Once the workflows that could potentially be carried out within the engine had been identified, they were taken into consideration when developing the prototype process management system.

This step in the process discovery stage had 4 objectives:

1. Separating lanes into separate pools on an organisational level (description of annotation used can be found in Section 3.2.2.1)
2. Once the pools were created, understanding the process from each participants point of view
3. Establish information requirements for the tasks
4. Identify which tasks or workflows could be supported by the process engine

The purpose of separating the BPMN ‘lanes’ into individual ‘pools’ was to highlight that each organisation has its own specific systems and tasks and therefore each organisation sees the process from a different point of view. By creating separate pools, it helps clarify what information is shared between each organisation and how certain tasks are completed within the organisation.

Figure 5-4 and Figure 5-5 describe a high-level overview of the capture of as-built information as well as the interaction between the asset operator and the lead appointed party.

Figure 5-6 and Figure 5-7 show the process and a subprocess of the interactions between, designers, lead appointed parties and asset operators when preparing asset information which can eventually be used for maintenance planning. The subprocess helps identify the main tasks that are carried out by the asset operator when validating the information imported into their asset management systems. Then the process related to snagging/punch listing is described in Figure 5-8 which shows the main steps where minor defects on a recently completed job will be identified and resolved. Figure 5-9 then shows a more detailed breakdown of the process and the interaction between the lead appointed party and the asset owner or their representatives. Each of the workshops had a specific theme which helped with understanding of the different points of view based on the role of the organisations and participants.

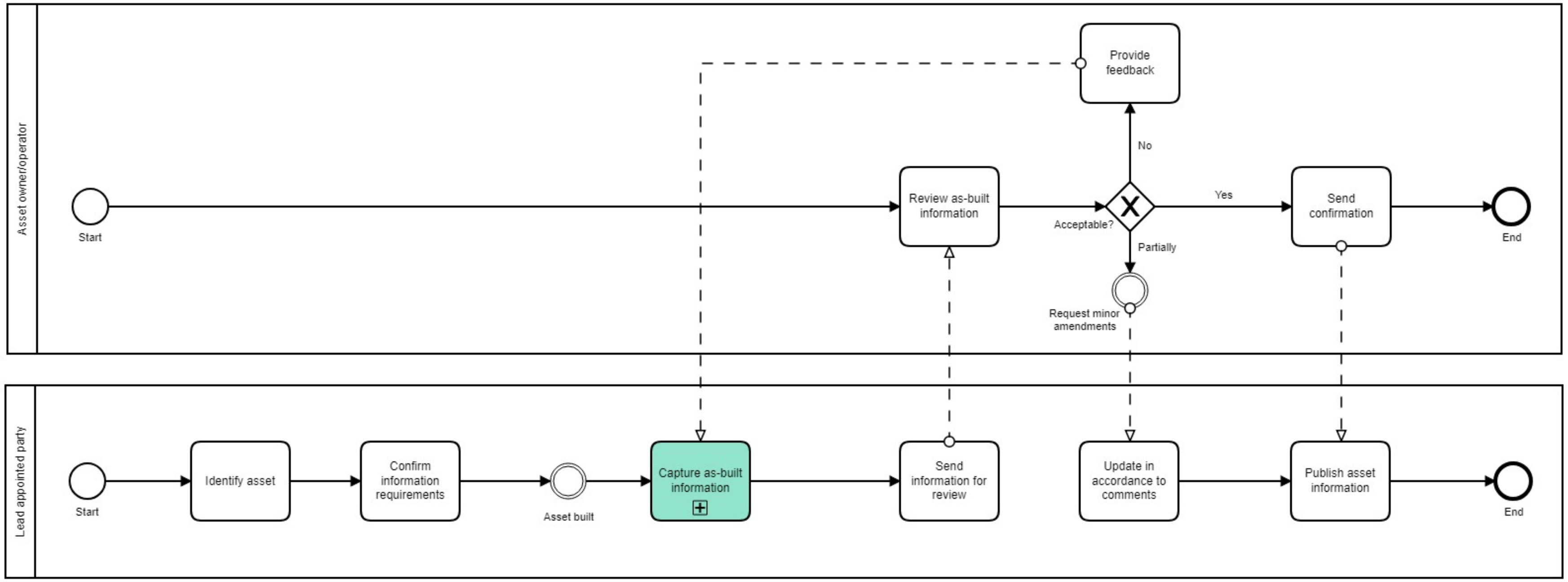


Figure 5-4 Process map describing process of capturing as-built information – Operational process model

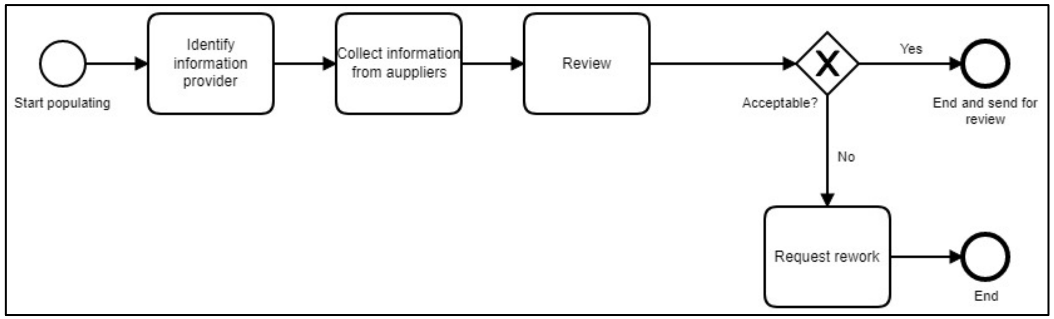


Figure 5-5 Capture as-built information – Operational process model

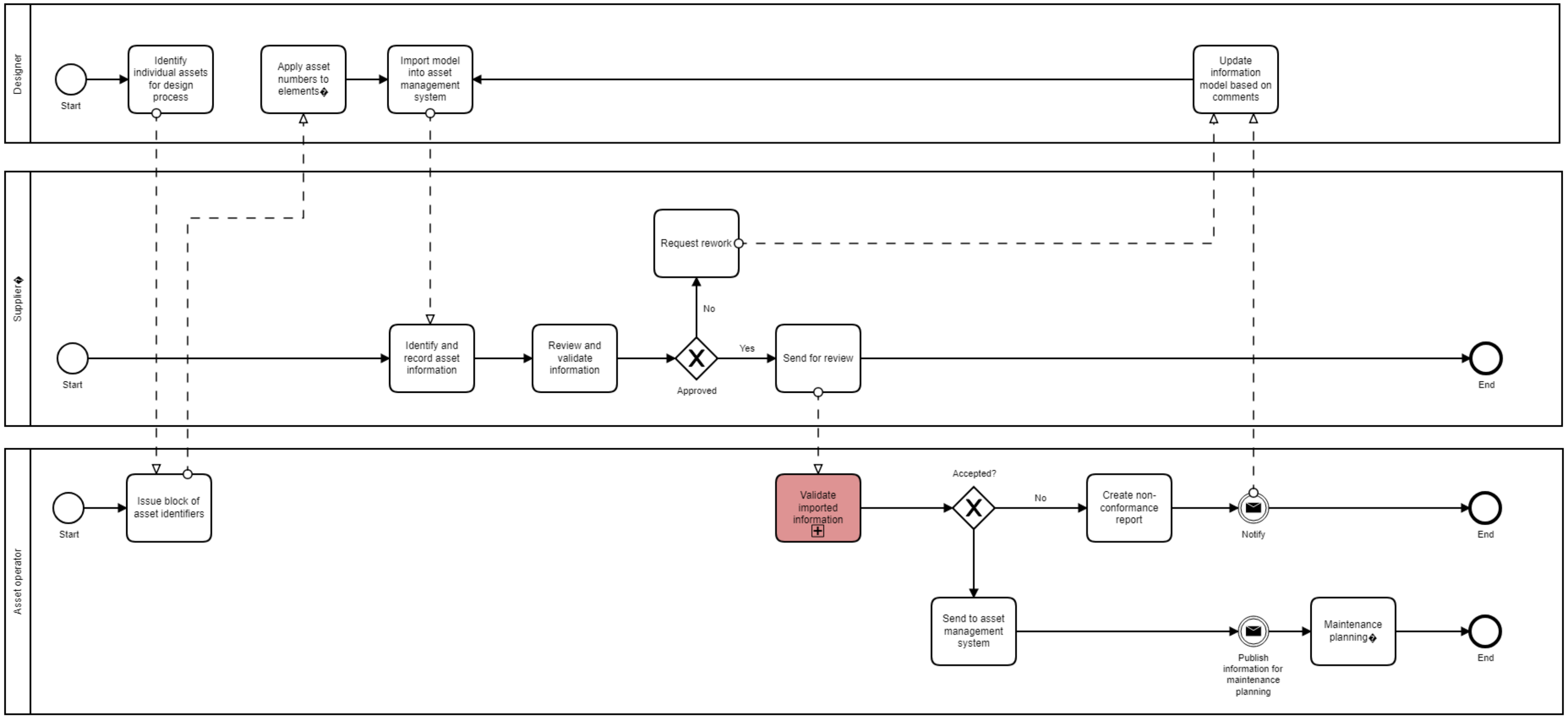


Figure 5-6 Preparation of asset information – Operational process model

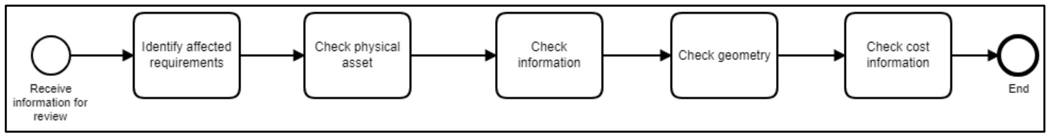


Figure 5-7 Validate imported asset information – Operational process model

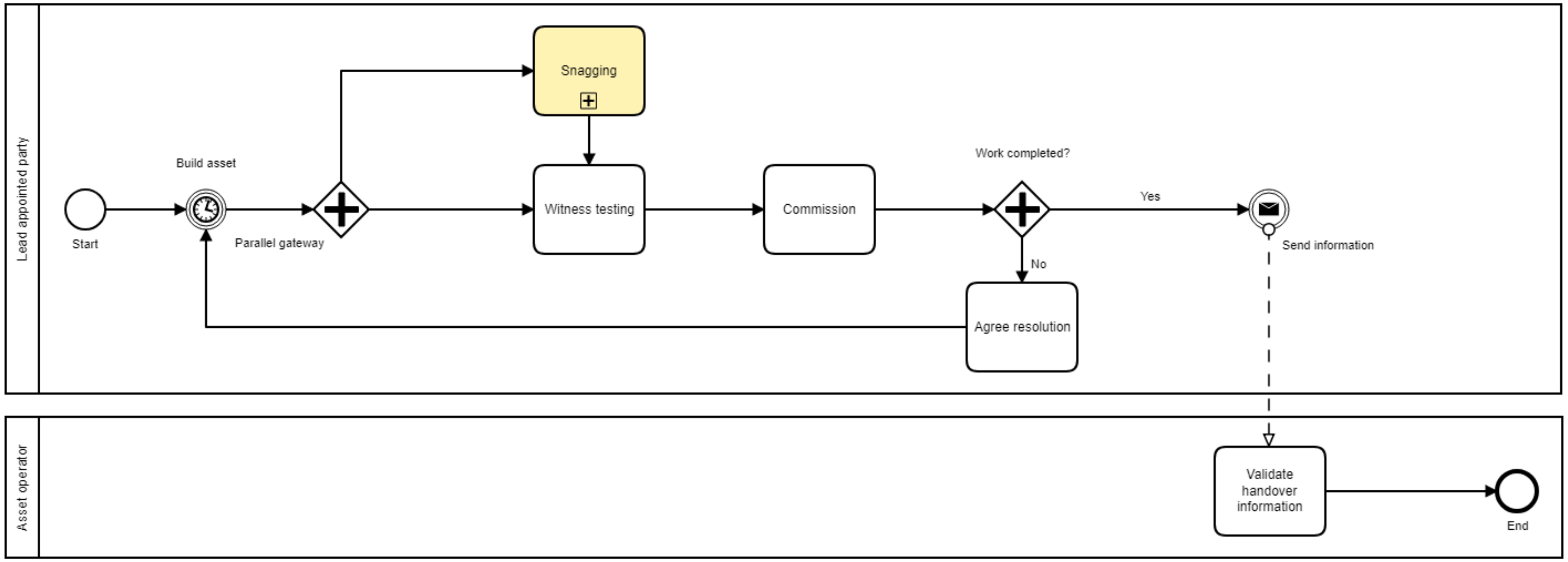


Figure 5-8 Handover preparation – Operational process model

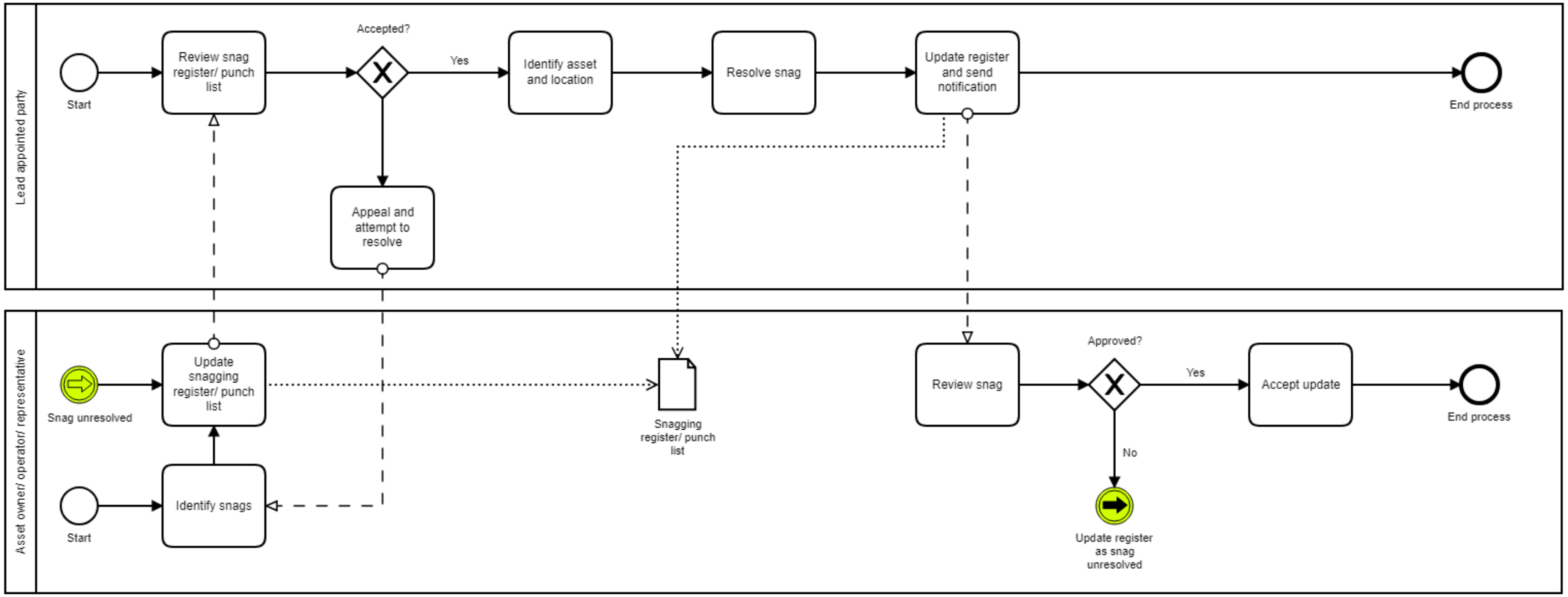


Figure 5-9 Snagging (linked to Figure 5-8) – Operational process model

5.7 Discussion

This chapter first aimed to validate the findings made on the EBL project and to identify whether the challenges that were faced were common throughout the industry. It was confirmed that they were and that they could be categorised under three broad headings as technological, SMP and process related and human and administrative issues. By identifying the individual challenges faced under these categories it provides an opportunity to ensure that they can be mitigated or avoided in future projects.

While information on the challenges being faced on projects were being gathered, three scenarios were formulated in order to understand what should ideally happen when implementing VDC and what triggers potential issues with the production or the quality of the asset information.

Scenario 1 was the most ideal in which all participants are aware of how they will create and utilise the information. This type of scenario will have all the requirements aligned with the industry SMP's and also have an appropriate contractual framework in place to ensure that the appropriate processes are implemented as needed. As there is a growing awareness of the VDC and its related standards the occurrence of this scenario should become more likely.

Scenario 2 is currently the most common the various organisational processes and standards do not align with each other and do not completely follow the industry standards. This may be attributed to ambiguities in the standards or to challenges faced when attempting to adopt them.

As a result of these findings an assumption was made that the likelihood of Scenario 3 occurring will reduce as there is a growing awareness of the benefits of implementing VDC over the lifecycle of a project. Upon analysis the aim would therefore be to ultimately shift towards Scenario 2 and then 3 type projects.

To aid the achievement of scenario 1, strategic process maps were created to understand the basic tasks that need to be carried out and the documentation that has to be created in order to ensure the streamlining of information over the course of an asset's lifecycle. These strategic process maps were then broken down further in order to define individual organisational processes from which operational process maps (human workflows) could be created. These process maps are beneficial as they can help organisations identify the uses of the information that is being generated.

Using these processes, a prototype system was developed to help automate some of the tasks defined in them and this will be described in detail in the following chapters. This prototype was validated by presenting some of the strategic process maps to engineers working on a Scenario 1 project and to further develop the processes so that they addressed the project specific information requirements.

The findings in this chapter were expected to first validate the conclusions made in the previous chapter, and then explore how the problems that were identified in Chapter 4 can be addressed. The findings made during these workshops showed that there is a need to ensure that specific information requirements are set, and processes are governed in order to ensure that these requirements are met.

A potential solution to alleviate the problems faced in Chapter 4 was to explore if the processes recorded in this chapter (1) can be automated (Chapter 6) and then (2) implemented on a project based on specific requirements (Chapter 7). Therefore, the next two chapters therefore aim to test the findings made in this chapter first on a technical level, and then on a practical level respectively. Testing the findings made in this chapter will contribute to the existing body of knowledge as it will help asset owners/operators enforce their requirements, and it will help suppliers improve the accuracy of the asset information they provide to their clients.

5.8 Conclusion

This chapter aimed to answer research question 3:

Upon identification of the main causes that hinder the adoption of BIM/VDC and affect the development of the AIM, how can current construction processes be redefined to alleviate these issues?

This series of workshops was beneficial for understanding the interactions between various organisations and their organisational level processes that eventually influence on the flow of project information. This chapter has presented the creation of a strategic process map and a set of operational process maps based on the points of view of individuals involved in various functions from a range of organisations. Answering this research question contributes towards:

- Understanding problem areas faced by all organisations involved in a project, and the knock-on effects they may have
- Identifying common scenarios that occur which affect the quality of the AIM and lead to potentially costly rework for the appointed parties involved
- Defining a strategic level process map and operational level process maps which are beneficial for identifying the way information is exchanged and developed within organisations based on their function.

Chapter 6 System development

The strategic and operational processes were mapped based on the findings made during the workshops (Chapter 5). These operational process maps were then analysed in order to understand which tasks could potentially be automated. The aim was to govern the information based on project specific information requirements. This chapter presents a prototype system that was developed over the course of this research that is able to parse and execute processes that are defined based on the information requirements.

6.1 Revisiting the research questions

This chapter aims to answer research question 4:

Can processes and information requirements that have been defined be automated, and what type of system can execute and govern these requirements?

This question was addressed first by analysing the findings made both during the EBL project (Chapter 4) and the feedback of the industry experts consulted in the workshops (Chapter 5). An observation was made that once the information and process requirements were recorded, they can be both represented within process maps and programmed in order to ensure that the information requirements are fulfilled. In order to govern these processes and requirements, open source web applications were analysed (Section 2.4.1) and then a system was developed in accordance to the methodology described (Section 3.2.3). The approach taken to develop this system was published by Goonetillake et al. (2018) and reformatted and expanded for this thesis.

6.2 Chapter aims and outline

The information requirements and the processes captured during the workshops (Chapter 5) were referred to, in order to develop the system. The aim was to test specific requirements and then create a prototype system based on the feedback given by industry experts. In order to govern construction information effectively, the participants suggested a system such as that described in Figure 6-1.

This type of system has the potential to be beneficial on projects such as the EBL, as it will have the capacity to share only the information that is needed and allows various parties involved on a project to add information only as required. This is controlled by setting parameters and rules in order to ensure that the information that is entered by the users matches the information requirements. These parameters are controlled by having features such as dropdown lists which then gives users a finite set of options to choose from, or text rules (set via Angular JavaScript) that accepts information based on certain semantic rules. The aim at this stage of the research was to follow an established methodology (the Design Science method described in Section 3.2.3) and create a prototype system which demonstrated that a system such as that described in Figure 6-1 can be developed.

The prototype system developed in this chapter consisted of a client application and a server. The server (BIMServer discussed in Section 6.5.2) has the capacity to parse and store IFC models at an object level, which enabled external web applications to interact and change specific components of an IFC model. The external web application that was used for this prototype had the capability of parsing process models and communicating with the server in order to exchange construction information.

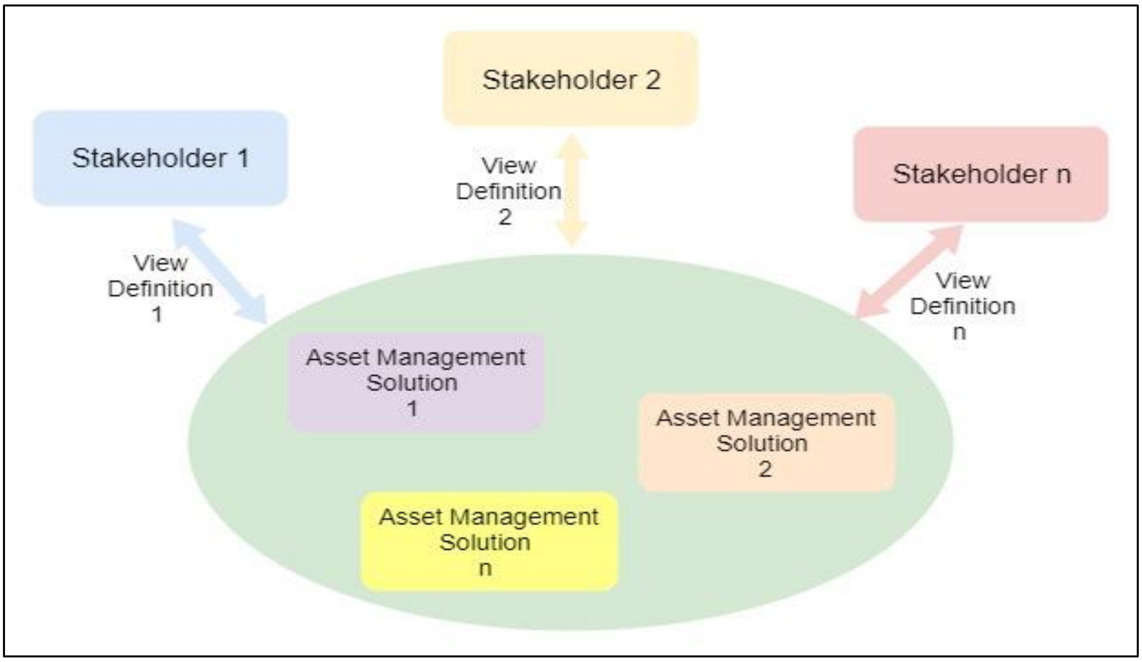


Figure 6-1 The ultimate goal for extracting asset information (Goonetillake et al., 2018)

6.3 Methodology and resources

The Design Science (DS) Methodology was used as described in detail in Section 3.2.3 along with why the particular steps were taken (

Figure 3-6 is an illustration of the stages involved in this methodology). Stage 1 of this process had been completed as it involved the problem identification, which has been discussed in detail both in Chapter 4 and 5. The next steps using this methodology were:

- Step 1 - Definition of objectives for a solution
- Step 2 - Design and development of the system
- Step 3 - Demonstration of the system
- Step 4 - Evaluation of the system

As highlighted previously, an iterative process was adopted when developing the system. Therefore, the next 4 sections of this chapter describe these stages of the process and discuss what occurred during each step.

6.4 Step 1 - Definition of objectives for a solution

The findings both in Chapter 4 and 5 showed that a large volume of information is produced in a file format, usually as PDF files. As a result of this, the information is not dynamic as it is stored in flat files, and the level of information is low as a result of the format in which the data is stored. It would therefore be better to have a system that could dynamically update the information within it in a controlled manner.

The processes were mapped, and in order to structure the information requirements, forms were linked to the tasks with the relevant information requirements within them. The construction information was to be stored in the openBIM format; Industry Foundation Classes (IFC). The objective was to transfer the information entered within the process task forms and transfer them into the IFC as needed.

As a result, the system to be developed had to have two components:

1. Construction information management system
2. Process management system

6.4.1 Construction information management

Sacks et al. (2018) and Mazairac and Beetz (2013) defined two types of systems with which information was managed on construction projects. They are:

1. File-level – systems that handle documents with supporting metadata (e.g. file name, revision number, upload date etc)
2. Object-level – systems that parse digital construction models (e.g. IFC) and then break them down into different entities, each with their own set of information

An observation was made that file-based systems are the most prevalent in industry and this is likely due to the current limitations of object-level management systems and standards. To overcome this, Lee et al. (2014) suggested the use of 'BIM-Servers' which act as object-level management systems and the use of Object-Relational IFC servers to parse the IFC models.

However, the feasibility of using an object-based system was still explored as it was assumed that, over-time, these types of systems will become more common. It was observed that Bentley Systems (2019) i-model, Autodesk (2019) BIM 360 and the Graphisoft (2019) BIM Server had already been developed for their own proprietary software. Further, Jotne EPM Technology (2010) has created an object-based system called the EDM Model Server for IFC.

A decision was made that the most suitable system to be used as a server was the Open BIMServer (2018). This opensource BIMServer has a schema independent database known (NoSQL), which is an alternative to traditional relational databases (Beetz et al., 2011, 2010a, 2010b). The server can read the IFC object classes and their properties and then stores them within a key-value-store database (Oracle BerkeleyDB).

6.4.2 Process management system

As was discussed in Section 2.4.2, a conclusion was made that a 'production workflow system' is the most suitable type of system to be used to manage the workflows and information requirements. This type of system generally does not allow the deviation of processes defined within it, and both human and automated tasks can be handled. These types of systems were explored both by carrying out rough tests on a series of platforms and also analysing literature related to them. A conclusion was made that the Camunda BPMS (which contains the Camunda process engine) (Camunda, 2019a) was the most suitable for this research, based on its process modelling capabilities and user interface.

The modelling tool used during the workshops also had the capability of synchronising and launching processes directly into web applications if set up correctly. Therefore, the models that were developed at the workshops could directly be linked to the engine that was chosen for this research.

6.4.3 Discussion

The design of the prototype system was based on the information gathered over the course of the workshops series. The overarching objective was to develop a prototype system that has the capability of orchestrating the flow of information based on project specific information requirements and processes.

6.5 Step 2 – Design and development

The information from the workshops (Chapter 5) were used for the design of the system. The participants defined certain system requirements which had the potential to influence the effective governance of construction information. The system presented in this chapter has the basic functions in order exchange information between a BPMS and BIMServer.

Section 6.5.1 introduces the various components that were used in the design of the system and how they interact with each other. Then Section 6.5.2 presents a detailed breakdown of how the system was developed.

6.5.1 System design

Figure 6-2 is a breakdown of the main components of the solution that was developed during this stage of the research. The inputs, processes and requirements within them (BPMN 2.0) had to be placed within the Business Process Management System (BPMS) (Discussed in Section 2.3.2). The construction information (IFC) created then had to be transferred into the BIMServer. Most CAD tools (Autodesk Revit, Civil 3D, ArchiCAD, AECOsim, Vectorworks etc.) have the capability to export graphical and non-graphical information into the IFC.

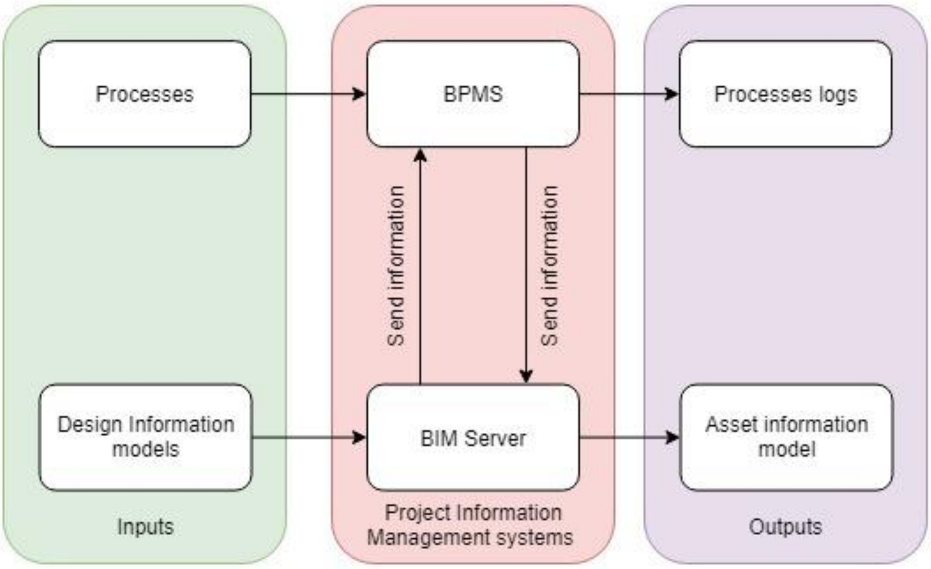


Figure 6-2 Overview of expected inputs, systems and outputs

Once the processes and information requirements have been established for a project, they need to be deployed in the Camunda BPMS. The IFC files were then placed within the BIM Server, then the processes ran in parallel on the BPMS and exchanged information when needed.

The intended outputs were an event log produced by the BPMS and an Asset Information Model (AIM) produced as a result. When developing this prototype system, the aim was to get these two components (BIMServer and BPMS) to make transactions between each other. This was to be a proof of concept of a system that aimed to act like the system illustrated in Figure 6-1 where a BPMS system or similar governs the flow of information between various parties either by executing and triggering processes or orchestrating workflows.

6.5.2 Server – BIMserver

The BIMServer was first proposed by Beetz et al. (2010) and has continued to be developed since then and can be found on a dedicated website (BIM Server, 2018). Beetz et al. (2010b) stated that the aim was to provide a customisable environment which enables users to work with models created in the open BIM formats such IFC and ifcXML.

Figure 6-3 is a simplified diagram that was published by Beetz et al. (2010) to describe the architecture of the BIM Server. It was created using a model driven architecture (MDA) (Object Management Group (OMG), 2001) based on existing IFC STEP EXPRESS models. It has a generic EXPRESS parser written in Java originally created by Lardet (2001). This is placed in a EMF (Eclipse Modelling Framework) model (The Eclipse Foundation, 2003) which is used to generate Java objects and its interfaces (JSON and SOAP). The information is then placed in a key-value database, Berkley DB (Oracle Corperation, 1994).

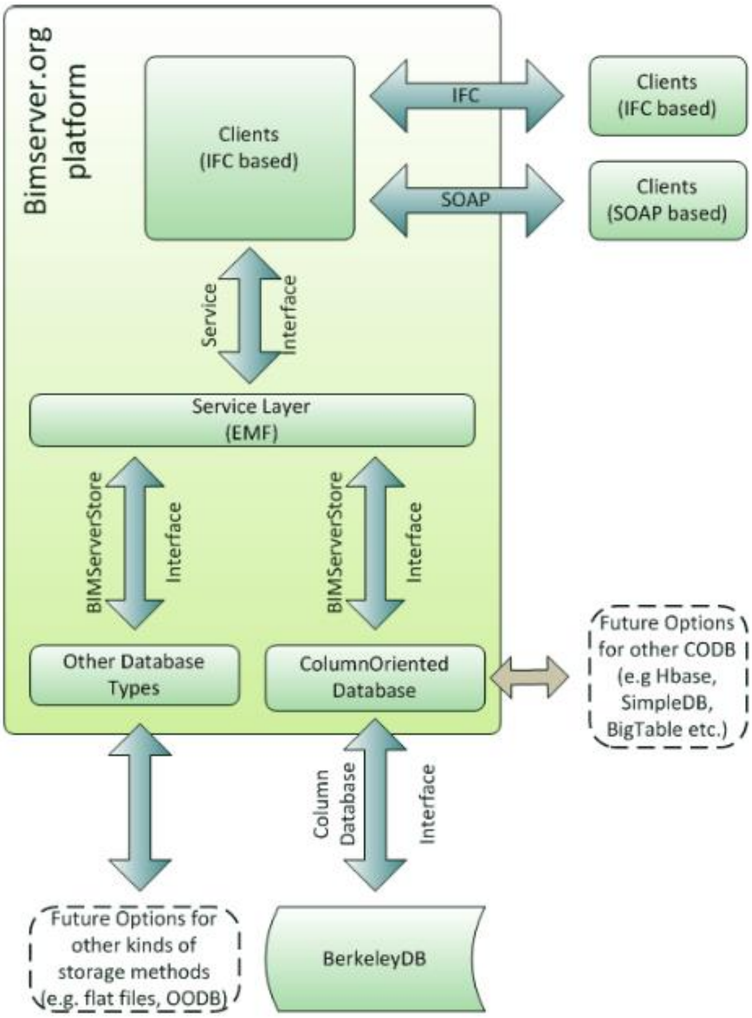


Figure 6-3 Simplified architecture of BIM server as proposed by Beetz, van Berlo, et al. (2010)

The BIM server acts as an IFC database, which has several Application Programming interfaces (API), plug-ins and an IFC based database. These comprise:

- API/ Connections – Web services, Authoring tools connections, visualisation, API (JSON, SOAP). The BIMServer JavaScript API uses the ECMAScript6 Modules concept.

- Plug-ins – Model checking, serialization/deserialization, render engine, services, compare, add/edit delete,
- IFC based database – Open standards, Object based versioning, Revisioning, User management, Merging

As described by the developers of the BIMserver.org platform (BIM Server, 2018), it has been created to aid programmers use it as a foundation to create BIM related web applications.

6.5.2.1 Application Programming Interface (API)

The BIMserver has three protocols which can be used; Protocol Buffers, Simple Object Access Protocol (SOAP) interface, and JavaScript Object Notation (JSON) interface. Upon review, the most suitable interface was the JSON API, as it was deemed to be the most useful for connecting to via web applications.

For the purpose of connecting to the BIMserver, a Java library has been developed by the open source BIM collective, 2016), and when creating the client applications (the BPM engine in this case) the dependency management was carried out using Apache Maven developed by the Apache Software Foundation (2018). When the Maven dependency for the BIMserver is referred to in the client application that was developed for this research, it dynamically downloads the relevant Java libraries and store them in a local cache. Once this has been done, it is possible to refer to the various dependencies within the BIMserver when developing the client application.

Figure 6-4 is a sketch of the expected workflow and the components that ideally interact with each other. The BPM Engine acts as the client application and the BIMserver as the server containing the relevant construction information. The client application governs the processes (BPMN) while the server contains the IFC.

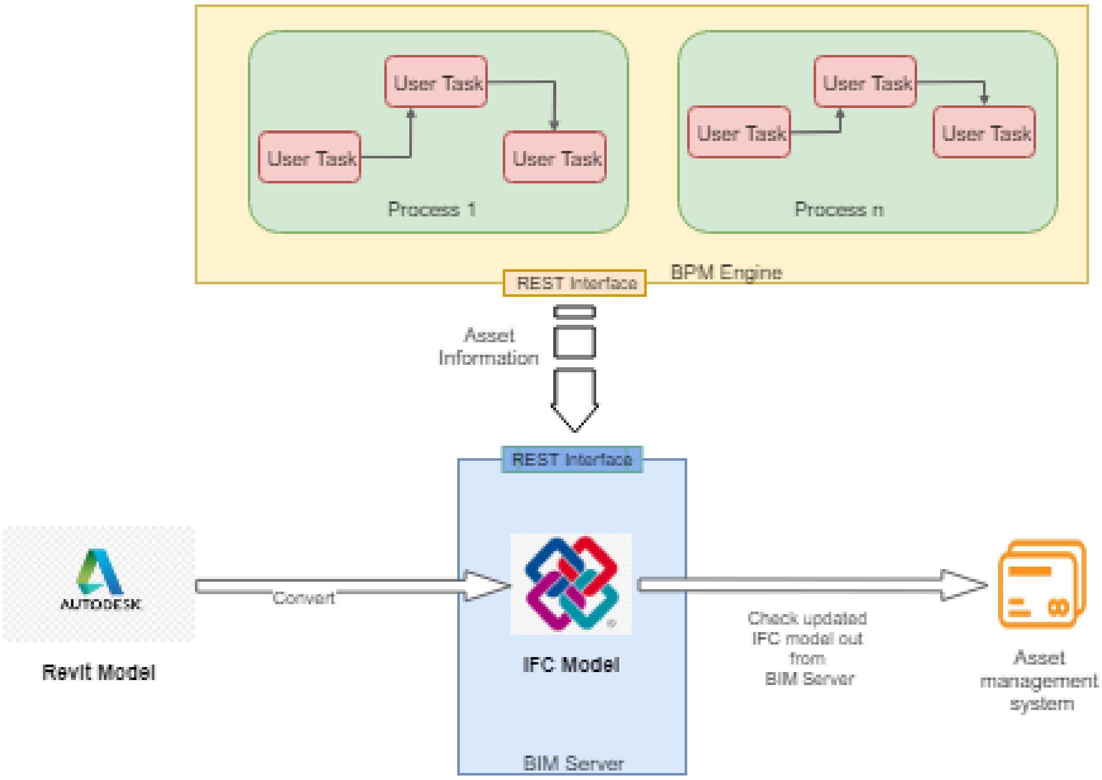


Figure 6-4 The expected workflow when using the proposed system

6.5.2.2 Methods of sending and receiving information

As was mentioned in Section 6.5.2.1, the BIMserver JSON interface was used to communicate construction information from the BPMS. The client application (BPMS system in this case) contains Java application which interact with the server as needed.

The client application contains a 'factory' which, in object-oriented programming, is an object which is used for creating other objects. This, together the other relevant application classes will then be used to interact with the server to send requests and receive responses as needed.

6.5.3 Client – Camunda BPMS platform

A conclusion was made in Section 2.3.2 that the most suitable engine to parse BPMN 2.0 was the Camunda Engine. The Community version (7.11) by Camunda (2019) was used, with an Apache Tomcat (Apache Software Foundation, 2018b) distribution. As shown in Figure 6-5, this BPMS (Business Process Management Suite) will store the process models and then interact via the server interface to send and receive information.

Figure 6-5 shows the various components of the overall system (this application will act as the client application). The 'Modeler' is the authoring tool that was used to map the BPMN diagrams (described in Section 5.3.3). These BPMN diagrams will have additional information such as Java classes, Scripts and forms added within it and uploaded to the file repository within the system which can be accessed by the engine.

These parsed process maps are accessed through a 'Tasklist' on the web application as shown in Figure 6-5 via the REST (Representational state transfer) interface of the process engine. The Tasklist allows users to trigger relevant processes and complete tasks if required. The 'Cockpit' is a GUI which allows users to monitor on-going processes and have an overview of all the various processes that have been defined. The 'Administrator' component of the application is available for the system administrator/ administrators to add new users and manage the system.

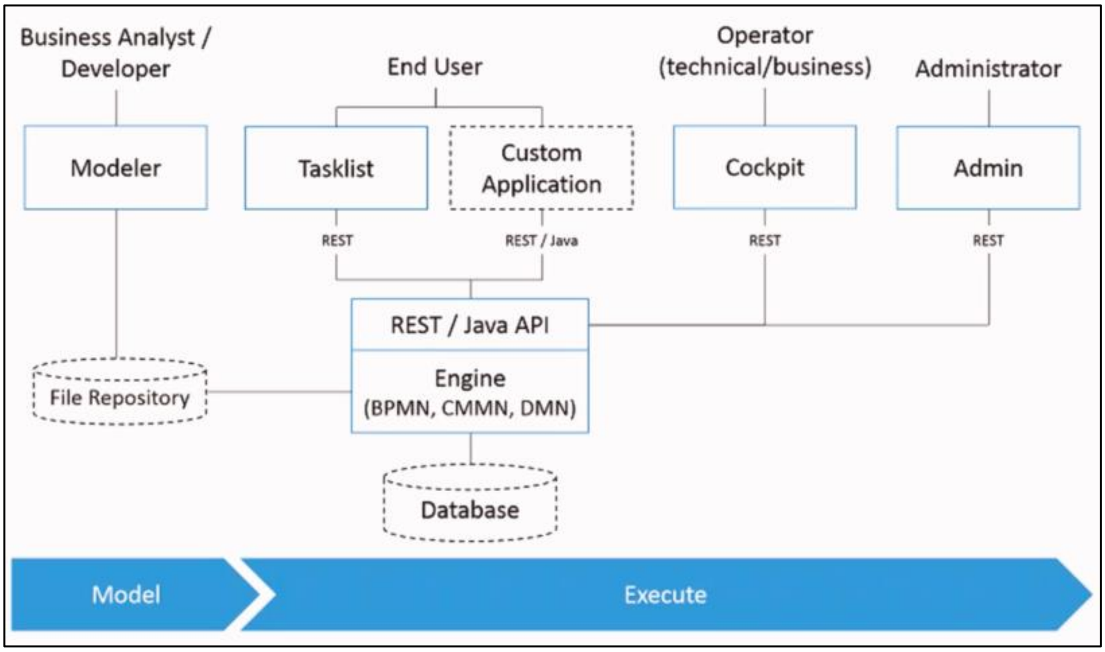


Figure 6-5 Camunda BPM Components (Camunda BPM, 2017)

6.5.3.1 The process engine

The engine has the capability of parsing BPMN 2.0 symbols, it is integrated with a Decision Model and Notation (DMN) Engine which can parse decision tables that can be embedded with the defined processes. As described in Figure 6-5, the engine has a REST interface which external web applications can communicate with.

This REST interface which is provided by the engine is beneficial as it can then perform tasks with external applications. Given the objectives of the research, the default Tasklist was used rather than creating a custom application.

6.5.3.2 Tasklist and Cockpit

These two components are a part of the Camunda BPM distribution that is accessible by default once the system has been set up. The Tasklist has a dashboard with three main components; a task filter, individual task list, and a task view (that shows the components of a single individual selected task).

The task view has the capability of showing the user forms that have been assigned to them (e.g. a product data template), as well as allowing them to view the history of the process and have an overview of the process. The 'Cockpit' is beneficial as it has the capability of showing how many processes are running and can be generally used as a monitoring tool.

6.5.4 System development

Figure 6-6 illustrates the main components of the prototype system created to make the BPMS interact with the BIM Server. The following subsection will first give a brief overview of the system and the interaction between its main components followed by a more in-depth analysis of the system.

6.5.4.1 Interaction between the systems

The BPMS orchestrates the flow of information and tasks both within the system itself as well as external applications such as the BIM Server. In Figure 6-6, the components labelled 1; (the HTML Forms and BPMN.xml), are the formats in which the information requirements and processes are represented. The Camunda modeller has the capability of creating basic HTML forms within certain tasks in the process maps, and the association between the task and the forms can be made directly using the tool. The programming of the application was carried out in Java (Eclipse IDE was used) and Java classes were created which were associated with the BPMN tasks.

A Maven project was created in the Eclipse IDE (Label 2, Figure 6-6), created with Camunda archetypes which therefore makes a Java project with the appropriate file structure. The process application/ applications were placed within this project and then linked to the Java classes that were also created within this same project. To ensure that the BIMServer client library was included within this application, the BIMServer dependencies were referred to in the application that was created.

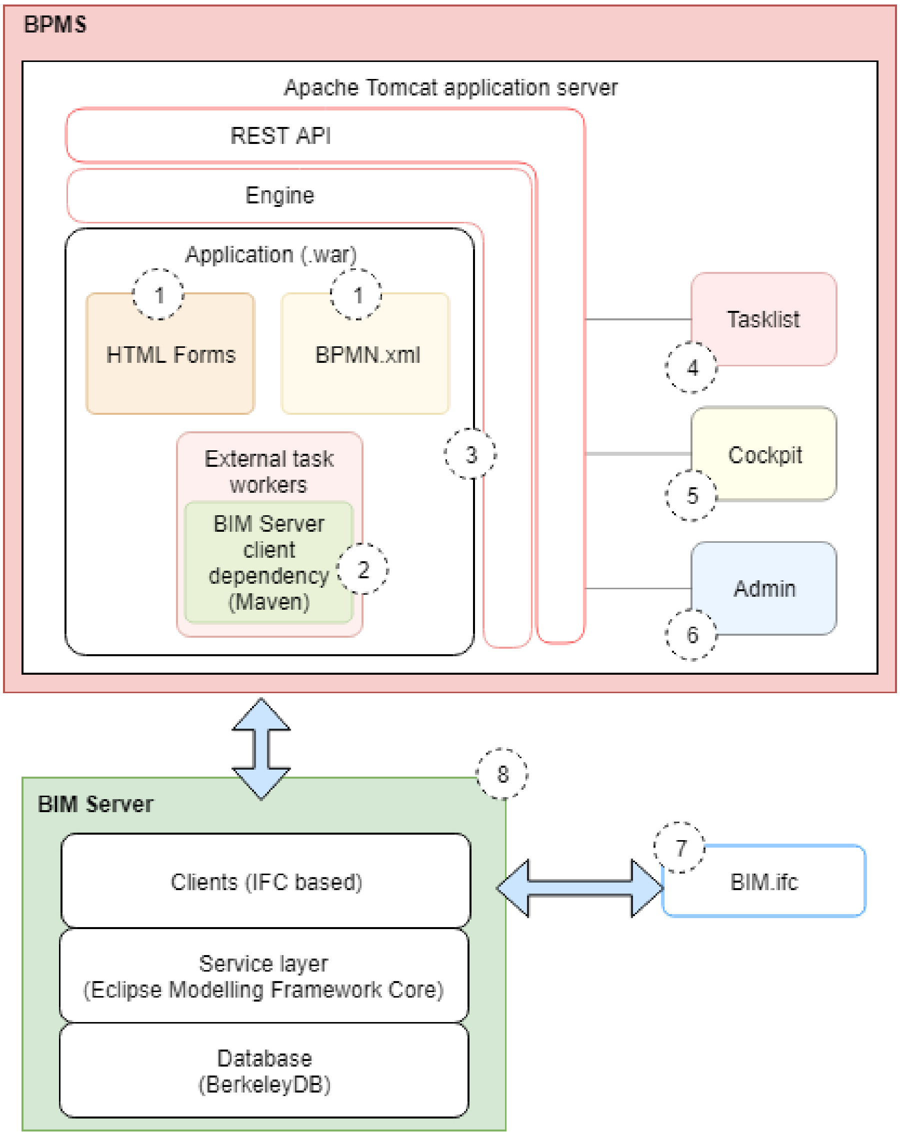


Figure 6-6 Components and interaction between the two systems

The BPMS was built on a Tomcat application server and contained the engine within it as shown in Figure 6-6. (The server was hosted locally). The WAR file, created as mentioned in the previous paragraph (Label 3, Figure 6-6), and was then uploaded into the application server. The BPMN engine was able to recognise and parse this WAR file, which then is then used via the various web applications within the Camunda system. The default applications within the BPMS were used and they were the; Tasklist (Label 4), Cockpit (Label 5), and Admin (Label 6) applications. Users who log-into the system are able to access these three applications. The 'Tasklist' is where users can initiate a process or execute a task that is assigned to them by a different user. The 'cockpit' gives users the ability to have an overview of running process instances and open tasks (interface shown in **Figure 11-1** in Appendix D). The 'Admin' application works based on the user access rights and controls what tasks the user can complete once logged into the application.

The BIMServer was also setup as required and the relevant IFC files were added within it (Label 7 and 8, Figure 6-6). As the client library had been setup within the WAR file placed in the BPMS and the appropriate server had been identified with it as well, the interaction between the BIMServer and BPMS worked in accordance with the tasks executed in the BPMS.

The following subsections break down the steps that lead to the conversion of the information requirements and their conversion into a format that can be recognised by the BIMServer. Figure 6-7 shows a basic BPMN process map that will have construction data submitted, which then will be embedded (in this case within an IFC file). The process starts with a form being brought up (Construction Data Submitted), the information submitted is transformed into a suitable format and the process ends with it being automatically embedded (Embed) into the IFC in the BIMServer.

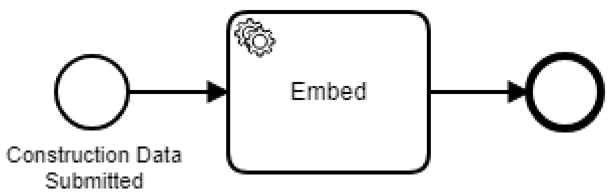


Figure 6-7 Simple process used to demonstrate the basic components that are parsed by the engine

6.5.4.2 Forms

When starting the process described in Figure 6-7, a form with the required information will appear for the user to enter the required information. Once this information has been entered onto the form, this information is converted into objects that can be recognised by the application and packaged in a format that can be transferred forward to the server. This form was written in HTML, which contains JavaScript that converts the information entered into the required format.

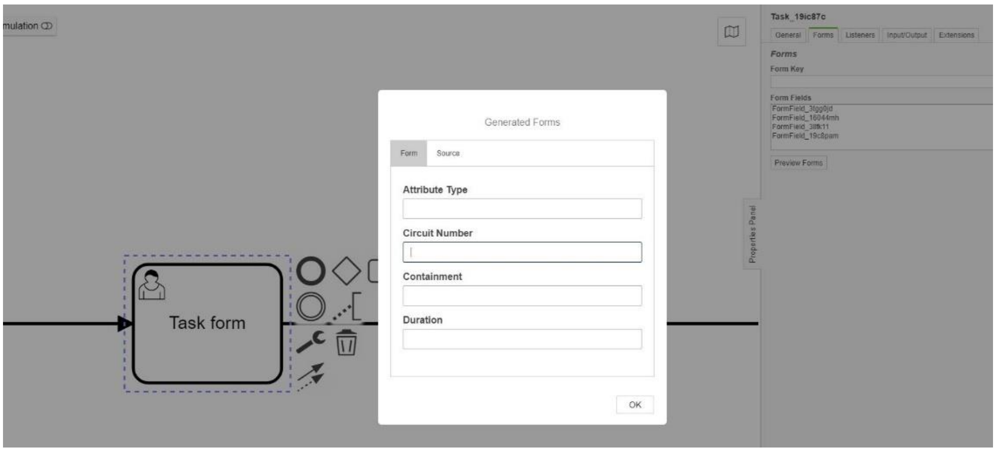


Figure 6-8 Screenshot of basic form created on modeler

As a starting point, a simple HTML form as shown in Figure 6-8 was created. Once this basic HTML form had been created based on the information requirements, then additional functions to each of the fields based on the user requirements to ensure that the information that was added was controlled and therefore consistent (Figure 6-9).

Figure 6-9 Screenshot of form with additional features such as dropdown menu and lists to assist users choose correct asset information

6.5.4.3 Information exchange

Figure 6-10 shows the transformation of the information requirements are used by the BIMServer client application that was created. The user fills in the form as required and then a custom script creates a JavaScript Object. The form is an AngularJS (AngularJS, 2018) form which binds the inputs to the defined object. This will be referred to in the executable BPMN process (Figure 6-7 'Construction Data Submitted' start task).

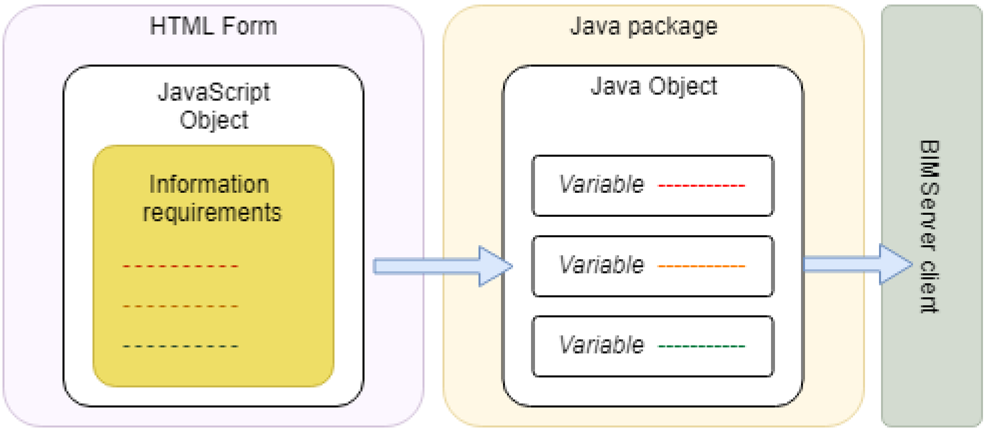


Figure 6-10 Conversion of information to Java objects which in turn will be used by the server client application

The executable process (Figure 6-7, 'Embed' task) contains a Java class that will access the relevant variables and transfer the information as required. As shown in Figure 6-6, this application will then be packaged as the WAR file to be parsed by the Engine. The Engine will parse the relevant tasks, forms and classes as defined by the user and orchestrate the processes as required.

6.6 Step 3 – Demonstration

In order to demonstrate the prototype system, a simple process map (Figure 6-7) with an embedded form was created and packaged as a Web Archive file as described in Figure 6-6. The user in this case was required to refer to the relevant model in the BIMServer and get the project's Universally Unique Identifier (UUID) which helps the client application communicate with the required project within the server. The UUID can be found from the project details in the BIMServer. Then the Global Unique Identifier (GUID) was required in the form in order to identify which exact object the information was to be transferred into.

In order to test the flexibility of the application, the user was able to specify which attribute will be changed within the IFC model. When the user entered the relevant attributes, the form was transferred and embedded in the IFC model within 15 seconds. As will be discussed in detail in Chapter 7, even when multiple attributes are sent to the server, the performance of the transfers are not greatly affected.

6.7 Step 4 – Evaluation

The system that was developed has the capability of parsing processes and information requirements. Users can then enter the information as required and the system automatically passes the information to the server which in turn embeds the information within the IFC stored within it.

To verify the system's applicability on construction projects, multiple processes were carried out in order to test whether the system was capable of handling large volumes of information simultaneously. The system that was developed in this chapter, when tested, ran over 2400 processes simultaneously on a 6-Core, AMD FX-6300 3.50GHz, 8GB RAM PC. Existing cases for the BPM engine shows that it can run well over 25000+ process instances at the same time, and is highly scalable (Camunda, 2019b).

Over the course of the project discussed in Chapter 4, A total of 26401 individual items (documents, models, images etc.) were collected in the project CDE in 2 years. Due to the system's capacity to execute such a large amount of processes simultaneously (25000+), and the volume of information that is produced on a highway project such as the EBL, this was considered to be a feasible solution for managing large volumes of construction information on a project.

The BPMS also has the capability of receiving and executing tasks from external applications. Even though this function was not explored due to the particular system requirements, this function could be valuable as it would enable other external applications communicate with the processes. This would be valuable as complex tasks can be performed outside the BPMS which will then execute tasks to complete the necessary process.

6.8 Conclusion

This chapter aimed to answer research question 4:

Can processes and information requirements that have been defined be automated, and what type of system can execute and govern these requirements?

This question was addressed by analysing the finings made in Chapter 5 in an attempt to understand how to analyse and execute processes and information requirements placed within them. The Design Science methodology was used in order to design the protype system which parses process and information requirements in order to exchange relevant information with a BIM server. By answering the research question, the solution to parsing and automating processes is to use a BPMS that can communicate with external applications. This type of system can both govern information by asking relevant users to complete tasks and have external applications execute tasks so that processes are followed in accordance to the specific requirements. When evaluating the system, and assessing its capacity to handle the typical volume of data that is produced on a highways project (Chapter 4), it is possible to conclude that that this system will be able to handle such vast quantities of data while also having the benefit of governing processes and the flow of information. Answering this research question contributed towards:

- Developing a prototype system that facilitates the exchange of construction information by governing specified processes. This included presenting the system architecture and the logic used.
- Demonstrating that the system developed at this stage of the research can efficiently log and exchange information with BIM applications such as the BIMServer.

Chapter 7 Framework development and validation

The findings in the previous chapter showed that there is a need to establish system and information requirements as well as processes. As a consequence, a framework that can capture these requirements has been developed based on the work presented in the preceding chapters. The framework is based on the assumption that the Standard Method and Procedures (SMP) adopted will conform with the likes of BS 1192 and/or the ISO 19650 and the advice given in their supporting.

7.1 Revisiting the research question

This chapter aims to address research question 5 restated here as:

Can the defined processes and system be adapted on an infrastructure project and what steps need to be taken to do so?

Once a prototype system had been developed in order to answer question 4, the next step was to analyse the operational process maps that had been developed to understand how compatible technical process maps could be created and linked to construction information management systems.

The framework seeks to align VDC processes with existing information management practices in order to ensure that the creation and handing over of information was carried out effectively. The framework is then tested by attempting to implementing it on a project with the aim of understanding the flexibility of the framework, and whether it can be implemented effectively.

7.2 Framework development

The framework comprised of two main elements:

1. Process discovery
2. Technical requirements identification

7.2.1 Process discovery

The processes that are to be adopted have to be established and then enforced at the start of a project. Therefore, it is essential that they are agreed upon and included in the contract and project documentation. Figure 7-1 has been derived from Figure 5-1 described in Chapter 5, the figure shows the main steps that were taken to create the human and technical process flows.

The strategic process model describes the main exchanges of information and related documentation, similar to that shown in Figure 5-2 and Figure 5-3 in Section 5.6.1.

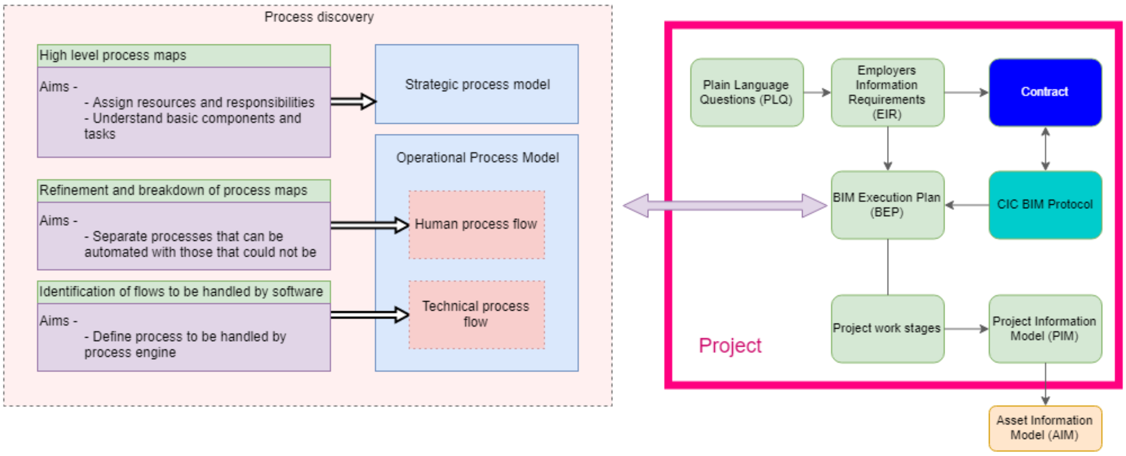


Figure 7-1 Process discovery on a project level

Once the strategic map has been created, the processes must be broken down in further detail to establish what processes can be automated and which ones cannot be. Further, it is useful to understand which tasks or processes can be fully automated such as the 'Embed' task in Figure 6-7 (Section 6.5.4). In some instance processes cannot be automated for example due to the complexity of the tasks or if they are tasks that have to performed manually. However, having a record of processes that cannot be parsed and governed such as those presented in Chapter 4 are beneficial to aid project engineers understand certain procedures.

7.2.2 Identifying technical requirements

To create a process management system that can meet project specific requirements, the steps illustrated in Figure 7-2 should be followed (Based on the Design Science methodology). Once the processes and requirements have been identified in accordance with the steps shown in Section 7.3.1, the system can be developed based on feedback given by project participants. This involved the project participants initially providing information of their current processes and the manner in which they shared information. Following this, they tested the system that was developed as a part of this research in order to identify the practicality of its application, and how they expected users to use and access the system.

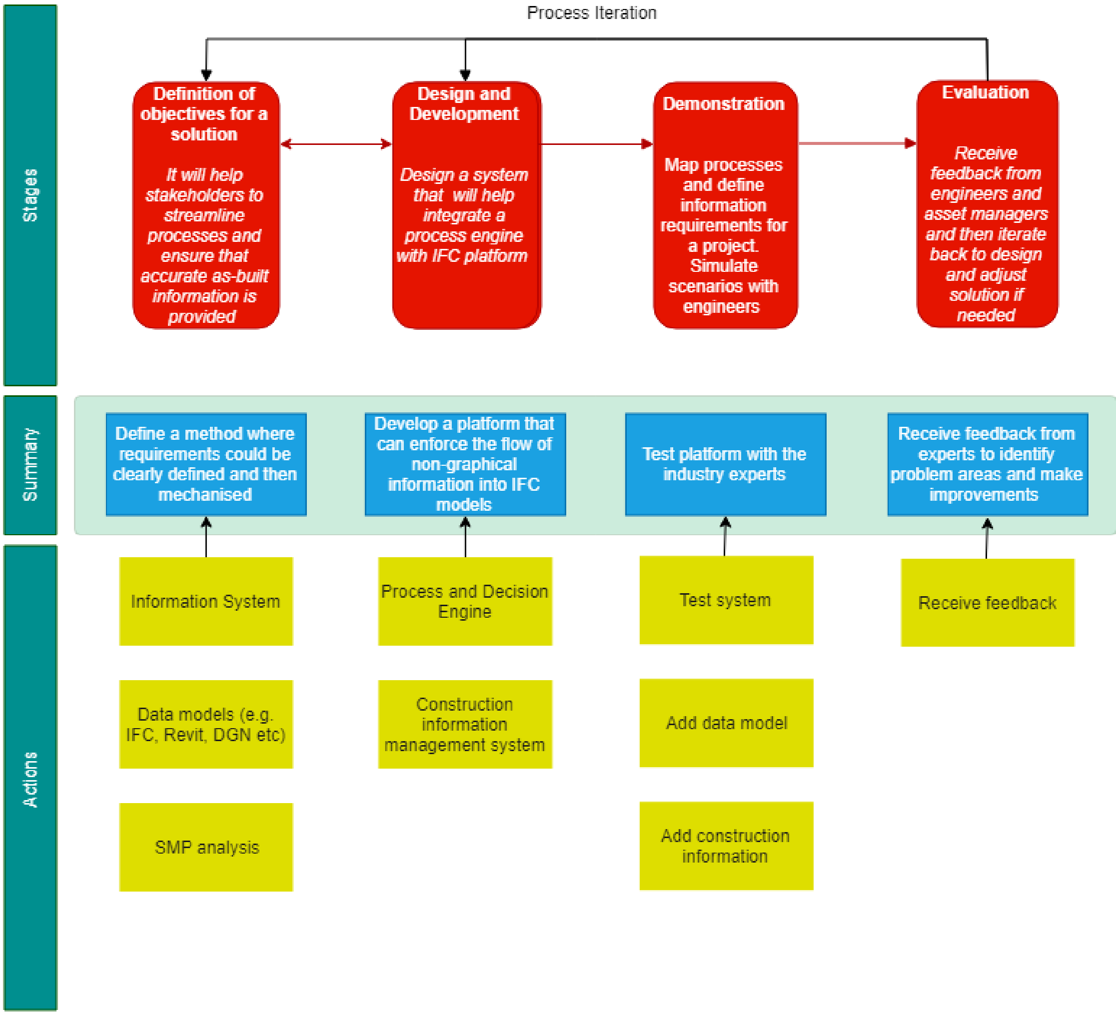


Figure 7-2 Iterative approach to understanding and developing system requirements

7.2.3 Proposed framework

The process discovery must occur in conjunction with the system development, as they will supplement each other. The technical development can potentially be influenced by the processes and vice versa. Figure 7-3 shows the main components of the framework that was proposed as a result of previous findings. Each of the components and which sections of the research that were referred to when creating the framework has been annotated in the figure. The next subsection of this chapter describes the validation of the framework on an infrastructure project.

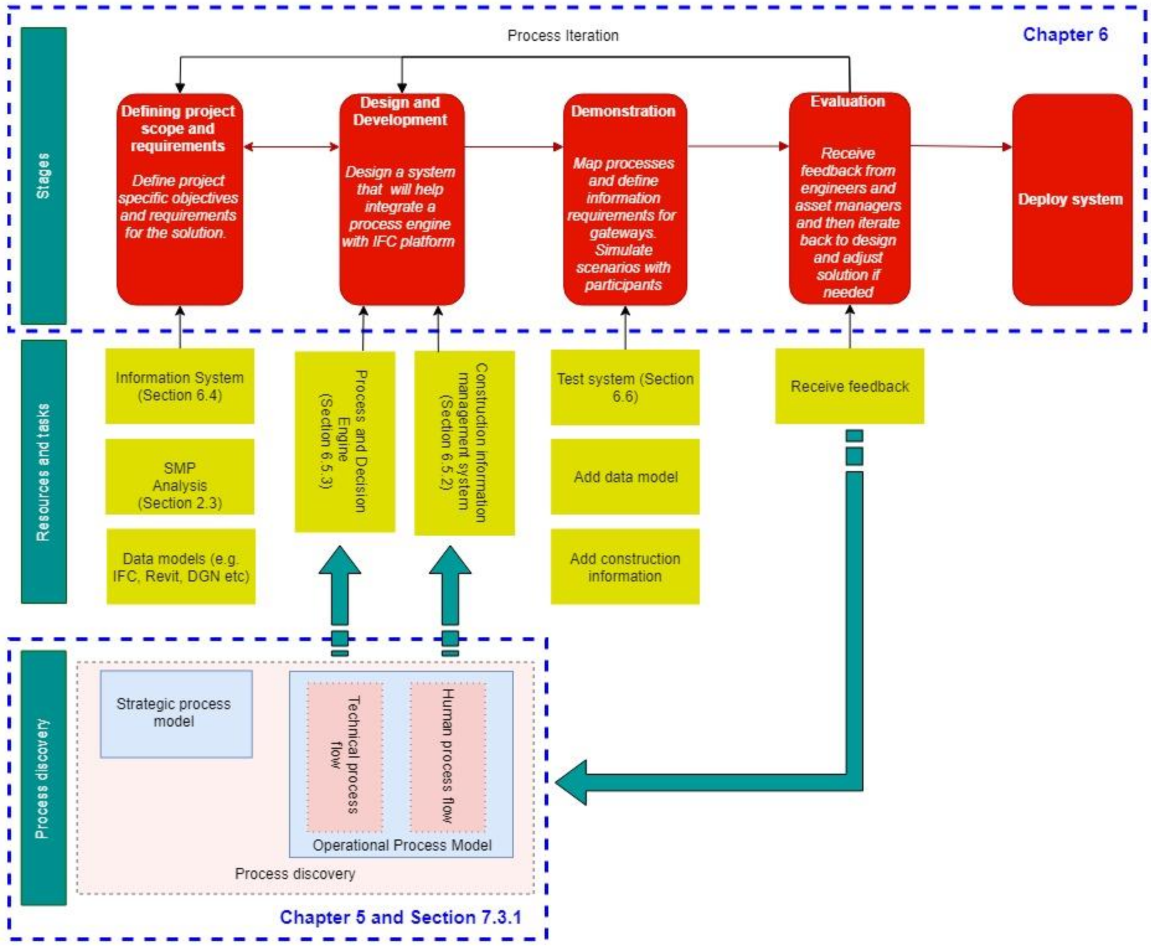


Figure 7-3 Framework components

7.3 Framework Implementation

The framework was validated by implementing it on an airport project in the UK. The aim of carrying out this trial on the development of an apron (airport) rather than directly on a highways project was that they shared similarities in terms of the linear nature of the assets. However, the manner in which the infrastructure was used and the network of roads linking the airport, the runway and aprons differed to that in highways. Therefore, even though there were certain similarities in which processes were carried out and the way information was stored in databases, there was an anticipation that the uses of the two types of assets (highways and airports) will influence the information requirements. This variation presented the opportunity to test the generic processes defined in Chapter 5, but also was useful to show that the framework was flexible enough to factor in the changes in tasks within certain processes depending on the type of asset that was being built/maintained.

Upon assessing the documentation and the SMP being used, the project was classified as falling into a Scenario 1 category as described in Table 5-4. It was also considered to be useful as the information requirements and the processes differed to those typically found on highways projects, which were the focus of the fourth and fifth chapters. This would therefore confirm whether the framework was flexible enough to deal with very varied project specific requirements.

7.3.1 Validation - Outline and motivation

The objective of the validation exercise was to introduce the framework to the engineers and information managers on a live project in order to test the feasibility and the efficiency of the research's proposals. The selected airport project had a comprehensive set of information requirements (AIR, OIR and EIR equivalents) setting out precise gateways, common language and asset attributes that needed to be handed over. The contractors had to produce a BIM Execution Plan (BEP) and documents such as competence assessments (sent to suppliers), asset integration strategies and delivery plans. The information was expected to be handed over into a centralised system which was going to be audited over the course of the project and then finally integrated into the asset management system at handover.

There were structural, architectural, mechanical and electrical models that were created following the preliminary design. An asset register was in place to record asset information as required by the asset operator. The UK standards (BS 1192 series and supporting documents) were being referred to when implementing VDC on the project. The models were to be authored using a specific version of Autodesk Revit and Navisworks was used for the coordination of the models. The Viewpoint Common Data Environment (CDE) was being used to manage project information. Certain information from this CDE is was then to be taken and uploaded into the asset operator's system for approval.

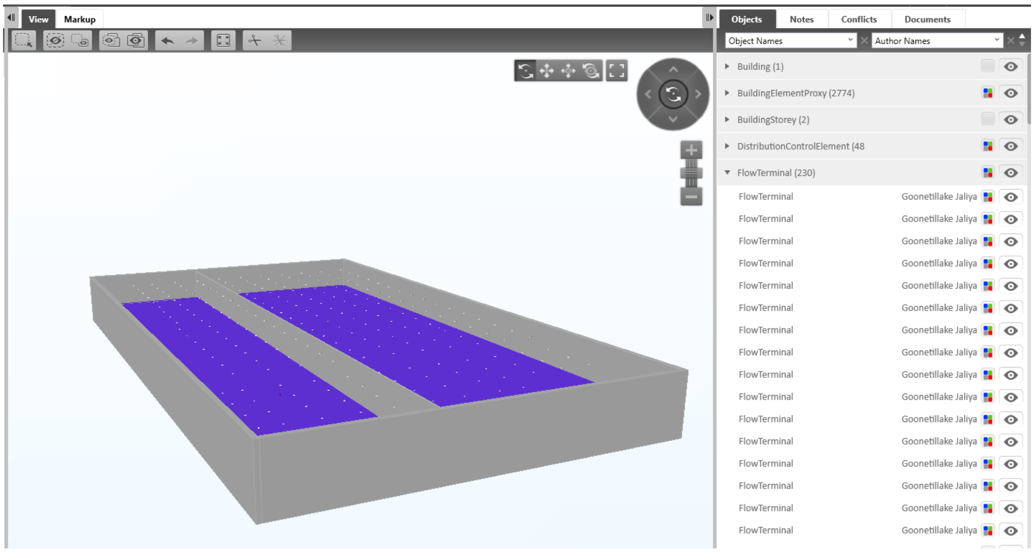


Figure 7-4 IFC model of the structure and lighting (Viewed on Tekla BIMsight)

The main structure that was being built was a box shaped structure which was to contain equipment in order to process baggage. Figure 7-4 is a screenshot of some of the structural and electrical elements represented in the IFC format that will be used to test the prototype system.

The next few subsections will cover each of the steps defined in the framework (Figure 7-3), where the various system and process requirements were recorded and used. Figure 7-5 shows the steps, actions and the resources taken both from the project as well as the project in order to implement the framework. Several iterations were made in order to define both the system and processes; therefore, the next few sections will discuss only the results of the final iteration.

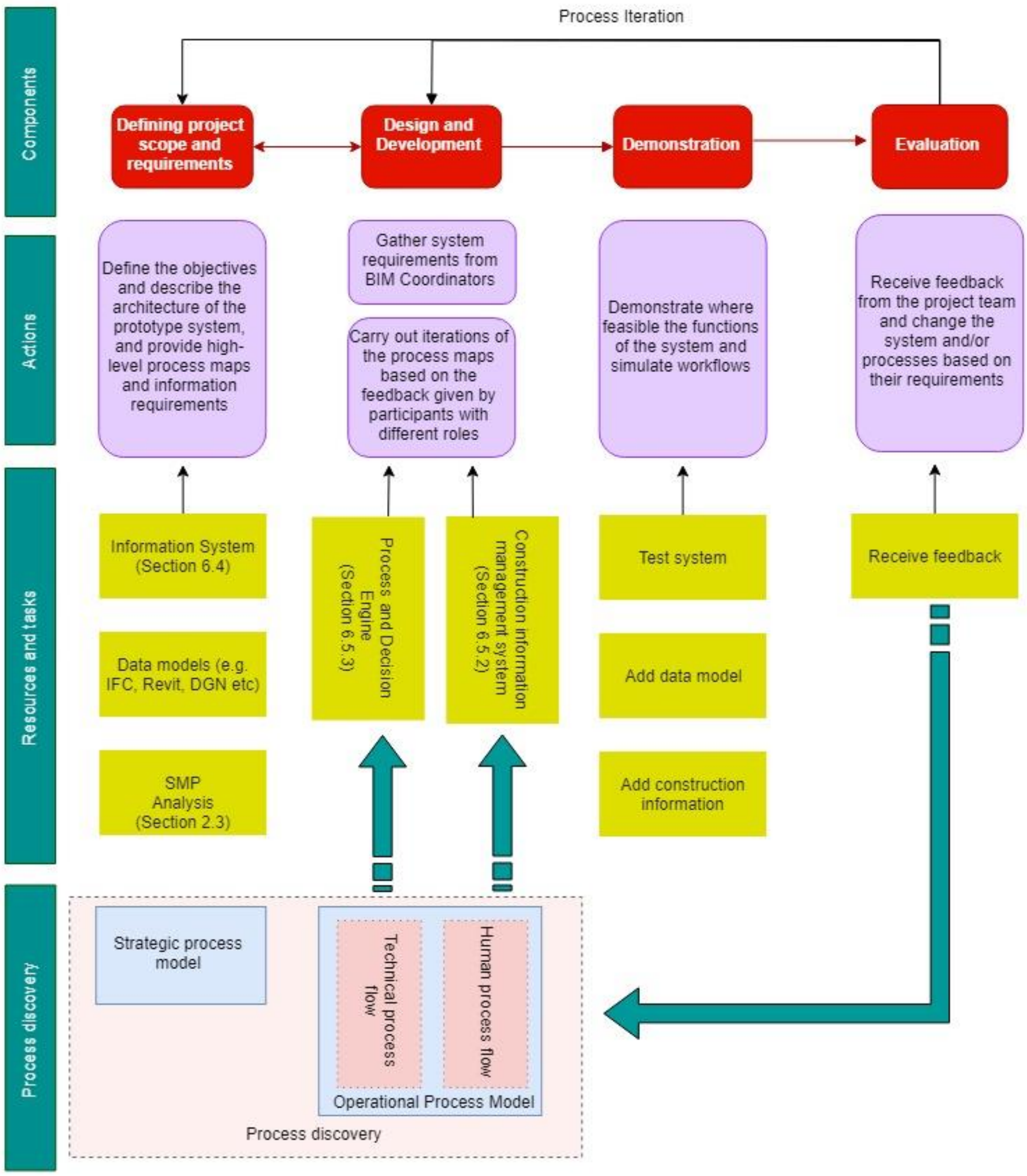


Figure 7-5 The workflow followed when validating the framework

7.3.2 Identifying project scope and requirements

In order to get an understanding of the project and the VDC related requirements, the project documents were reviewed first. Further, several discussions were held with the project engineers in order to gain an appreciation of the project and the manner in which VDC was deployed on the project. This was deemed necessary, as the industry standards were ambiguous and therefore tend to be interpreted in many ways (Section 4.7). Therefore, it was important to establish the way VDC was being interpreted on the project. The main documents that were reviewed can be seen in Table 7-1.

Document	Description
Asset Information Requirements (AIR)	This document described the employer's asset information requirements in detail
Asset Information Modelling Standard and its appendices	Described the modelling standards; equivalent to CAD standards. The appendices covered very specific details of the modelling requirements
Common Language and its appendices	Covered the employer specific common language that was aligned with Uniclass 2015
Employers Information Requirements (EIR)	General EIR referring to other external and internal standards
BIM Execution Plan (BEP)	The execution plan based on the requirements that have been set

Table 7-1 Project specific documents that were reviewed

When referring to the 'defining project scope and requirements' step of the framework illustrated in Figure 7-5, there were three resources that had to be referred to. These resources were; the information system currently being used, the types of data being used, and the analysis of the SMP (highlighted in yellow in Figure 7-5). The project stages and gateways were identified based on those that were presented in Figure 2-1 and Figure 2-2 (Chapter 2) as well as the project specific gateways. The Level of Model Definition (LOMD) and general uses were placed as shown in Figure 7-6 alongside the stages and gateways. The LOMD is a combination of the Level of model Detail (LOD) and Level of model Information (LOI) as defined by the PAS 1192-2:2013, (2013). A summary of the actions, documentation and information models to be exchanged have been summarised in Table 7-2.

Existing information systems

The project information was stored in a Common Data Environment (CDE) chosen by the lead appointed party (Viewpoint 4Projects). The system was set up in accordance with the post tender BEP and the information was managed on a file-based level. The asset operators had their separate asset management system to which the project information was to be transferred into at previously agreed milestones.

Data

The asset register created by the operator specified the exact requirements for each type of asset or system. Some of the information was to be produced in flat files as well as information models both in native file formats (Revit) and also IFC. However, as IFC for infrastructure (IFC4) was still not a stable format at the time, a decision had been made that the information had to be delivered in the IFC 2x3 format along with the native files.

SMP Analysis

The project participants were expected to comply with the BS 1192 series of standards and their supporting documents. It was evident that the asset owners/operators had interpreted the standards in a flexible manner so that information produced on projects such as this complied with the standards but was also compatible with their existing asset information.

7.3.3 Strategic process model

This stage occurred in conjunction with what was done in Section 7.3.2 as the information requirements and the basic process were identified based on the project documentation. Some processes created in Section 5.6 were also shown to the BIM team working on the project, which allowed them to build upon or change these processes based on their requirements. A scoping document was created as a part of this step to help the participants understand the objectives of the exercise. The gateways that were defined (G1 – G6 in Figure 7-6) are the various instances were information was to be exchanged or reviewed either externally or internally within the organisation. The main sequence of events in which as information is captured were broken down roughly during the discussion (Table 12-1 in Appendix E) and then a strategic process map was created based on these steps.

The maps were derived from some of the information that was gathered and summarised in Table 7-2 as well as feedback from the participants. The documentation that was provided by the asset operator clearly stated the requirements and was aligned with the relevant SMPs. A decision was made to focus only on the information exchange and related processes between G4 and G6 as the research primarily focused on the construction phase of projects and what type of information is produced and handed over.

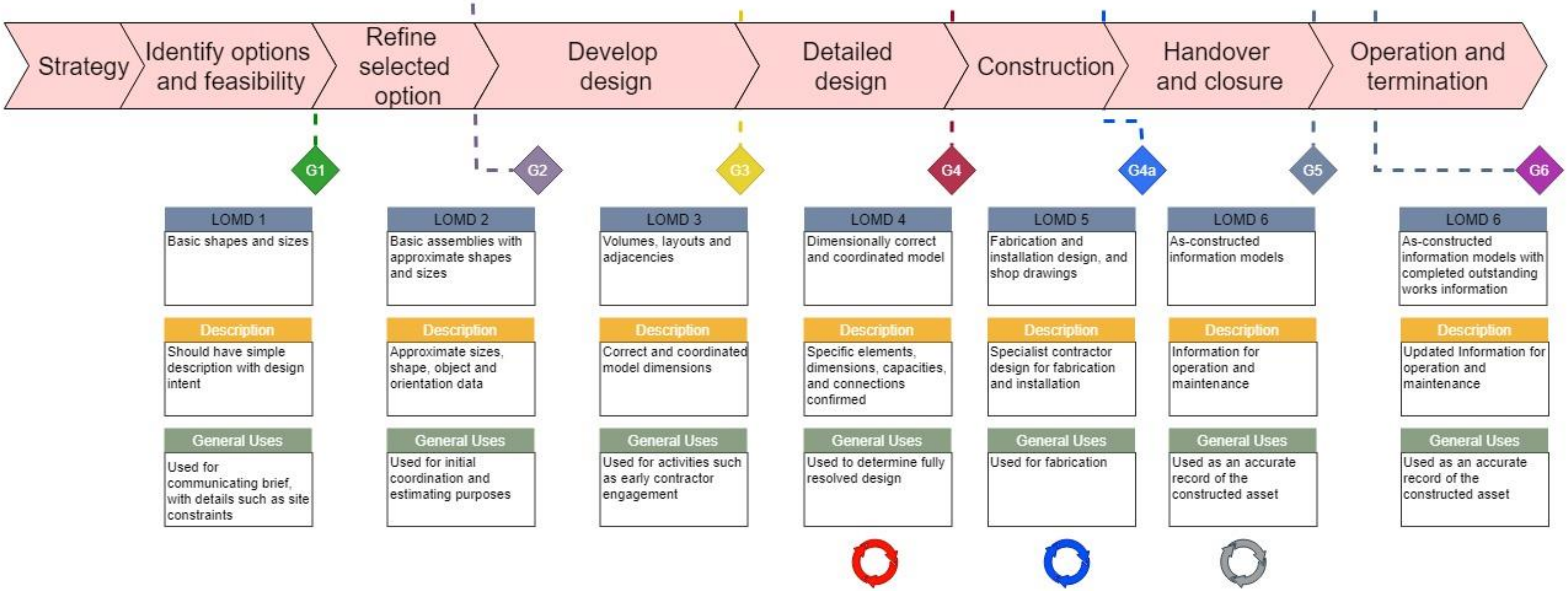


Figure 7-6 Diagram showing information exchange gateways between the early strategical stage and the operation and termination of a project.

Gateways				Description	Actions	Documents	Models/drawings
G3				Project scope matrix		o	
G3				Handover deliverables schedule		o	
G3				Bringing into Use plan	o	o	
G3				Baseline schedule	o	o	
G3				CAD models and drawings supplied to client with Information Modelling Certificate of Compliance			o
G3				BIM Execution Plan published by the project designer and delivery integrator to be accepted by asset owner's data manager			o
G3				NCR issues resolved for G3	o	o	o
G3	G4			Maintenance and support model documented	o		
G3	G4			Maintenance training and /or familiarisation requirements and plan	o		
G3	G4			Asset registration/modification	o		
G3	G4			Spare parts requirements agreed	o		
G3	G4			Specialist tools/equipment/software and license requirements agreed	o		
	G4			Project scope matrix updated and published with all tier 1 supplier details		o	
	G4			Project specific Handover Deliverables Schedule updated and published		o	
	G4			Bringing Into Use Plan	o	o	
	G4			Production designer Design Certificates of Compliance complete and transmitted	o	o	
	G4			Asset information registered in client system	o		
	G4			Preliminary models & drawings with asset numbers	o		o

	G4			Preliminary models and drawings supplied to client with Information Modelling Certificate of Compliance			o
		G5		New, modified and removed assets updated in client asset management system	o		
		G5		Asset labelling complete	o		
		G5		Complete Commissioning and Certification	o	o	
		G5		Production Certificates of Compliance	o	o	
		G5		Specialist tools, equipment, keys, passwords, software and licences supplied	o		
		G5		Snags identified and resolved where necessary for stage	o		
		G5		As-built CAD models and drawings and Information Modelling Certificate of Compliance			o
		G5		H&S File - Project details section, Facility management section, and O&M (i.e. all sections)	o	o	
		G5		Asset information released to users	o	o	o
			G6	Snagging	o		
			G6	Outstanding works register (recording asset changes)	o	o	o
			G6	H&S File completed based on Outstanding works register	o	o	o

Table 7-2 Actions, documents and graphical models/drawings to be submitted at each stage

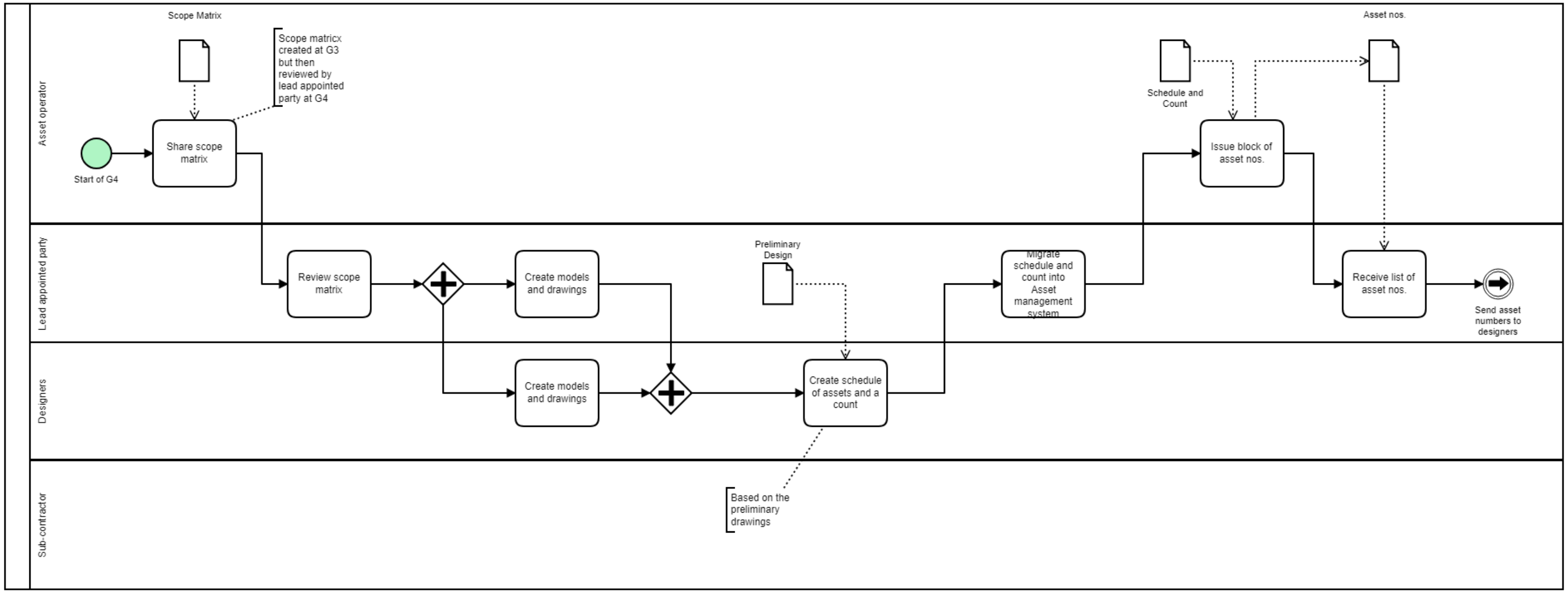


Figure 7-7 G4 – Assignment of numbers - Strategic process map

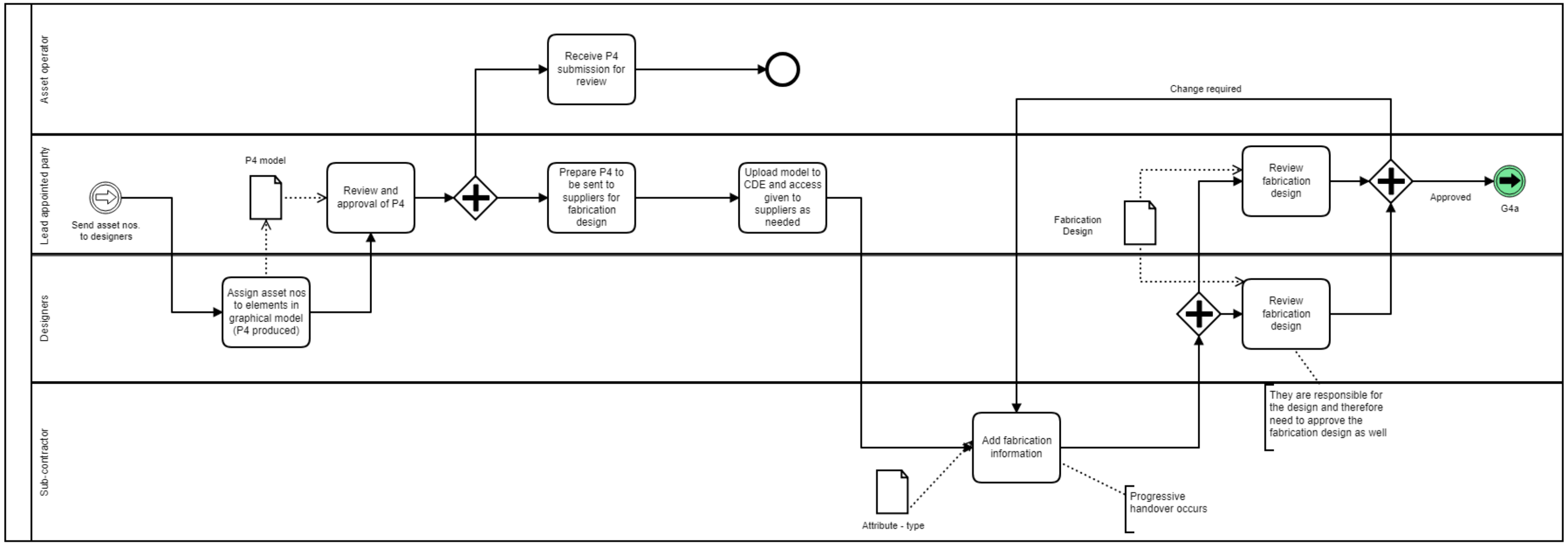


Figure 7-8 Assignment of asset nos. G4a - Strategic process map

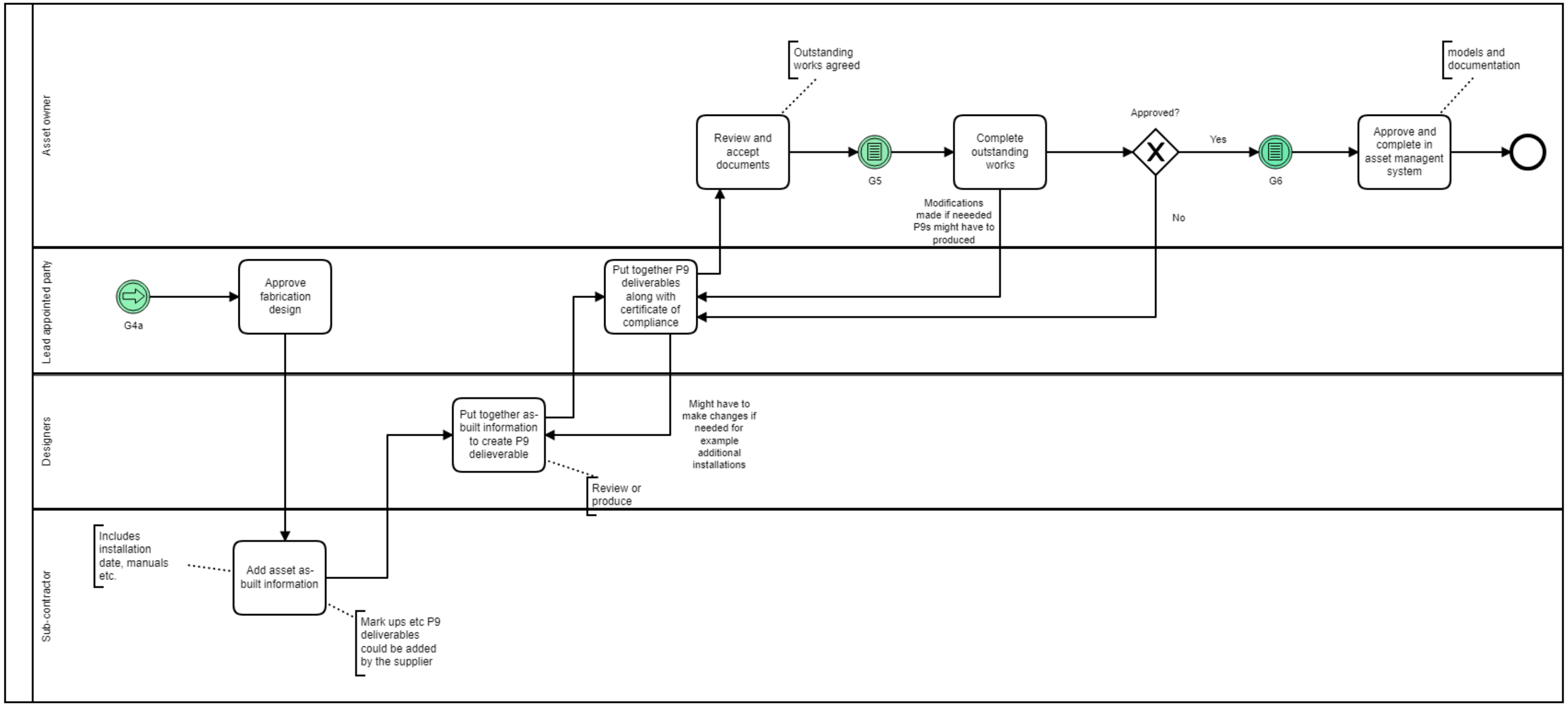


Figure 7-9 G4a to G6 - Strategic process model

The strategic map was broken down into three parts (Figure 7-7, Figure 7-8 and Figure 7-9) in order to visualise it clearly. The map starts with the asset operator sharing a scope matrix. Then based on the count given to them following the preliminary design, a block of asset numbers is issued and transferred to the lead appointed party. Figure 7-8 shows the flow of information between the creation of shop/ fabrication drawings and an internal review carried out by the lead appointed party. Figure 7-9 shows the main steps for creating and putting together the as-built information before finally adding this information into the asset management system.

7.3.4 Operational process models

The operational process models were created in order to identify which processes and tasks could be placed within the process engine. The aim was to develop a system where there were no silos created between various project participants over the course of the project.

In order to highlight that certain internal processes had not been finalised when the operational process maps were created, there were instances where certain 'pools' in the process maps were left blank with arrows only showing the information that needed to be produced by the participant in the pool (e.g. Designers in Figure 7-10). Figure 7-11, Figure 7-12 and Figure 7-13 describe processes and subprocesses leading to the eventual integration of asset information within the asset management system. Figure 7-14 describes the process of adding information within the BIMServer during construction. The aim of recording these operational processes was to understand which tasks or processes could be automated. As discussed in the next few subsections, the objective was achieved by taking into account the processes recorded in this section, as well as the information and system requirements that were given.

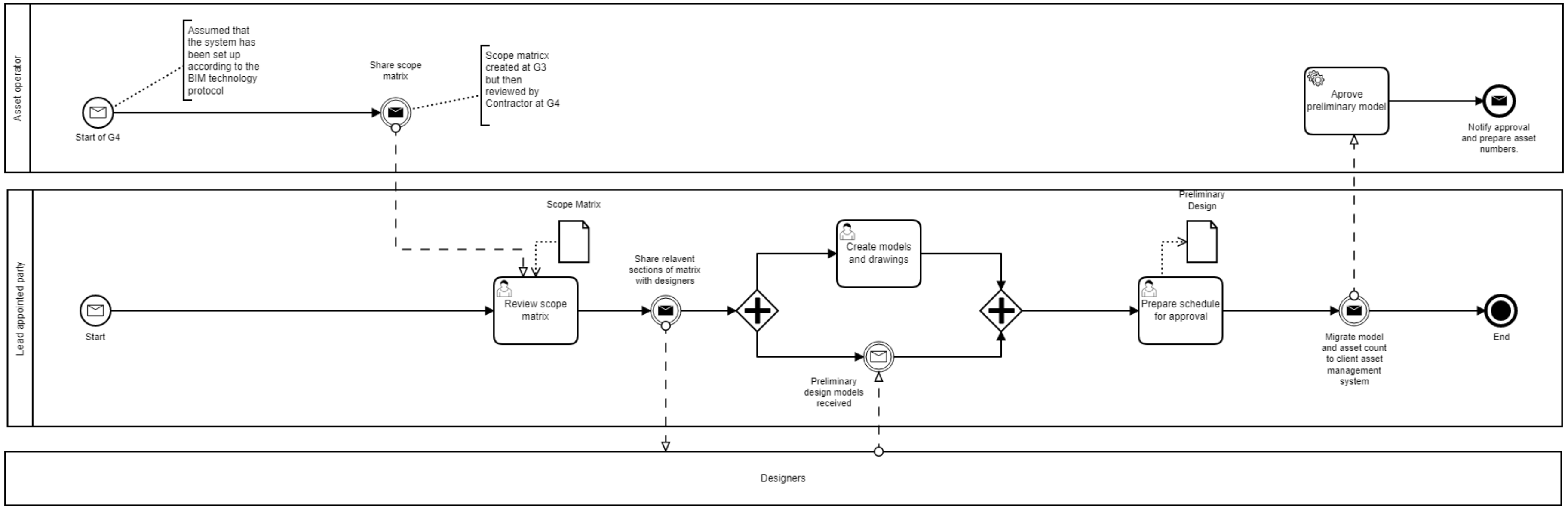


Figure 7-10 Preliminary design approval - Operational process map

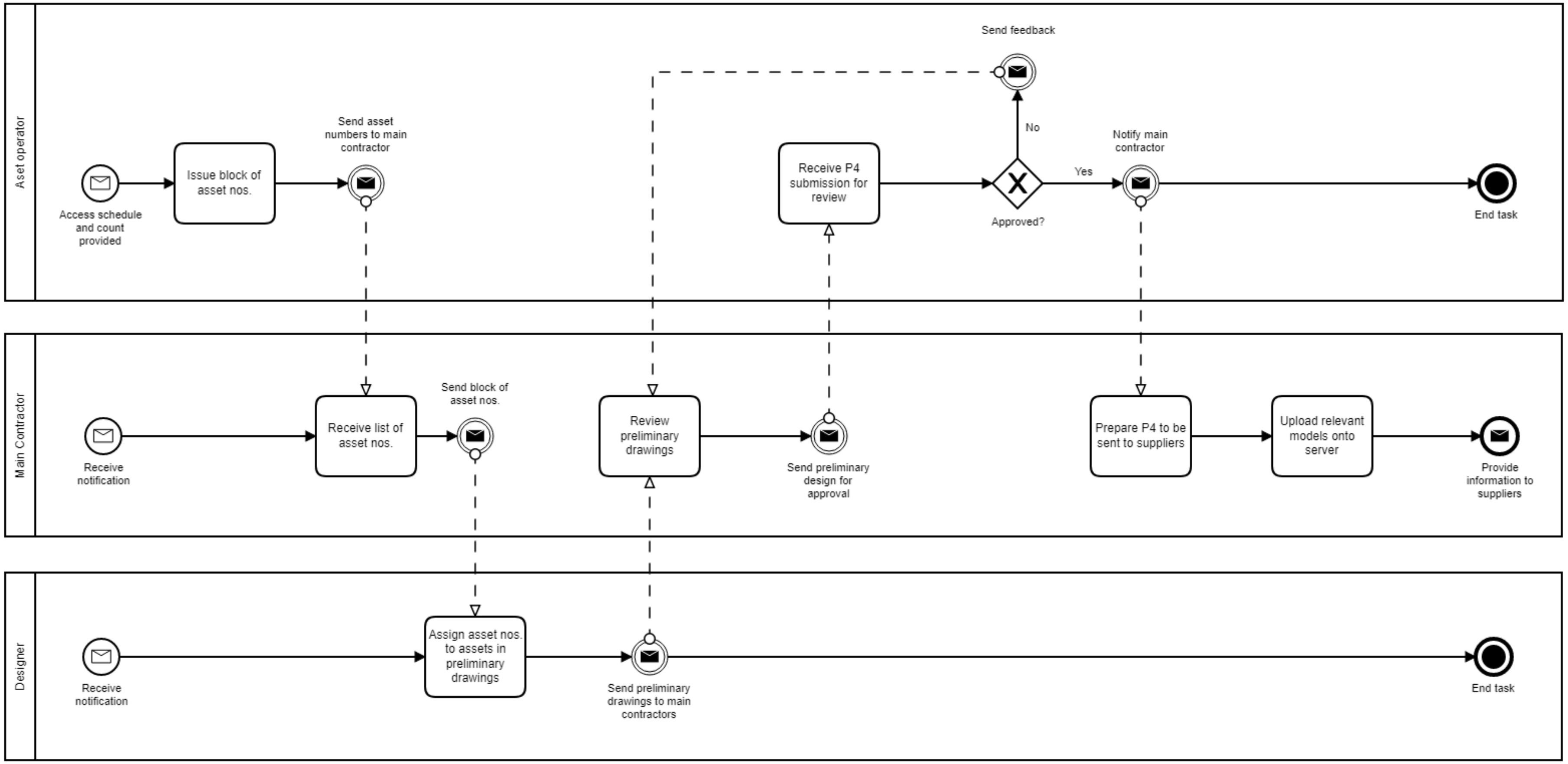


Figure 7-11 Provide information in order to develop fabrication design – operational process map

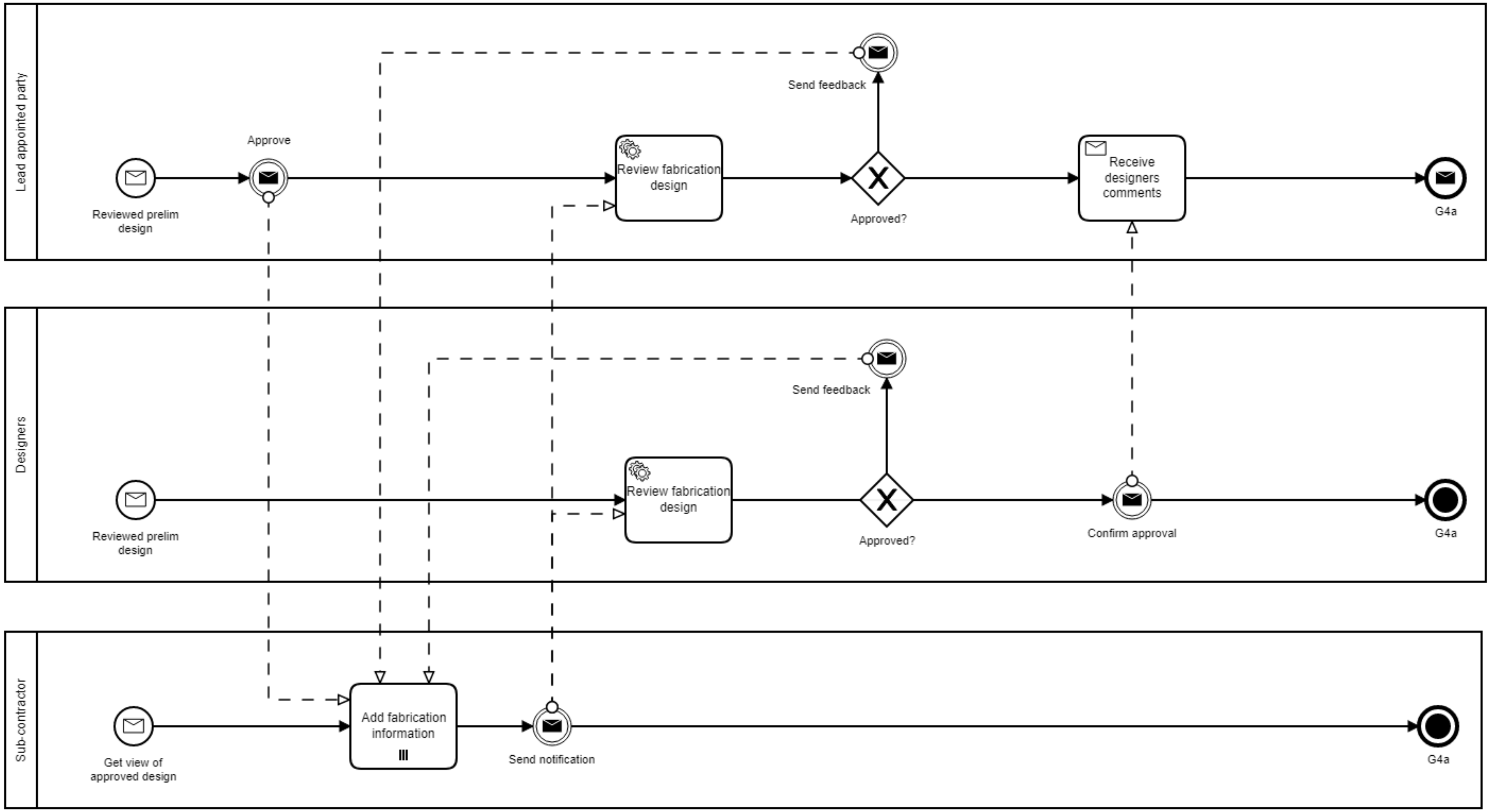


Figure 7-12 Information exchange and internal gateway – operational process map

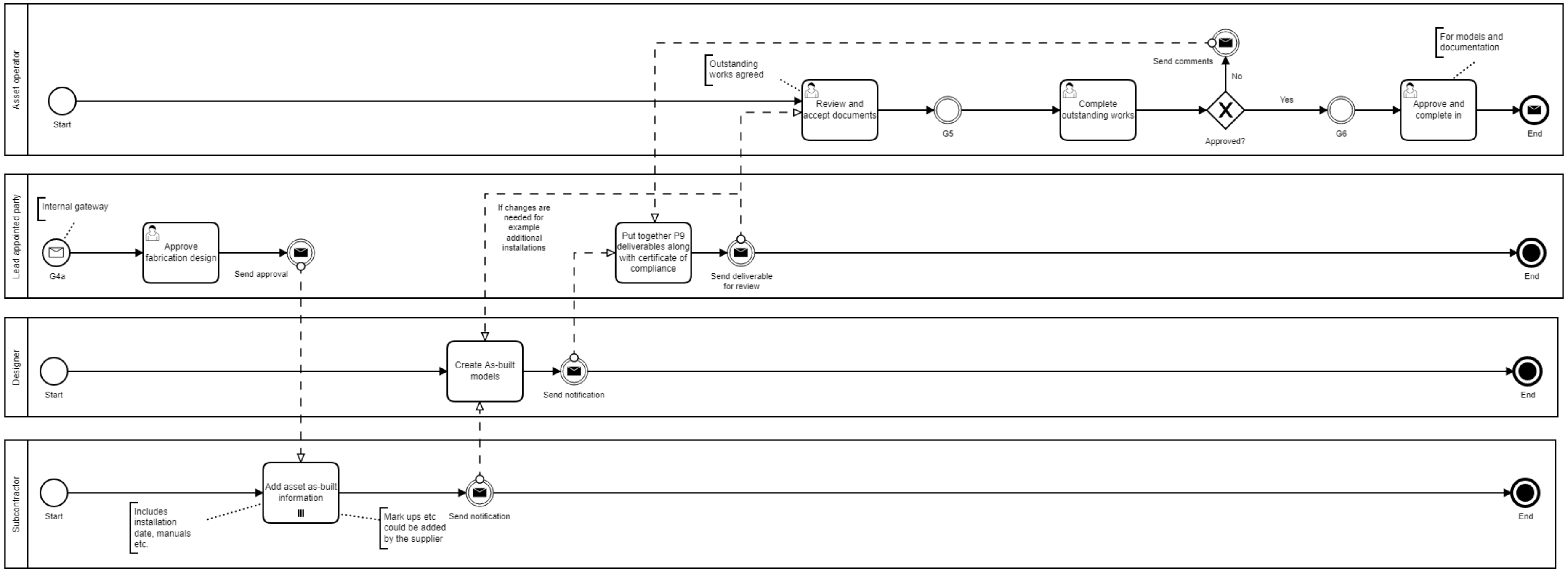


Figure 7-13Adding and handing over construction information – Operational process map

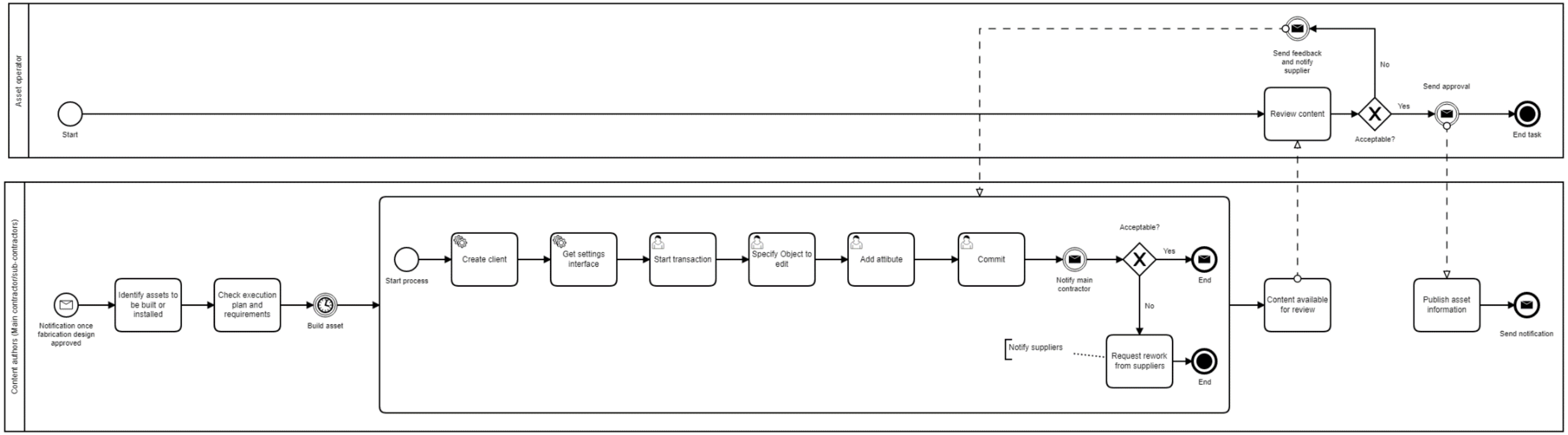


Figure 7-14 Subprocess for adding information on server -operational process mode

7.3.5 Design and development

As seen in Table 7-2, there are actions to be undertaken, and documents and models to be produced over the course of the project, sometimes with an overlap between what is required at G3 and G4. It is therefore important to recognise that some of these tasks cannot be orchestrated by the engine. The capability of being able to upload and view certain documentation as well as communicate between the BPMS and external applications was explored. However, the emphasis was on the link between the BPMS and the BIMServer.

The system architecture shown in Figure 6-6 was used, as it was agreed that this was suitable for this project. The project required that the information be delivered in Revit as well as IFC.

7.3.5.1 Versioning

The model was created on Revit by the designers and the basic non-graphical information was added to the geometry. This Revit model was then exported with the necessary attributes including the Global Unique ID (GUID) that is assigned to each element by Revit. This GUID was then be referred to when adding information via the engine. The aim was to be able to have an interaction such as that described in Figure 7-15 so that the information set in the form could be transferred directly into the relevant IFC objects.

An observation was made that when creating the model on Revit, regardless of model changes, the GUID for objects should remain the same. However, on the server, each individual object must also have a unique Object ID (OID) as it is important to ensure that the server stores each version of an element separately. Therefore, each time an element was changed via the server, the GUID remained the same, but the OID was changed for each instance.

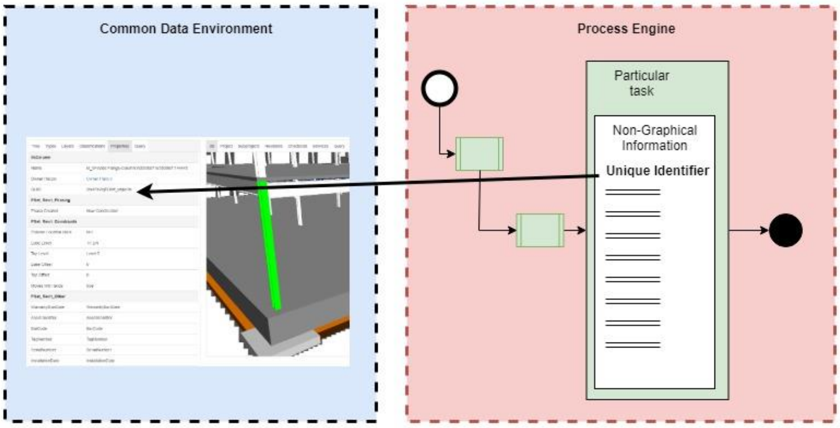


Figure 7-15 An overview of what was expected to occur when transferring information from the object specification form to the IFC model object

7.3.5.2 Adding information requirements

The project asset information requirements were first analysed to understand how the as-built information can be collected and then embedded within a graphical construction model. The steps taken to transfer the information into the BIM Server are shown in Figure 6-10 (Chapter 6).

1234-567-8910 *(Asset identifier)*	Fitting on external side of Location X
Location	Location X
Asset Number	23932032
Label Type	A2
Emergency Escape Lighting - Light Fitting - Self Contained Light Fitting	LED Strip
Circuit Number	DB A9/5/5L1
Duration	1000h
Self-Contained or CBU	Self-Contained
Type- Maintained/Non-Maintained	Maintained
Planning Type - Manual/System Monitored	Manual
System	N/A
Test Point	Key switch at distribution board
Location	323455
Manufacturer	Manufacturer Z
Model Number	XYZ LED
Serial Number	XYZ
Install date	dd-mm-yyyy
Warranty Date	dd-mm-yyyy

Table 7-3 Sample asset information sheet

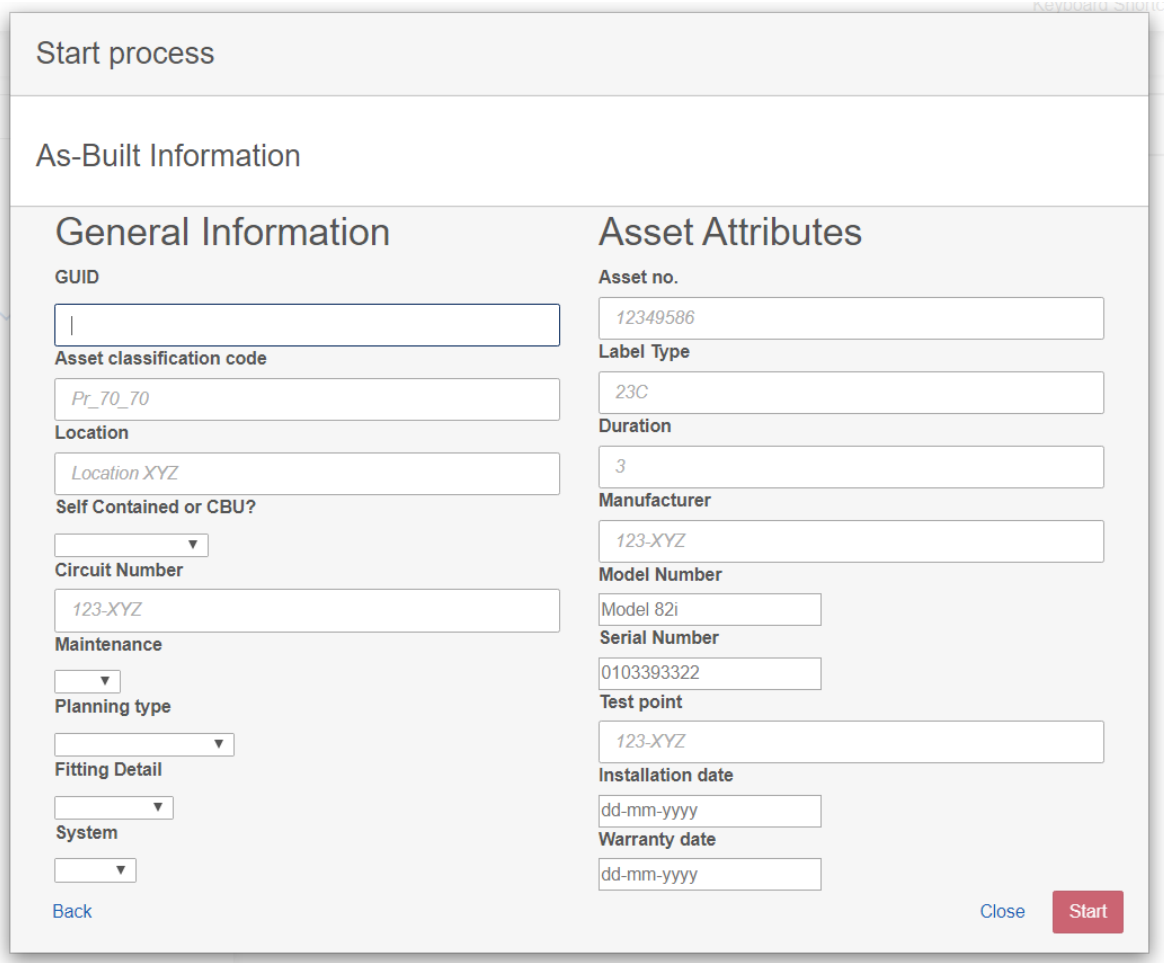


Figure 7-16 Form that is brought up when a task is brought up by the BPMN engine (with the attributes shown in Table 7-3)

Figure 7-16 is a screenshot of sample asset information shown in Table 7-3 represented in an HTML form within the BPMS. The aim was that depending on the information requirements at a specific stage of the project, HTML forms such as those shown in the figure could be brought up when a task is triggered, and then assigned to the relevant user.

Once this form had been completed, the information was stored as separate variables which could either be logged into the system, loaded back into the BPMS or transferred to an external application (the BIMServer in this case) based on the required tasks. The code which was used to create the form shown in Figure 7-16 can be found in Appendix E. The code includes JavaScript that helps store the variables which can then be used again in later tasks of the process.

7.3.5.3 Transferring information to server

The information that was collected from the HTML forms then had to be exchanged with the server so as to embed this information within the IFC files stored in it. To do so, this information had to be first stored as variables in a Java object. Then a BIM Server client Java application was created to communicate this information to the BIM Server. The BIM Server client application was referred to by a task within a process which triggers the application to communicate with the server. Figure 7-17 and Figure 7-18 shows the simple pseudocode for the client application that was to be triggered by the BPMS system when needed.

```
// Create a Java Class for the entered HTML data
Create Java class -> Data

// Create seperate Java object variables for each of the JavaScript (JS)
variables created in the HTML form
data (JS) -> Data (Java)
      variableX (JS) -> VariableX (Java)
      variableY (JS) -> VariableY (Java)
      variableZ (JS) -> VariableZ (Java)
```

Figure 7-17 Creating Java Object Variables from serialised JavaScript (JS) objects

```
// Establish connection with BIM server
Add BIMServer client Maven dependency to the application Project Object
Model (POM)

// Create a client factory and get authorisation from BIMServer
create bimServerClient -> JSON BIMServer client

// Get settings interface for BIMServer
bimServerClient.getSettingsInterface

// Access low-level interface
lowLevelInterface -> bimServerClient.getLowLevelInterface

// Access data added via the HTML form and link to specific project UUID
Data -> getVariable.HTMLData
Project -> getProjectByUUID

// Get lastest IFC model revision
latestModel -> getLastRevision

// Start transaction with Low Level Interface of BIMServer
Transaction -> lowLevelInterface.startTransaction

      // Identify which element by GUID the information should be added to
      Element -> latestmodel.getByGuid
      setAttributes -> latestModel()

// Commit transaction
Commit -> lowLevelInterface.commitTransaction
```

Figure 7-18 Components of the main Java application

Figure 7-17 illustrates the subroutine where the information from the HTML form (Figure 7-16) gets translated to information that can be understood by the Java application. The code shown in Appendix E (HTML Form) starts with an AngularJS script which creates a JavaScript Object and binds it to a variable (called 'element' in this example). This is then added to a process variable which was serialised as JSON. This serialised object is then be linked to the Java Object (Figure 7-17), which stores all the JavaScript Objects within it over the lifecycle of the relevant process.

Figure 7-18 describes the code that refers to the Java Object mentioned in the previous paragraph and the transfer of the relevant information within it to the BIMServer. This Java application is then be referred to by the BPMN process map, packaged as a WAR file as described in Figure 6-6, so that it can be parsed by the BPMN Engine. When creating the application, the BIMServer Maven dependencies need to be referred to within the application's Project Object Model (POM). The POM then loads the relevant Maven dependencies so that they can be referred to by the Java application. The application will first create a client, which establishes the settings interface of the BIMServer and loads the 'low level interface'. This 'low level interface' is what the client applications use to make changes to the IFC attributes of a model stored in the BIMServer.

Once a connection with the low-level interface had been made, the variables that were stored in the Java Object (Figure 7-17) could be referred to. The latest revision of the model stored in the server was referred to, and then a transaction between the BPMS and the BIMServer was started. The relevant information then was transferred and finally the transaction was committed which enables the BIMServer to embed the relevant information into the IFC. The automation of this subroutine was valuable as this information was being manually added by users and were not directly associated with the graphical model.

7.3.6 Demonstration

As described in Figure 7-5 this step involved the testing of the system and demonstration of its functions. Prior to the final iteration of this stage of the framework, the main components of the server and client were shown to the participants in order to understand specific user requirements. The final iteration involved the execution of processes defined in Section 7.3.4 in order to test the system that was developed. The volume of information that needs to be exchanged varies, and generally is lower at the early stages of a project.

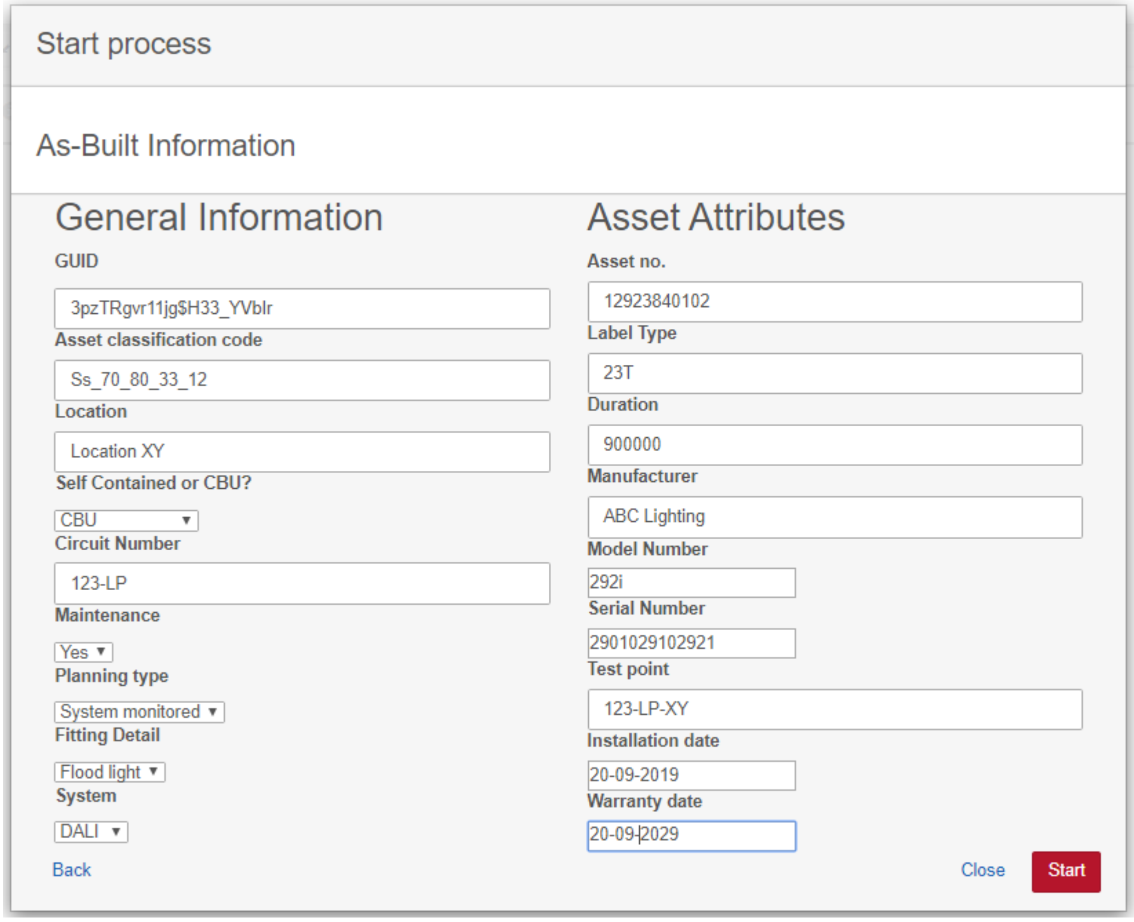


Figure 7-19 A filled in form (blank form shown in Figure 7-16) showing information for an emergency light fitting to be transferred to the BIMServer

In this test, the user had to enter the GUID for the element that the attributes were to be transferred to. The service task that processed the information and transferred it to the server was configured so as to send the information to the required individual attributes within the element (Emergency light in the case of Figure 7-19). A UUID was not required as described in section 6.6 as it would refer to the entire project and was therefore pre-programmed within the process application. Once the information is completed, the information was parsed, logged, and then sent to the BIMServer. All the information in the form was logged on the client application console almost instantaneously. The information was parsed, embedded within the relevant element and a response received from the BIMServer in just under 20 seconds as shown in the log in Figure 7-20. This information was being recorded by entering information within a spreadsheet and associating the information to a particular asset via a unique asset number as provided as shown in Figure 7-11. The advantage of recording the information in this manner was that the information was directly associated to the graphical model and this was beneficial as it automated the process as well as reduced potential human error that can be caused by manually associating attributes to elements in a model.

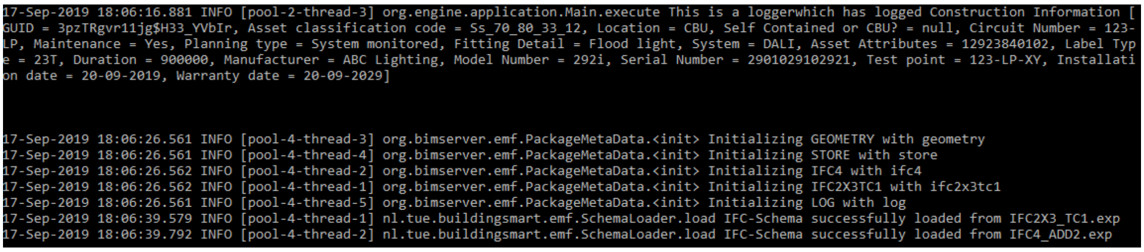


Figure 7-20 The Apache Tomcat console showing the transaction of the asset information in Figure 7-19 to the relevant IFC elements placed within the BIMServer

7.3.7 Evaluation

Similarly, to what was observed in the EBL project (Chapter 4), as-built asset information tends to be added manually and therefore can be challenging to query and update. The system that developed in Section 7.3.5 was able to take the information that was entered and add it within IFC objects automatically. The system that was developed over the course of this research helped with the process of meeting information requirements, monitoring processes, and carrying out the tasks efficiently. The system that was developed allows users to define the exact asset attributes that are required at each task of the process, this therefore ensured that there was unnecessary information that was added to the graphical model. The setting up forms within the system developed over the course of the chapter also gave users the option of defining the exact type of information that is entered within a form (Figure 7-19).

In terms of efficiency, embedding attributes within a non-graphical model took approximately (4-6 minutes) during the EBL project (Chapter 4) as it involved manually linking attributes with each other. In comparison, the system that was developed in this chapter embedded information within 20 seconds. Further, the ability to enter as-built information directly onto a form which then transferred the information directly, rather than manually adding attributes reduced the chances of human error.

There were several iterations that were carried out in order to develop the processes as well as the system that was developed when implementing the framework presented in Section 7.2. The outcomes of the implementation of the framework included maps of project specific processes and information requirements as well as a system that can parse these processes in order to govern the flow of project information. The process maps that were defined will be useful for project participants to understand certain workflows and these maps will be valuable when referring to in future projects.

7.4 Conclusion

This chapter aimed to answer research question 5:

Can the defined processes and system be adapted on an infrastructure project and what steps need to be taken to do so?

Chapters 4, 5, and 6 showed that there was a need to clearly define and govern processes on construction projects. The chapters also demonstrated how processes can be recorded and then executed in order to exchange information efficiently at an object level. Based on these findings, a framework was formulated (Section 7.2) in order to help participants on projects define information requirements and processes in order to manage them effectively. When the framework was implemented on a project, the participants provided their project specific information requirements and processes. These requirements were analysed and then added to a system developed based on their requirements. Section 7.3 presents the implementation of the framework in the context of an infrastructure project and the outcomes such as the process maps as well as the automation of a task that will help embed asset information within a graphical model.

Answering this research question contributed to:

- Formulating a framework which will aid participants on infrastructure projects align processes with information and system requirements in order to streamline the flow of information
- Providing process maps that can be altered and used on other projects

Chapter 8 Conclusion

This chapter will refer back to the research questions mentioned in Chapter 1 and will provide a summary of the work done in order to answer these questions. A summary of the attained research findings is proposed as well as their contributions to the body of knowledge. Subsequently, the limitations of the conducted research and recommended future work will be presented in order to build on the findings made.

8.1 Main research findings

This section will discuss the answers to five research questions that were formulated in order to test the research hypothesis. Each of the research questions will be restated along with a discussion on how they were addressed and then up followed by a discussion of the research hypothesis.

8.1.1 Outcomes of implementing VDC on an infrastructure project

The first research question was:

How is BIM/VDC implemented on linear infrastructure projects and what kind of information is generated during the process?

The answer to this research question aimed to complement the findings made during the literature review. The UK Standard Methods and Procedures (SMP) were implemented on the Eastern Bay Link (EBL) project (Chapter 4) in order to analyse the type of information that is produced during construction and what type of information is then handed over in order to manage the built asset.

Just over 21% of the information generated during the project was transferred to the asset operators. A large volume of the Asset Information Model (AIM) consisted of flat files (Almost 90% of the information was in PDF and JPEG format) given the higher suitability of this format in relation to current asset management systems. The construction phase evidenced that a preliminary agreement in relation to processes and adoption of certain systems will lead to the more effective implementation of BIM on projects. An observation was made that having this information in a machine readable and structured format based on the operator's asset information requirements has the potential for being of great value.

The outcomes of this stage evidenced a greater need for all project participants to clearly define their information requirements and execution plans. Further, these requirements and plans have to fit within contractual frameworks and have to be enforced in order to fully benefit from implementing VDC on projects.

8.1.2 Categorisation of challenges faced during implementation

The second research question was:

What are the main challenges that are faced when implementing VDC on this type of linear infrastructure project (The Eastern Bay Link)?

The implementation of VDC on the EBL project was useful to identify the potential challenges faced when attempting to align the SMP with existing construction processes. The challenges were grouped into three main categories (human related, processes related and technical challenges). This categorization benefitted the identification of the areas which needed to be addressed in order to effectively adopt VDC processes.

The literature review (Chapter 2) provided an overview of the challenges faced by industry as well as their potential faults. Despite rapid technological advances towards process and usability improvement, there is a need for a fundamental shift in the way organisations adopt these processes in order to benefit from them. As was shown in some surveys analysed in the review, there is still a large volume of jargon and contradictory statements within the SMP's that tends to lead towards the ineffective use of VDC on a project.

The implementation on the EBL project highlighted some of the challenges posed as a result of issues connected to human, process and technical problems. The research anticipated that technological issues such as those with shared coordinates (challenge 1, Appendix B) will be addressed by software vendors eventually. However, issues with receiving the appropriate Level of model Detail and Information (LOD and LOI) must be coordinated more effectively in order to ensure that uses such as clash coordination can be implemented effectively. The findings made when attempting to answer this research question showed that there is a need to ensure that information requirements and execution plans are governed more effectively in order to gain the full benefits of implementing VDC.

8.1.3 Definition of information requirements in a machine-readable format

The third research question was:

Upon identification of the main causes that hinder the adoption of BIM/VDC and affect the development of the AIM, how can current construction processes be redefined to alleviate these issues?

The answers to the previous two research questions showed that there can be a lack of coordination on projects leading to issues faced during construction as well as at handover. In order to fully benefit from the asset information produced during construction, asset operators should clearly define their information requirements. An observation was made that in certain instances, the lack of specific information requirements led to the production of information that is not compatible with existing asset management systems.

This research question was addressed by participating in a series of workshops that was attended by several industry experts (Chapter 5).

The findings attained at this research stage confirmed the occurrence of the challenges highlighted in research questions 1 and 2 in the context of infrastructure projects. In order to answer this research question, three scenarios leading to quality loss of the AIM and potentially costly rework were identified. These common sequences of events were recorded in order to understand which measures had to be taken by the asset operators, lead appointed parties and other appointed parties in order to effectively implement VDC.

These identified scenarios aided the mapping of construction processes and the information that is exchanged at various stages of a project. First a strategic process map was created in order to understand overall strategies and then a detailed set of process maps was presented in order to identify specific tasks. The approach taken to identify these scenarios and the processes fed into the framework that was proposed in the ensuing stage of the research.

8.1.4 Automation of specific processes

The fourth research question was:

Can processes and information requirements that have been defined be automated and what type of system would be able to execute and govern these processes?

Having identified specific processes and tasks, the ability to automate some of them was explored. The Design Science (DS) approach was used in order to create a prototype system that orchestrated the exchange of information between a 'process engine' and a server capable of handling Industry Foundation Class (IFC) models (Chapter 6).

The basic developed prototype system was initially tested by running a simple process which required the user to provide specific model-related data. These consisted namely in the information model placed in a BIM Server, a specific object within it and the attribute that the user wanted to add information to. The user was further requested to add the required value which was then transferred to the server containing the model and added to the relevant object.

The methodology adopted to define these system requirements as well as the prototype system was referred to when answering research question 5. The ability to define information requirements that are defined by users and get a Business Process Management System (BPMS) to execute them was deemed to be beneficial. The methodology adopted at this stage contributed to the formulation of the system development component of the framework proposed in Chapter 7.

8.1.5 Combination of process, information and system requirements

The fifth research question was:

Can the defined processes and system be adapted on an infrastructure project and what steps need to be taken to do so?

The outcomes of the work carried out in Chapters 5 and 6 demonstrated the potential to record processes and add information requirements within them. Grounding on these findings, a framework was presented in order to collect project specific requirements. The proposed framework guides users to refer to resources, then carry out a sequence of tasks in order to gather information and system requirements prior to deploying a system to manage project data.

Following to the framework definition, its validation was conducted on a project with the aim of understanding whether it is has the potential to be a feasible solution for other infrastructure projects. Therefore, sample information (Chapter 4), a basic process map (Chapter 5), and the system architecture of the prototype (Chapter 6) were presented to the project participants. The workflow dictated by the framework was followed in order to identify the project specific system requirements, information requirements and processes. Each of the steps and outcomes were discussed in Chapter 7 in order to show that the proposed framework can be implemented on other projects and will help users identify tasks that can be automated. The outcomes of answering this research question also provides sample information that is valuable for users using this framework on future projects.

8.1.6 Revisiting the research hypothesis

The discussion of the five research questions aided the final evaluation of the research hypothesis which is re-stated here as:

"Implementing Virtual Design and Construction processes on infrastructure projects is advantageous. Aligning these processes with existing asset and organisational information requirements will help achieve greater benefits over the lifecycle of an asset."

The individual components that led to the formulation and validation of the proposed framework were analysed at each stage of the research. Initially, the SMP's and general processes were implemented on an infrastructure project in order to identify the benefits as well as challenges faced during implementation. During the initial phase of this research it was highlighted the need for processes and information requirements to be project specific in order to fully benefit from the implementation of VDC. Most of the challenges that were identified at this stage of the research had to be addressed by formalising information requirements and their related processes. Agreeing on the processes to be executed and then governing them over the course of a project was deemed to be an effective solution to the problems identified during the first phase of the research. In order to address the challenge identified, the problem was broken down into two further stages. One of the stages was process discovery, and the next stage was system development which then led to the formulation of the framework presented at the end of this research.

In order to align existing processes with those prescribed in the SMP's, a series of steps had to be taken. First, existing organisational and asset requirements were gathered. Then a series of gateways were defined, and processes were mapped out to identify the interaction between various project participants.

The processes recorded were analysed, and where needed they were placed within an engine to execute the defined workflows and exchange information with external applications. By being able to orchestrate these processes, the potential of controlling the flow of information and meeting the project specific information requirements was shown. The automation of certain processes has the potential to also reduce certain human errors and can save time by reducing the amount of data entry that has to be done manually. This accurate machine readable as-built information can prove to be of great value when operating the asset.

8.2 Contribution to the body of knowledge

The contributions from this thesis relate to the development of a framework which can be used in order to gather information and system requirements in order to adopt VDC on projects effectively. Each of the Chapters from 4-6 developed and analysed various contributing elements which led to the development of the framework in Chapter 7. The contributions have been restated in this section in order to illustrate the contribution from this thesis.

Findings from current practice

- The handing over of an Asset Information Model for an infrastructure project showed that 21.02% of the Project Information Model was used, with 66.57% of the asset information being in PDF format
- Several common scenarios that occur when adopting SMP's on projects were presented in order to identify the stages of a project where issues have the potential to arise

- A series of process maps and linked information requirements were presented which are useful to understand the type of asset attributes that are required on projects
- A generic set of project stages and internal and external gateways were presented as they can be referred to in future projects when formulating information requirements and execution plans

Technical contributions

- A prototype system which has the capability of parsing processes and transferring information into a BIM environment was presented
- A workflow for recording processes and relevant information requirements which can then be added to the prototype system was introduced and tested

Overall contribution

- A framework that can be used in order to gather system and information requirements as well processes in order to deploy a system that can then govern them was presented and tested on a project

8.3 Limitations and future work

Despite the contributions delivered by the presented research, a few limitations exist and their consideration for future work is needed. Many of these limitations are related to specific system and programming requirements when implementing the framework.

There were a few limitations related to the logistics of implementing a system such as the one proposed in the project discussed in Chapter 7. IFC was chosen over other formats in order to privilege interoperability instead of proprietary extensions. Due to limitations related to the server used for the prototype system, there was a need to ensure that the attributes from the IFC file hosted within the system was transferred to an updated graphical model that is uploaded into the server. As a result of this, there will be a need to ensure that the system has a mechanism that will be able to update attributes within an updated model automatically.

The framework was implemented in order to understand project requirements and therefore did not fully investigate the development of the prototype system. There are several advantages in using to use BPMN to map processes and it was observed that due to the simple graphical representations of the model project participants were able to understand and interact with the models easily. Tools such as the BPMN lint tool that was used was useful to establish rules in order to ensure that the processes that were mapped met with the modelling standards. However, the system itself was developed in an experimental manner and therefore the code still has the potential to be optimised in order to make the exchange of information more efficient. One of the system requirements when implementing the framework was that users will be able to visualise the process alongside the IFC models. Using a solution such as bpmn.io (discussed briefly in Chapter 2) to visualise processes within the context of an IFC interface will benefit from being explored further.

The prototype system focused only the exchange of information between process tasks and IFC models. As was briefly discussed in Chapter 7, the process management system has the capability of transferring and parsing files and other forms of information. There is value in exploring the capabilities of the BPMS system and how it can be used to govern the flow of all the project processes in order to create an effective Digital Plan of Works (DPoW). Further, related modelling standards such as DMN for decisions was not explored fully when mapping processes and exploring system requirements. Including decision tables and graphs within process maps has the potential to make the system efficient and easier to use.

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Appendix A – Standards Review

USC	University of Southern California Capital Construction Development and Facilities Management services - *Building Information Guidelines* (University of Southern California, 2010)
Indiana	Indiana University - *BIM Guidelines & Standards for Architects, Engineers and Contractors* (Indiana University, 2012)
Senate	Senate Properties - *COBIM (Common BIM Requirements)* (Senate Properties, 2012)
Statsbygg	Statsbygg - *Statsbygg BIM manual 1.2.1* (Statsbygg, 2013)
COE	New York District, U.S. Army Corp of Engineers - *Official Manual For BIM projects* (U.S. Army Corps of Engineers, 2009)
GSA	General Services Administration - *GSA BIM Guide* (General Services Administration, 2007)
VA	Department of Veterans Affairs - *The VA BIM Guide* (U.S. Department of Veterans Affairs, 2010)
Ohio	State of Ohio General Services Division - *State of Ohio Building Information Modeling Protocol* (Ohio State, 2011)
NATSPEC	NATSPEC - *NATSPEC National BIM Guide* (NATSPEC, 2011)
NBIMS	National Institute of Building Sciences - BuildingSmart Alliance - *US National BIM Standard* (National Institute of Building Sciences, 2015b)
Singapore	Building and Construction Authority - *Singapore BIM Guide* (BCA - Building and Construction Authority, 2013)
CanBIM	CanBIM - *AEC (CAN) BIM Protocol* (CanBIM, 2012)
UK (S)	(Sacks review) BSI Standards Limited Industry - *BS 1192-4 and PAS 1192- 2:2013* (British Standards Institution, 2016c)
UK (G)	(Goonetillake review) BSI Standards Limited Industry - BS/PAS 1192 suite of standards, and related SMPs (British Standards Institution, 2016c)
ISO (UK Annex)	International Organisation for Standards - *ISO 19650-1, ISO 19650-2, PD 19650-0:2019 and referred to SMPs* (British Standards Institution, 2018b)
FHWA	Federal Highways Authority - *3D Engineered Models and e-Construction documents* (U.S. Department of Transportation Federal Highway Administration, 2017b)

Table A-1Summary of standards reviewed

	Employer	BIM team members							BIM manager's responsibility											
									Organisational				Technical							
	Owner/Architect /Contractor	BIM manager	BIM modellers	Construction	3D detailers	Designers	Coordinator	Data management	Coordination of BIM team	Strategic planning	Control of model editing permissions	Information process design	Model and data synchronisation	Interoperability practices	Model control	Data security/backup protocols	Clash detection/spatial coordination	Cloud or other storage	Updating the as-built BIM model	Specification of software tools
UK (S)	O	✓	✓		✓	✓			✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
UK (G)	O/E/C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
ISO (UK Annex)	O/E/C																			

Table A-2 Role of BIM Manager

Key
A - Architect
E - Engineer
O - Owner
C - Contractor
ND - Not Defined

	Mode of collaboration			Scope of functional requirements		
	Mandatory meetings	Big room	Digital collaboration	Model management	File sharing	Review and quality control
UK (S)			✓			
UK (G)			✓		✓	
ISO (UK Annex)			✓		✓	

Table A-3 Modes of collaboration

	Renovation	Laser scanning	O&M	COBie requirements
UK (S)				
UK (G)	○	●	●●●	●●●
ISO (UK Annex)	○	●	●●●	●●●

Table A-4 Operations and maintenance requirements

	Template provided? (Y/N)	Descriptive/ Prescriptive (D/P)	Legally binding? (Y/N)	Owner approval required? (Y/N)	Aspects defined or prescribe by the BEP							
					Roles and responsibilities	Collaboration/ communication/ information exchange	Analysis tools	Document update procedures	BIM project scope	Deliverables/ documentation	Modeling requirements	Model management
UK (S)	N	D	N	Y		✓		✓		✓		✓
UK (G)	Y	D	N	Y	✓	✓		✓	✓	✓	✓	✓
ISO (UK Annex)	N	P	N	Y		✓		✓	✓	✓	✓	✓

Table A-5 BIM Execution Plan

	Energy model and simulation	Model correctness/ clash detection	4D simulation	Cost estimation and analysis	Lighting	Acoustics	Security	Accessibility
UK (S)	●	●		●				
UK (G)	●	●	●	●				
ISO (UK Annex)	●	●	●	●				

Table A-6 Simulations

Key

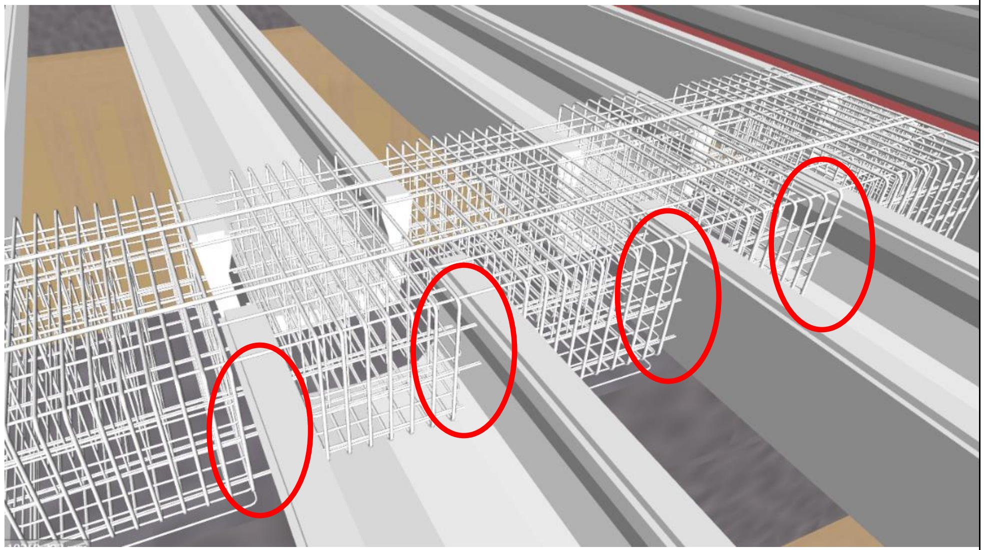
●● - Simulation type and software specified

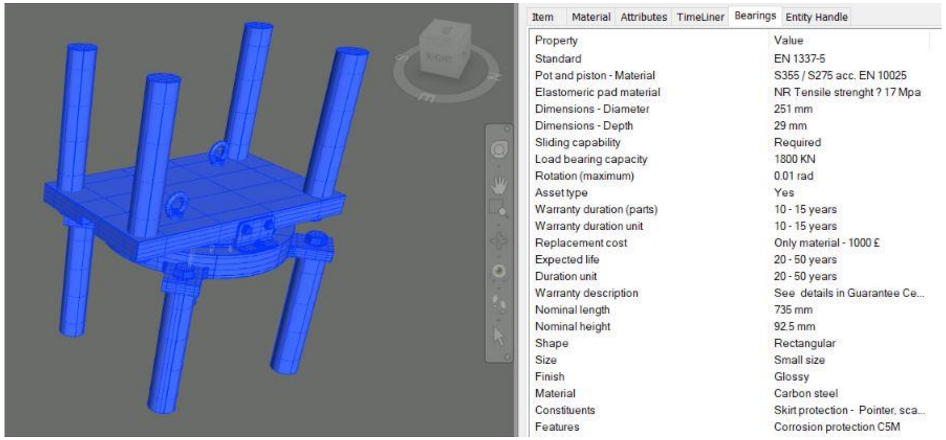
● - Simulation type specified

○ - Simulation is mentioned

Chapter 9 – EBL Lessons learned

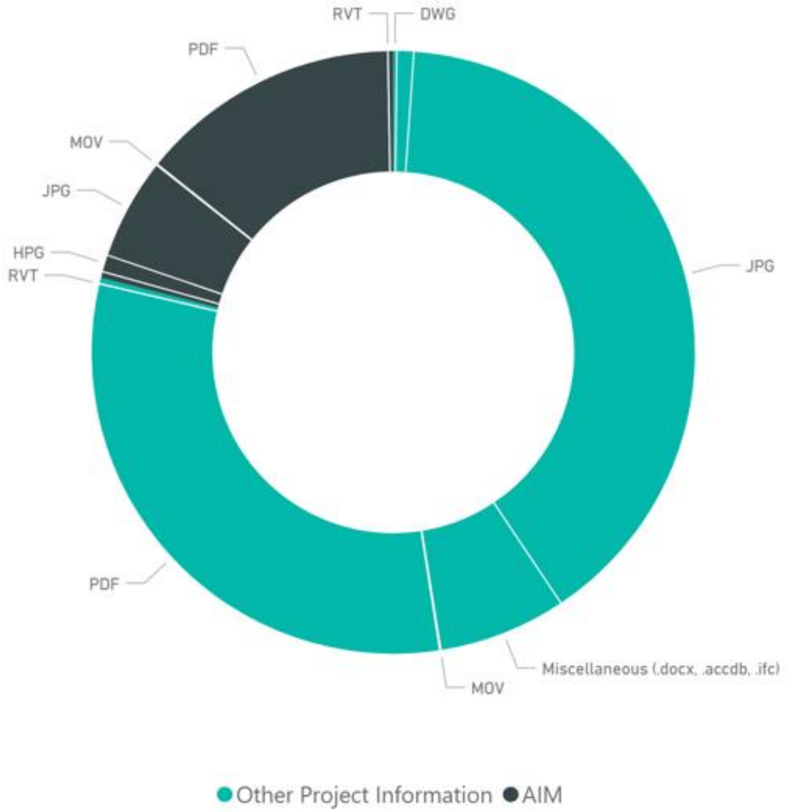
No.	Challenge faced	Description	Observations and potential solution
1	Shared coordinates	During the export from the authoring tools to the Navisworks cache file (.nwc) format, some models had mismatching coordinates. Therefore, the separate cache files had to be re-adjusted to ensure that the separate discipline specific models could be placed accurately within the federated model.	The various authoring tools being used would have been the cause of the export not occurring accurately. Further, the requirements were set in a manner where 3D models that could be placed within Navisworks should be produced. The models were produced by multiple supplier with a varying range of versions of authoring tools. Ideally the tool that the graphical information was to be produced in should have been specified clearly in the information requirements as well as agreed upon in the BEP. Even though the various models were adjusted to align with each other, there was a lack of confidence in using it.
2	Level of Detail (LOD)	The 'for construction' model should have had a	The model was created to a certain level of detail and then the construction drawings were finally produced in 2D. This eventually led to

		high enough level of detail to ensure that clashes were checked and therefore problems did not occur on site.	the clashing of rebar as clash checks were not run at this level of detail. Figure 9-1 is an example where the rebar was modelled for one of the bridge diaphragms.  *Figure 9-1 Zones that should have ideally been modelled, and where rebar clashed with the precast beams* The LOD was not appropriate in instances such as this, which therefore led to clashes that ideally could have been avoided. The BEP should have clearly specified that the models had to contain an acceptable level of detail.

3	Coordination with suppliers	The initial cost of buying software and hardware as well as training employees up deters SME’s and small manufacturers to adopt VDC processes and technology. Therefore, engaging with suppliers and ensuring that information is delivered in the required BIM format does not always occur	The suppliers had standard formats and specifications that were already being used, therefore it was not always feasible for them to provide information in the format required for the specific project. Product Data Templates were given to the relevant suppliers however, integrating this information in the asset owner’s asset management system did not bring much value.  *Figure 9-2 Bridge bearings with asset information embedded within it* Figure 9-2 is an example of the result of the successful coordination with a supplier which led to a model and product data being issued which was then embedded within it.
4	Coordination with designers	As was mentioned in problem 2, there were several clashes that could have been avoided.	Various disciplines were engaged in the design, and therefore it was essential that compatible tools were used, but also that when potential clashes were

		Ideally a workflow should have been set to ensure that there were clash coordination meetings to fix potential issues	suspected, an appropriate procedure was in place to fix the detected issues. This led to certain clashes that could have been avoided to occur.
5	Regularly updating the BEP	The MIDP should have been constantly updated based on the changes of the program. This led to the MIDP being outdated which led to certain information not being coordinated on time.	An agreement was not specified in terms of when the MIDP should be updated, and as a result had a knock-on effect which led to problem 1 and 2 occurring. If the milestones set on the MIDP were changed to correspond with schedule changes, activities such as clash coordination and 4D simulations could have been carried out more efficiently.

Chapter 10 – EBL project information breakdown



Model	Type	Count
AIM	DWG	89
AIM	HPG	238
AIM	JPG	1436
AIM	MOV	16
AIM	NWD	1
AIM	PDF	3694
AIM	RVT	1
AIM	XLS	74
Other Project Information	DWG	50
Other Project Information	HPG	238
Other Project Information	JPG	10437
Other Project Information	Miscellaneous (.docx, .accdb, .ifc)	1809
Other Project Information	MOV	14
Other Project Information	NWD	3
Other Project Information	PDF	8216
Other Project Information	RVT	4
Other Project Information	XLS	83
Total		**26403**

Figure 10-1 Breakdown of the information collect over the course of the EBL project

Chapter 11 – Screenshots

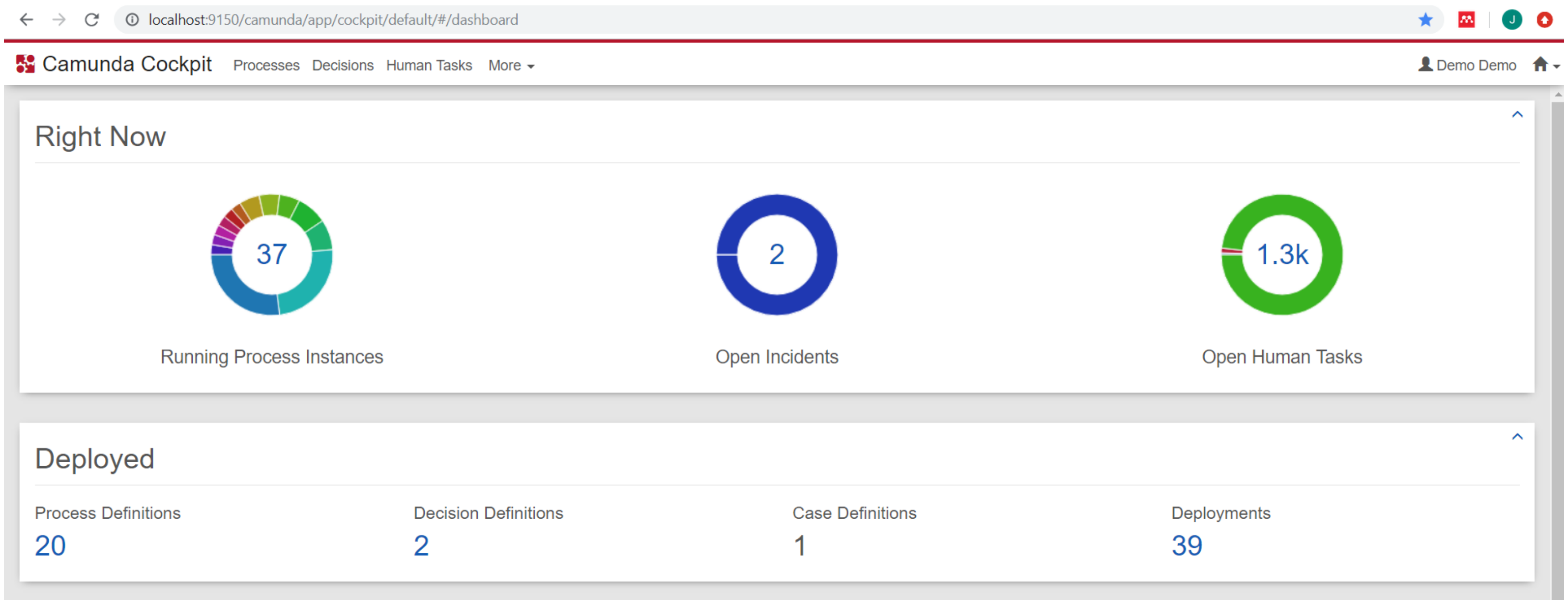
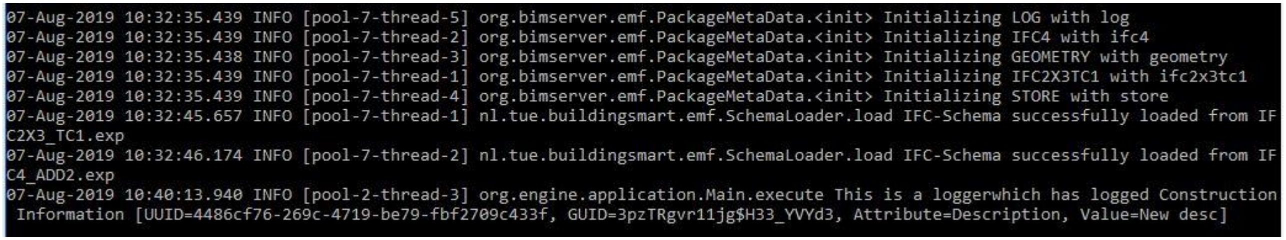


Figure 11-1 BPMS interface



```
07-Aug-2019 10:32:35.439 INFO [pool-7-thread-5] org.bimserver.emf.PackageMetaData.<init> Initializing LOG with log
07-Aug-2019 10:32:35.439 INFO [pool-7-thread-2] org.bimserver.emf.PackageMetaData.<init> Initializing IFC4 with ifc4
07-Aug-2019 10:32:35.438 INFO [pool-7-thread-3] org.bimserver.emf.PackageMetaData.<init> Initializing GEOMETRY with geometry
07-Aug-2019 10:32:35.439 INFO [pool-7-thread-1] org.bimserver.emf.PackageMetaData.<init> Initializing IFC2X3TC1 with ifc2x3tc1
07-Aug-2019 10:32:35.439 INFO [pool-7-thread-4] org.bimserver.emf.PackageMetaData.<init> Initializing STORE with store
07-Aug-2019 10:32:45.657 INFO [pool-7-thread-1] nl.tue.buildingsmart.emf.SchemaLoader.load IFC-Schema successfully loaded from IF
C2X3_TC1.exp
07-Aug-2019 10:32:46.174 INFO [pool-7-thread-2] nl.tue.buildingsmart.emf.SchemaLoader.load IFC-Schema successfully loaded from IF
C4_ADD2.exp
07-Aug-2019 10:40:13.940 INFO [pool-2-thread-3] org.engine.application.Main.execute This is a loggerwhich has logged Construction
 Information [UUID=4486cf76-269c-4719-be79-fbf2709c433f, GUID=3pzTRgvr11jg$H33_YVYd3, Attribute=Description, Value=New desc]
```

Figure 11-2 Camunda Tomcat servlet log

Chapter 12 – Raw results from implementation of framework

No.	Asset operator	Lead appointed party	Designers	Suppliers
1	Create a scope matrix			
2		Create certificate of compliance for approval		
3	Approve certificate of compliance			
4			Start design and handover preliminary model and asset schedule	
5	Send empty asset register to Main contractor along with a set of asset numbers			
6		Send register to various designers		
7			Designers assign numbers	
8				Register sent to suppliers to fill in asset info
9				Filled register sent back to Main Contractor
10		Upload the register into the asset management system, often manually		

Table 12-1 Basic steps that were first defined on the airport project

Sample HTML form

```
<form role="form" class="form-horizontal">

<div class="row">

  <script cam-script type="text/form-script">

    $scope.containments = [ 'Self Contained', 'CBU'];
    $scope.fittingDetails = [ 'LED Strip', 'Flood light'];
    $scope.assetLabellings = [ 'Yes', 'No'];
    $scope.maintenanceRegimes = [ 'Yes', 'No'];
    $scope.systems = [ 'DALI', 'Other'];
    $scope.types= ['Maintained', 'Non-Maintained', 'Exit sign'];
    $scope.planningTypes = ['System monitored', 'Manual check'];

    var element = $scope.element = {};

    camForm.on('form-loaded', function() {

      // declare a 'json' variable 'element'
      camForm.variableManager.createVariable({
        name: 'element',
        type: 'json',
        value: element
      });
    });

  </script>
  <div class="col-xs-6">
    <h2>General Information</h2>

            <div class="control-group">
            <label for="attributeType">
              Asset classification code
            </label>
            <div class="controls">
            <input class="form-control"
                    name="attributeType"
                    cam-variable-type="String"
                    cam-variable-name="attributeType"
                    placeholder="Pr_70_70"
                    type="text"
                    ng-model="element.attributeType"
                    />
            </div>
          </div>

          <div class="control-group">
            <label for="location">
              Location
            </label>
            <div class="controls">
            <input class="form-control"
                    name="location"
                    cam-variable-type="String"
                    cam-variable-name="location"
                    placeholder="Location XYZ"
                    type="text"
                    ng-model="element.location"
                    />
            </div>
          </div>

             <div class="control-group">
               <label class="control-label" for="containment">
                 Self Contained or CBU?
               </label>
```

```
                <div class="controls">
                  <select id="containment"
                           name="containment"
                           cam-variable-type
                               ng-model="element.containment"
                               ng-options="containment as containment for
containment in containments">
                  </select>
                </div>
              </div>

              <div class="control-group">
             <label for="assetNo">
               Circuit Number
             </label>
             <div class="controls">
             <input class="form-control"
                    name="circuitNumber"
                      cam-variable-type="String"
                      cam-variable-name="circuitNumber"
                      placeholder="123-XYZ"
                      type="text"
                      ng-model="element.circuitNumber"
                      />
             </div>
           </div>

           <div class="control-group">
                <label class="control-label" for="fittingDetail">
                   Maintenance
                </label>
                <div class="controls">
                  <select id="maintenanceRegime"
                               ng-model="element.maintenanceRegime"
                               ng-options="maintenanceRegime as
maintenanceRegime for maintenanceRegime in maintenanceRegimes">
                  </select>
                </div>
              </div>

              <div class="control-group">
                <label class="control-label" for="planningType">
                   Planning type
                </label>
                <div class="controls">
                  <select id="planningType"
                               ng-model="element.planningType"
                               ng-options="planningType as planningType for
planningType in planningTypes">
                  </select>
                </div>
              </div>

           <div class="control-group">
                <label class="control-label" for="fittingDetail">
                   Fitting Detail
                </label>
                <div class="controls">
                  <select id="fittingDetail"
                               ng-model="element.fittingDetail"
                               ng-options="fittingDetail as fittingDetail for
fittingDetail in fittingDetails">
                  </select>
                </div>
              </div>

              <div class="control-group">
                <label class="control-label" for="system">
```

```
                  System
                </label>
                <div class="controls">
                  <select id="system"
                                 ng-model="element.system"
                                 ng-options="system as system for system in
systems">
                  </select>
                </div>
              </div>

    </div>
    <div class="col-xs-6">
      <h2>Asset Attributes</h2>
          <div class="control-group">
              <label for="assetNo">
                Asset no.
              </label>
              <div class="controls">
              <input class="form-control"
                      name="assetNumber"
                      cam-variable-type="String"
                      cam-variable-name="assetNumber"
                      placeholder="12349586"
                      type="text"
                      ng-model="element.assetNumber"
                      />
            </div>
            </div>


            <div class="control-group">
              <label for="assetNo">
                Label Type
              </label>
              <div class="controls">
              <input class="form-control"
                      name="labelType"
                      cam-variable-type="String"
                      cam-variable-name="labelType"
                      placeholder="23C"
                      type="text"
                      ng-model="element.labelType"
                      />
              </div>
            </div>

            <div class="control-group"> <!-- Scroll -->
              <label for="duration">
                Duration
              </label>
              <input class="form-control"
                      name="duration"
                      cam-variable-type="Double"
                      cam-variable-name="duration"
                      min = "1"
                      placeholder="3"
                      type="text"
                      ng-model="element.duration"/>
            </div>

            <div class="control-group">
              <label for="manufacturer">
                Manufacturer
              </label>
              <div class="controls">
              <input class="form-control"
                     name="manufacturer"
```

```
          cam-variable-type="String"
          cam-variable-name="manufacturer"
          placeholder="123-XYZ"
          type="text"
          ng-model="element.manufacturer"
          >
  </div>
</div>

<div class="control-group">
  <label for="modelNumber">
    Model Number
  </label>
  <div class="controls">
  <input class="control-group"
          name="modelNumber"
          cam-variable-type="String"
          cam-variable-name="modelNumber"
          placeholder="Model 82i"
          type="text"
          ng-model="element.modelNumber">
</div>
</div>

<div class="control-group">
  <label for="serialNumber">
    Serial Number
  </label>
  <div class="controls">
  <input class="control-group"
          name="serialNumber"
          cam-variable-type="String"
          cam-variable-name="serialNumber"
          placeholder="0103393322"
          type="text"
          ng-model="element.serialNumber">
</div>
</div>

<div class="control-group">
  <label for="assetNo">
    Test point
  </label>
  <div class="controls">
  <input class="form-control"
         name="testPoint"
          cam-variable-type="String"
          cam-variable-name="testPoint"
          placeholder="123-XYZ"
          type="text"
          ng-model="element.testPoint"
          >
  </div>
</div>

<div class="control-group">
  <label for="installationDate">
    Installation date
  </label>
  <div class="controls">
  <input class="control-group"
          name="installationDate"
          cam-variable-type="String"
          cam-variable-name="installationDate"
          placeholder="dd-mm-yyyy"
          type="text"
          ng-model="element.installationDate">
</div>
```

```
          </div>

          <div class="control-group">
            <label for="warrantyDate">
              Warranty date
            </label>
            <div class="controls">
            <input class="control-group"
                   name="warrantyDate"
                   cam-variable-type="String"
                   cam-variable-name="warrantyDate"
                   placeholder="dd-mm-yyyy"
                   type="text"
                   ng-model="element.warrantyDate">
          </div>
          </div>
</div>
</div>
</form>
```